The Dahlia Greidinger International Symposium - 2009

Crop Production in the 21st Century: Global Climate Change, Environmental Risks and Water Scarcity

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Crop Production in the 21st Century: Global Climate Change, Environmental Risks and Water Scarcity

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Preface

The symposium aimed to re-examine knowledge gaps and R&D directions and needs, and to identify –based on this examination– possible modes and new approaches for coping with the increasing severity of water scarcity and quality and soil degradation. These issues were considered in terms of their effects on food security, that is, the foreseen difficulties in *Crop and Food Production in a World of Global Changes, Environmental Problems, and Water Scarcity*. Attention was also devoted to problems in arid and semi-arid regions, and specifically in the Eastern Mediterranean or in similar climatic regions, where problems of both fresh water supply and trans-boundary concerns must be managed. Accordingly, nine sessions were devoted to cover the main and diverse issues relevant to the objectives of the symposium. Thanks to the generous support of **BARD** and the **Dahlia Greidinger Fund**, a unique opportunity was provided for gathering a significant number of leading scientists and researchers from the US, Israel, Europe, China and India, to discuss the important issues and present approaches from different disciplines. This assembly of experts allowed a multi-disciplinary yet integrative and comprehensive view of *Crop and Food Production in a World of Global Changes, Environmental Problems, and Water Scarcity*.

The first four topics addressed in the symposium (and thus four chapters in the proceedings) dealt with more general and global aspects: *Global Climate Change and Water Issues,*" "*Agriculture and Global Changes,*" "*Irrigation, Plant Nutrition, and Pollution*" and "*Carbon Sequestration and Soil Productivity.*" State of the art knowledge and information with special reference to the symposium's main theme were highlighted by worldwide leading experts. These were followed by presentations in which "*Advances in Plant Sciences*" were introduced by leading scientists in this discipline. In the next four sessions emphasis was placed on the more technical aspects relevant to the main theme: "*Water Resources Management*" (with an emphasis on region-specific and transboundary aspects), "*Advances in Soil-Water-Plant Modeling,*" followed by "*Irrigation with Reclaimed Wastewater*," where key questions related to the sustainability of using reclaimed wastewater were highlighted, and ending with "*Advances in Irrigation*."

At the end of this proceedings book, there is a summary highlighting the important findings and the main points stressed in the presentations as well as the subjects that require further investigation or issues that should serve as key topics for future research. This is followed by a short summary of the minutes taken at the final panel discussion held after all of the sessions had been concluded.

We would like to reiterate our appreciation to **BARD** and the **Dahlia Greidinger Memorial Fund** for their generous support, which made this important meeting possible. Thanks are also due to the Grand Water Research Institute – GWRI and the Faculty of Civil and Environmental

Engineering at the Technion, and Fertilizers and Chemicals Ltd., who contributed their time and effort and resources to support this event. Special thanks are also given to members of the Scientific Committee, the staff of the Department of "Environmental Engineering, Water and Agriculture, and particularly to Mrs. Lee Cornfield, who efficiently coordinated all the administrative arrangements and took responsibility over editing and publishing the Calls, The Book of Abstracts and finally these Proceedings.

In the name of the organizing committee,

Avi Shaviv and Ramesh Kanwar

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Session 1: Global Climate Change and Water Issues

FUTURE PREDICTIONS OF MOISTURE BUDGET OVER THE EASTERN MEDITERRANEAN BASED ON A SUPER-HIGH-RESOLUTION GLOBAL MODEL

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ABSTRACT

Three different spatial resolution climate datasets, Era-40 reanalysis, CRU and 20 km JMA's GCM, as well as the IMS's observed dataset are employed to study the current wet season (from Oct. to Apr.) moisture field in a rectangular domain of about 3.96×10^6 km^2 over the eastern Mediterranean and part of the Middle East region. The research time period is from 1979 to 2002. The future (2075-2099) moisture field changes based on the prediction of the 20km GCM was also carried out.

We found that among the three climate datasets, the 20km GCM better presents the current precipitation regime over the E. Mediterranean (EM) compared with the other two datasets. The precipitation is much underestimated, even by a factor of two in some places, from ERA-40. The evaporation result from ERA-40 dataset was also under-evaluated by about 200 mm/wet season compared to the 20km GCM in the EM. The future projection of the moisture field based only on 20km GCM suggests that at the end of this century, an increasing evaporation with the magnitude of 150-200, 200-250 and over 300 mm/season at the water bodies of eastern Med., Red Sea and Persian Gulf, are projected; a significant decrease of precipitation is found at the western part of Turkey, western part of Syria, entire Israel and Lebanon, with a magnitude of over 200 mm/season. The famous Fertile Crescent precipitation strip, located in the Mid-East, also becomes much drier. An increase of precipitation is projected over Iraq and part of Iran. The total moisture budget as expressed by the precipitation minus evaporation (P-E) analysis further confirmed that a drier scenario is inevitable at the end of this century for the water body area and

most of the coastline countries. Consequently, a water crisis is an inevitable challenge for the drier countries within the research region in the future.

INTRODUCTION

The Middle-East (ME) located on the border between the mid-latitudes and subtropics, is interesting both in its meteorological and climatological aspects being predominantly a semi-arid to arid region with sharp climate gradients. Lack of water is one of the greatest problems as it is a key resource affecting social health and political stability in the ME. This problem may become even more severe under global warming and make the ME extremely vulnerable to any (natural or anthropogenic) reductions in available surface water, rendering it highly sensitive to changes in climate. The IPCC fourth assessment report suggested that the eastern Mediterranean (EM) region would become significantly drier under a future climate scenario, with potentially devastating impact on the population (IPCC, 2007). Therefore, a better understanding of the distribution of the atmospheric moisture budget of this region, especially for the main two components of atmospheric moisture budget, i.e., precipitation (P) and evaporation (E), is of great significance.

The exact mechanism controlling precipitation in the ME region is complex, and precipitation amounts and distributions are largely affected by the topography and land-sea distribution (Ozsoy, 1981). However, numerous studies concerning the precipitation regime in the ME have been conducted during the past several decades by using different kinds of data sets, such as observed data, reanalysis data, satellite data, as well as the climate model data (Alpert et al., 2002; Mariotti et al., 2002a,b; Alpert et al., 2007). Based on the focus of the research of precipitation in the ME, it might be classified as dynamical, climatological or hydrological. Dynamically, Zangvil and Druian (1990) investigated the relation between the upper air trough and the location of precipitation in Israel. Price et al. (1998) even investigated the relationship between the El Niño and precipitation in Israel. Krichak and Alpert (2005) studied the relations between the EM precipitation and the indices of the East-Atlantic West Russia pattern. Climatologically, Alpert et al. (2002) have analyzed observational databases over several areas of the Mediterranean basin during the 20th century, and concluded that there exists a dominant increase in extreme daily rainfall events together with a slight decrease in total values. Seager et al. (2007) studied the climate change of the southwestern North America by using an ensemble of regional climate models; their results also suggest that the Mediterranean region will be drier at the end of this century. Hydrologically, Mariotti, et al. (2002a,b) carried out a detailed study of the hydrological cycle and water budget in the Mediterranean region.

The climate models have been widely used to do both global and regional scale of climate study since it has been introduced, particularly with some high temporal and spatial resolution climate models. However, the global climate model (GCM) is usually with relative coarse spatial resolution, about 100 km to 300 km; therefore, it cannot capture well the small scale factors which have an important influence on the local climate, particularly over the Mediterranean. On the other hand, the regional climate model (RCM) has relative fine spatial and temporal resolution, but besides being computationally expensive, it also needs the lateral boundary condition data, which usually comes from the GCM to drive the RCM. The very high spatial resolution GCM model employed here addresses the disadvantages that exist in both the GCM and RCM. It avoids the problems of the unfit-in-scale of the lateral boundary condition, but also can incorporate interactions between global scale and regional scale explicitly. Here, we study except for several traditional datasets, also a high-resolution 20km grid GCM, which was developed in the Japan Meteorological Agency (JMA) in order to investigate the current and future precipitation regime in the ME.

METHODS

Data

To study the current precipitation regime of the EM, several datasets have been used here. These include, first, the global time series dataset based on rain gauge measurements (land only) from the climate research unit (CRU, in brevity; Mitchell and Jones, 2005). The grid horizontal resolution is 0.5×0.5 degree, and the time period is available from 1901 to 2002. Second is the The European Center for Medium-range Weather Forecast (ECMWF) reanalysis dataset (ERA-40, in brevity; Kallberg et al., 2004). This data covers the time period from mid-1957 until 2002. Originally, ERA-40 has a spectral representation based on a triangular truncation at wave number 156 or at 1.125 degree. horizontal resolution using a Gaussian grid (Gibson et al., 1997). However, the spatial resolution of ERA-40 data used in this study is 2.5 ×2.5 degree. The third database is based on daily precipitation for several selected observed stations inside Israel from the Israel Meteorological Service (IMS) with different time periods. The fourth database is the Japanese Meteorological Agency's (JMA) super-high spatial resolution (about 20 km) grid GCM, which is a climate-model version of a GCM. A detailed description of the model is given in Mizuta et al. (2006). Two runs of the 20km GCM cover the time periods 1979-2007 for current/control run and 2075-2099 for the future run. The monthly mean precipitation taken from datasets 1, 2 and 4 are used here while the daily mean precipitation is also available for dataset 4. Since the current 20km run covers the time period 1979-2007, while the ERA-40 and CRU data are available only until 2002, the time period selected for the current atmospheric moisture budget research is 1979-2002, in order to make all main three datasets cover the same period.

Research Area and Study Time Period

The study area covers the main part of the EM and a good part of the ME, and was chosen to be 27°-41°N and 22°-50°E with a total area of about 3.96×10^6 km^2. Also, in order to study the moisture field over the ME, a sub-region within this area was defined by the latitude 30°-37°N and longitude 30°-40°E with Israel located approximately in the center of this area.

Since the main rainy season in the EM region is October-April, only this 7 month wet season period over 23 years was chosen to study the precipitation regime, as the remaining dry season has only very little influence on the total annual precipitation.

RESULTS OF THE MOISTURE BALANCE COMPONENTS AND DISCUSSIONS

Seasonal Precipitation

The average total precipitation for the wet season (Oct.-Apr.) of the ME and zoomed in of the EM from 1979 to 2002 is given in Fig 1. In general, the less than 50 mm precipitation contour line can be clearly defined from these three charts with more or less the same locations. The latitudinal gradient is the predominant feature of precipitation in the EM. A clear precipitation strip with one peak zone of precipitation, approximately located at 37°N, forms the famous "Fertile Crescent"strip due to the rain shadow effects generated by the mountains of Taurus, Elburz and Zagros in this area. However, the peak of total precipitation of the crescent strip from ERA-40, CRU and 20km GCM are different, with the corresponding values of 500-700, 700-900 and 900-1100 mm, respectively. Another maximum of average total precipitation also can be identified along the eastern and northern coastlines of EM, with the amount of precipitation of 350-500, 500-700 and over 1100 for the ERA-40, CRU and 20km GCM, respectively. The zoomed-in ME in Fig.1 shows the more detailed distribution of the precipitation in this region, with a sharp eastward decreasing gradient of precipitation that starts from the eastern coastline of the Mediterranean. This gradient can be explicitly defined only in the CRU and 20km GCM, with the 20km with sharper patterns to be discussed later in comparison with rain gauges. The 20km GCM further shows its two centers of peak precipitation in the east and north coast line of EM with the value over 1100 mm/season, but the results from CRU and ERA-40 are significantly lower compared to values in the 20km GCM. Does the over evaluated amount of precipitation from 20km GCM reflect the reality of precipitation regime in this area?

To ascertain that the average total seasonal precipitation that results from the three different datasets fits with the observed data, six points are selected sequentially from south to north, which make an approximate south-to-north cross-section along the EM coast, and covers the countries of Egypt, Israel, Lebanon and Turkey. The detailed information about these six points is shown in Table 1. The reason for selecting these six stations, which are all located near the coast line, was as follows. Both the land-sea interaction and the significant change of topography from sea to land have a strong influence on the precipitation regime of the coastal area. Fig. 2 shows that the seasonal averaged total precipitation of the six selected stations results from ERA-40 are significantly underestimated compared to the observation data, except for the stations of Cairo and Beer-Sheva. ERA-40 even catches less than the half of the total precipitation in Tel-Aviv and Beirut.

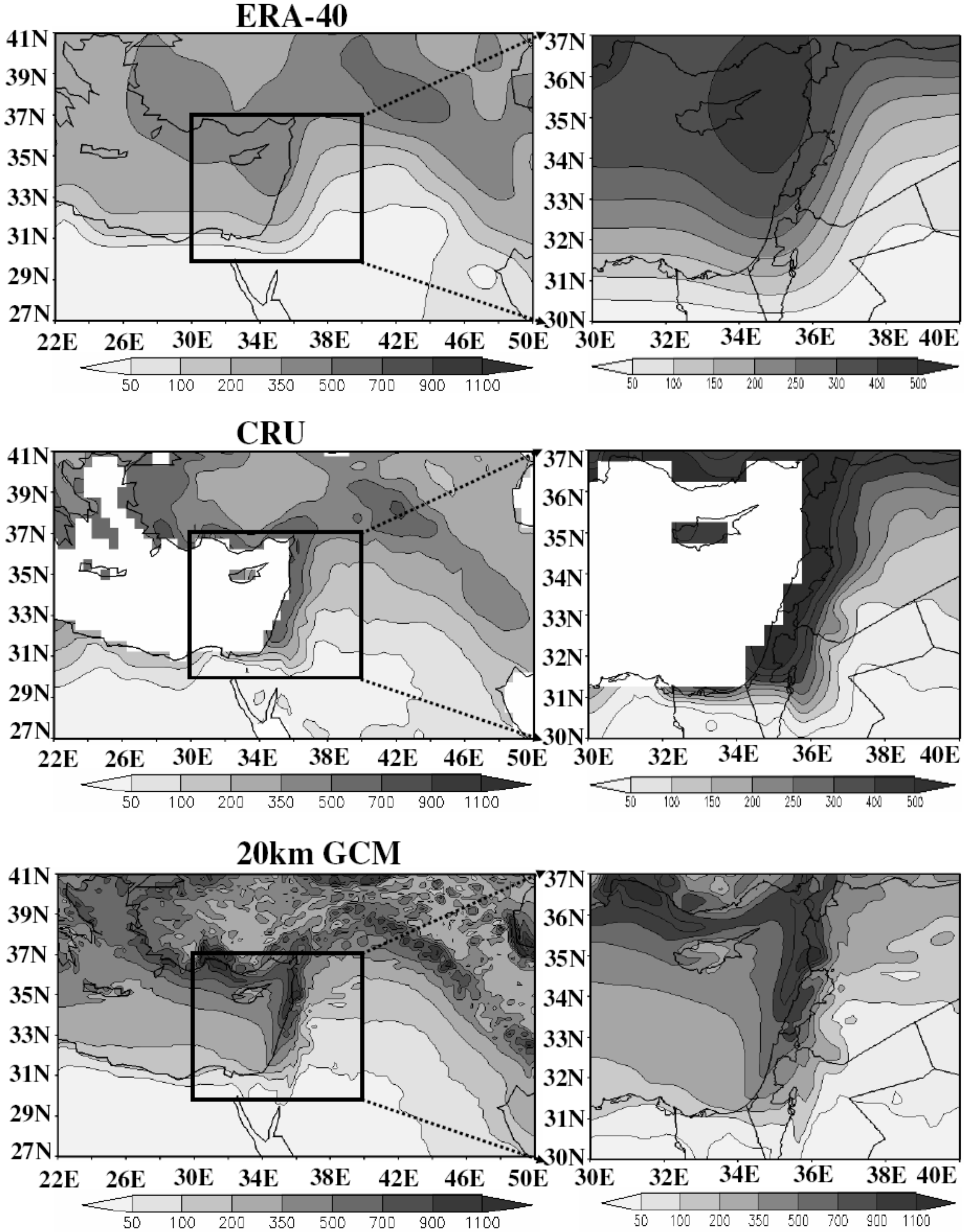

Fig. 1: Total seasonal (Oct.-Apr.) precipitation for the Eastern Mediterranean(EM) and the Middle-East (left panel) and zoomed in over the EM (right panel). Averaging time period is 1979 - 2002. Unit: mm/season.

This finding is consistent with Mariotti et al. (2002a), in which several IPCC datasets were used to study the hydrological circle of the Mediterranean. The CRU and the 20km GCM results show a better estimation, and the 20km GCM's results are quite close to the observed data. The standard deviation of errors for each model is shown in Table 1 and further confirms this fact. However, the CRU is unable to reproduce the peak precipitation in Beirut, but with an error of over 150 mm. It can be concluded that the 20km GCM better captures the total amounts of precipitation for the selected six stations.

Table 1. Geographic location of the stations used for the models' evaluation. Observed total seasonal (Oct.-Apr.) precipitation is based on sources listed under the Table. The right-most column shows the standard-deviation of the errors for each model. The accurate values of precipitation were obtained by the same interpolation method (GrADS). For comparison, the ERA-40, CRU and 20km GCM run are listed in units of mm/season.

	Cairo	Beer-Sheva	Tel-Aviv	Haifa	Beirut	Adana	SD(E)
Longitude	31.37°E	34.90°E	34.77°E	34.98°E	35.51°E	35.32°E	-
Latitude	30.05°N	31.25°N	32.02°N	32.82°N	33.98°N	37°N	-
Observed	26*	201**	527**	534**	840***	550***	0
ERA-40	8	165	245	320	380	425	167
CRU	21	220	560	520	680	670	91
20kmGCM	39	210	480	590	780	550	43

*WeatherUnderground **Israel Meteorological Service *** Weatherbase.com

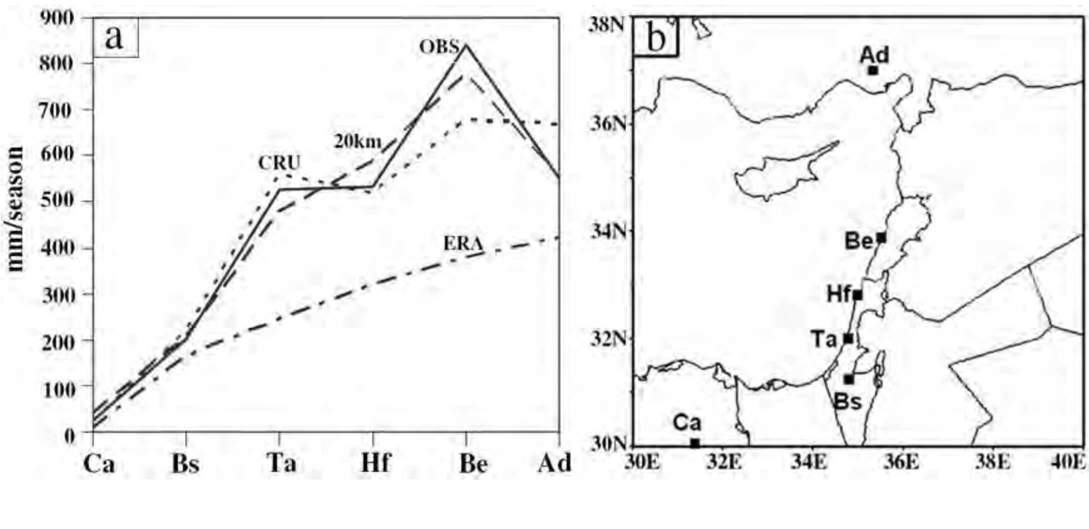

Fig 2: (a) Comparison of average total observed seasonal precipitation with three model data for the selected 6 stations, which make an approximate south-to-north cross-section along the EM coast. The six stations are from south-to-north, Egypt---Cairo (Ca,); Israel---Beer-Sheva (Bs), Tel-Aviv (Ta), Haifa (Hf); Lebanon---Beirut (Be) and Turkey---Adana (Ad). The three models are the European reanalysis (ERA, — - —), the Climate Research Unit (CRU, - - - -) and Japanese Meteorological Agency's 20km GCM run (20km, — —). Unit: mm/season. (b) Eastern Mediterranean map indicating the location of the six stations.

Monthly Distribution of Rainfall

It is also interesting how the 20km GCM captures the monthly precipitation regimes. The state of Israel was selected, not only because it is a transition zone between hyper-arid and relatively humid regions, but also because it is a complicated topographic zone for this small country. Therefore, the region of Israel was arbitrarily divided into three parts, northern, centeral and southern parts, see Fig.3. For each part, two stations are selected to calculate the monthly mean precipitation based on rain gauge data with the time period from 1979 to 2002. Fig. 4 shows that, in general, there is a good agreement between the precipitation from the rain gauge and the 20km GCM, with the correlation coefficient for the monthly precipitation between northern, centeral, southern parts and the 20km GCM -0.97, 0.93 and 0.96, respectively, with 99% level of statistical significance. The model credibly describes the dry period from May to August when only very little precipitation amounts are observed. However, Fig. 4 shows that the model underestimated the precipitation of the autumn, and a larger error can be seen in Jerusalem at an altitude of 750 meters, probably due to the fact that the spatial resolution of the model is still not fine enough to accurately describe the orographic rainfall. The importance of the high-resolution in Jerusalem was highlighted by Shafir and Alpert (1990). Another model deviation is its overestimation of the precipitation for most of the wet seasons in Elat. But the absolute quantity of precipitation in Elat is very small. Overall, it can be concluded that the 20km GCM performs very well in simulating the current monthly rainfall distribution in the research region.

Fig.3 : Geographic map indicating the selected six stations focused on Israel. Empty squares denote northern stations, cross (+) for central stations and solid squares for the southern part of Israel. Contour lines show the topography (m) with 200 m interval.

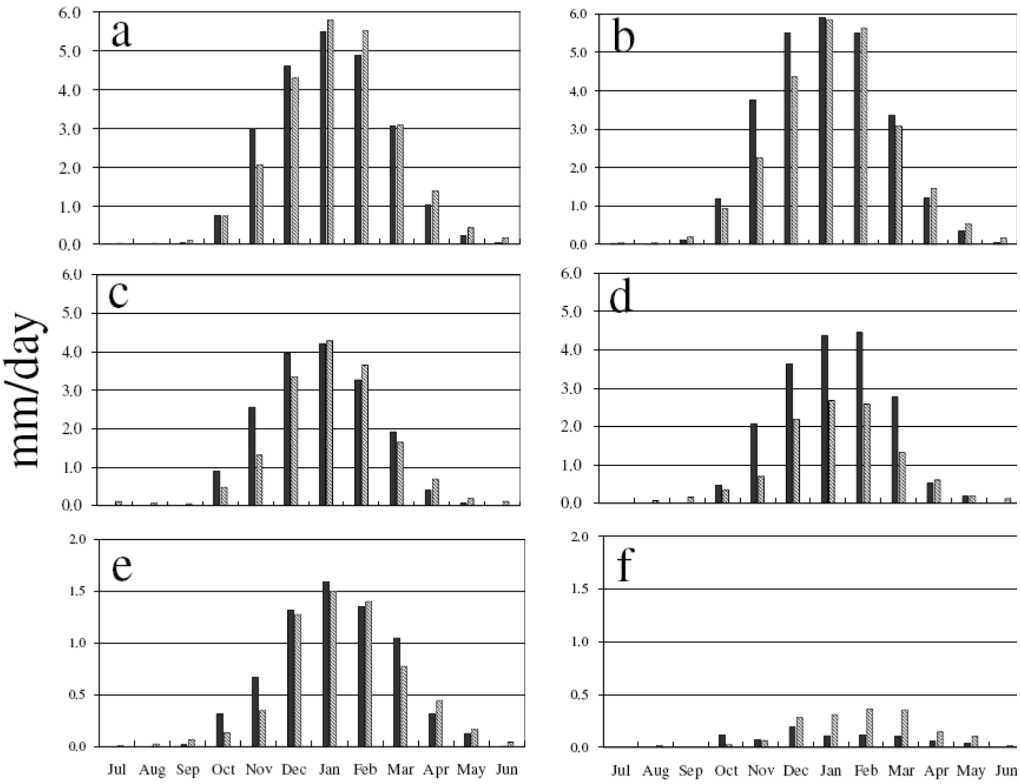

Fig. 4: Comparison of monthly mean precipitation from observed rain gauges (black column) and 20km GCM (grey column) for selected six stations in Israel based on their locations. Unit: mm/day. The selected stations are: *Northern Israel*: (a) Har-Knaan, (b) Eilon; *Center Israel*: (c) Tel-Aviv, (d) Jerusalem; *Southern Israel*: (e) Beer-Sheva, (f) Elat.

Evaporation

Fig. 5 shows the evaporation (E) results from the ERA-40 and the 20km GCM. As expected, the water body shows larger evaporation values than the land area. The ERA-40 does not show the sharp land-sea boundary as in the 20km. Three maxima centers of evaporation over the ME are noticed, Red Sea and Persian Gulf can be obviously seen both in the ERA-40 and the 20km GCM. The E peak is located at the center of the EM in the ERA-40, but it is located in the northeast corner of EM in the 20km GCM. It looks reasonable that the maximum evaporation is located where the maximum precipitation is as seen from the 20km GCM simulation. The maximum evaporation in the EM is 900-1100 mm/season in the ERA-40 compared to over 1100 mm/season in the 20km GCM. This suggests that the E is underestimated in the reanalysis data over the Mediterranean region as also suggested by Mariotti et al. (2002a).

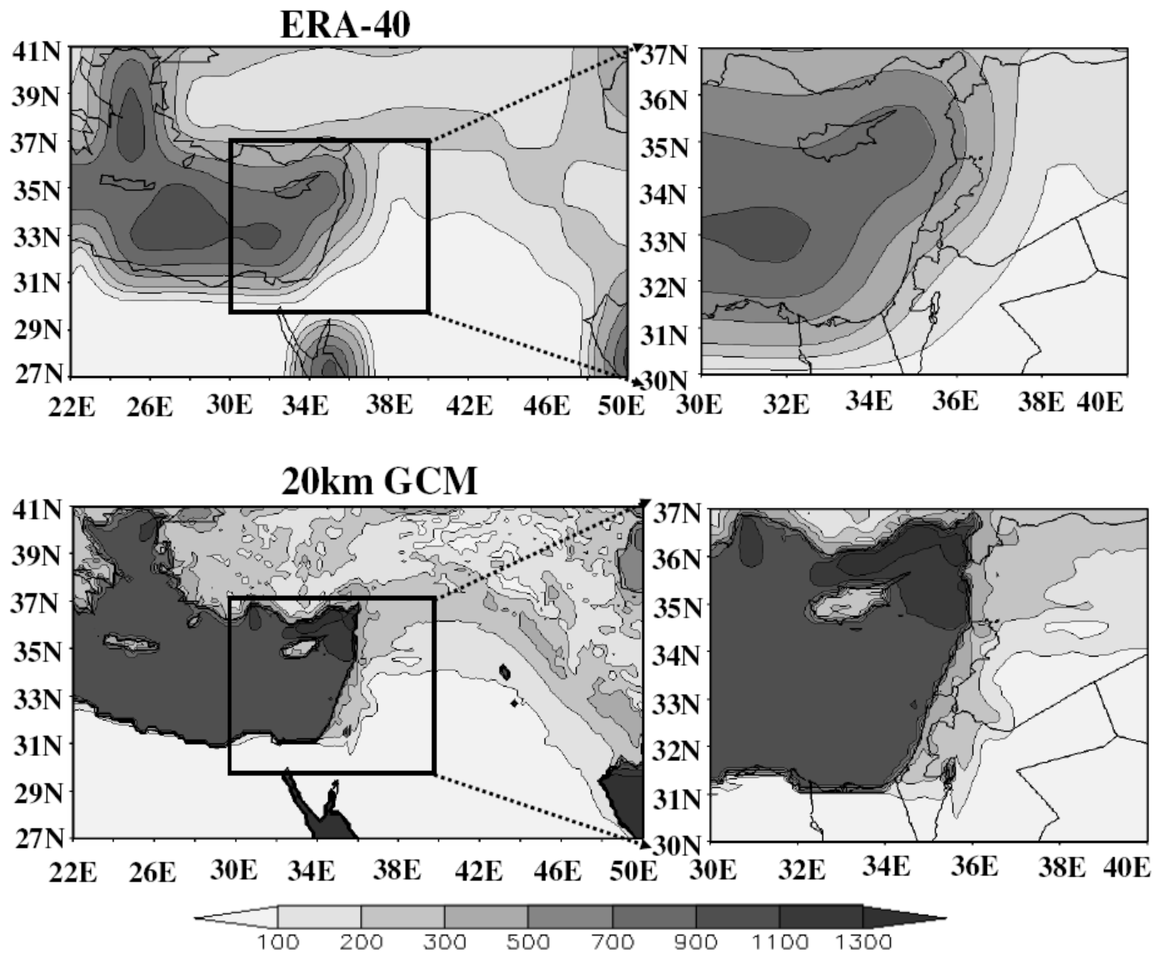

Fig.5: Same as Fig. 1 but for evaporation.

Future Changes of E, P and P-E

Fig. 6 shows the difference of E, P and P-E between the future (2075-2099) results from a certain emission scenarios defined by IPCC and current climate (1979-2007). The E increase is clearly noticed over the water body, with maximum value of 150-200, 200-250 and over 300 mm/season at the EM, Red Sea and the Persian Gulf, respectively (Fig. 6a). The center of E increases in the EM is located along the northern boundary with the magnitude of 150-200 mm. A small increasing area over the “Fertile Crescent” can also be seen. There are small changes in North Africa and most of the inland Middle East countries. An evaporation decrease can only be found in some islands inside the EM, i.e., island of Crete and Cyprus, as well as the joint boundary between Israel and Jordan.

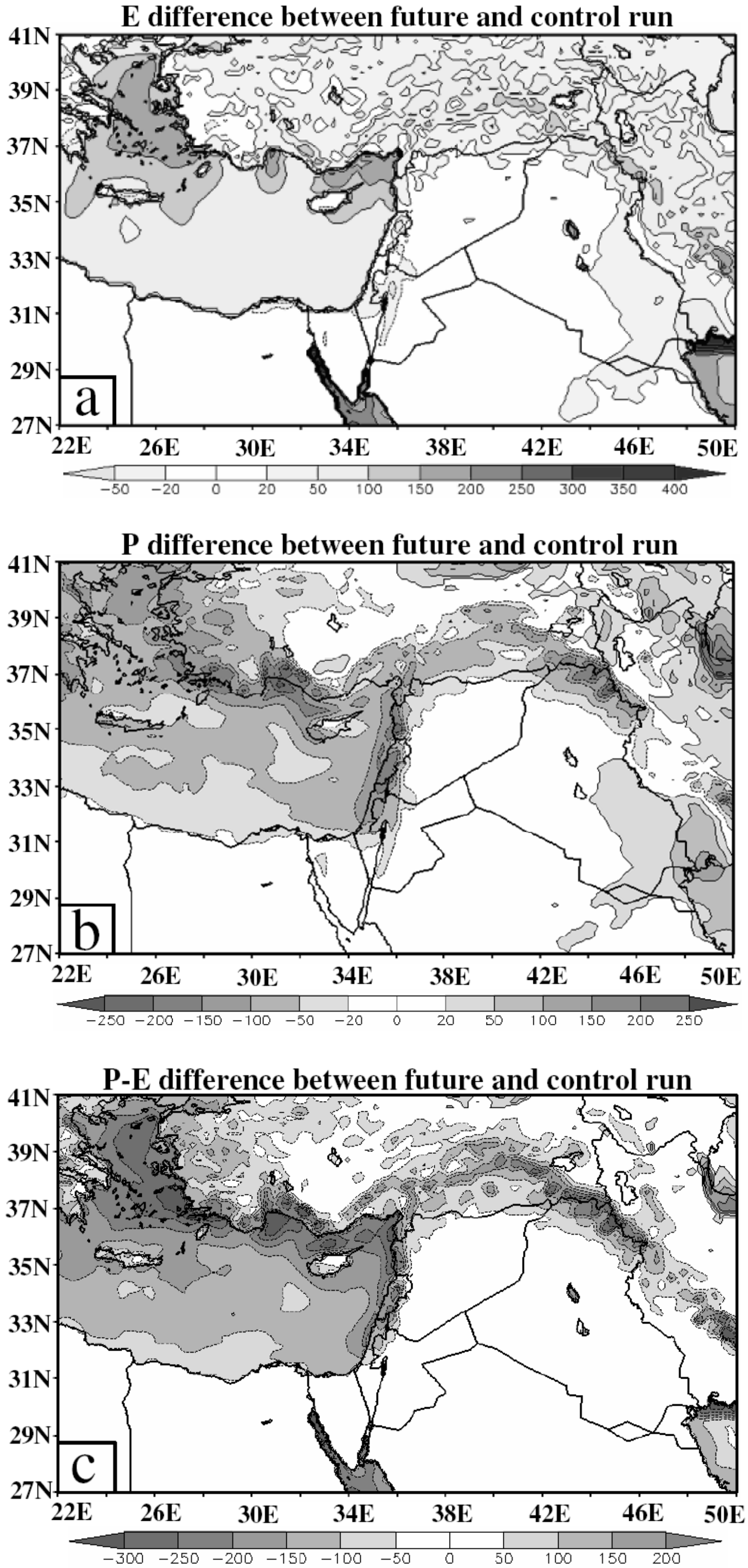

Fig.6: Difference of seasonal total E, P and P-E between the future (2075-2099) and current (1979-2002) 20 km GCM runs. Dashed contour lines indicate the negative changes, i.e., reduction in the future. Unit: mm/season.

P differences show (Fig.6b) that the P of the entire EM is decreasing with an average value of over 100 mm/season, with maximum P decreases located at the northern and eastern coastline area of the EM with a magnitude of over 250 mm/season. The western part of Turkey and most part of the "Fertile Crescent" are also projected to be drier, as reported also by Kitoh et al., (2008). Fig. 6b suggests that the eastern coastline countries, i.e., Israel, Lebanon and the western part of Syria, will become drier in the future by about 200 mm/season. On the other hand, a precipitation increase belt is found at the most easterly part of research region, including the eastern part of Iraq and western part of Iran. A potential explanation for the P increases there is that they are perhaps due to the evaporation increases over the water bodies surrounding this area, which increased the available moisture; also, the mountain region provides strong orographic forcing.

P-E is an important indicator in study of long term climate changes of the moisture fields. The advantage of using the P-E term is that it shows the moisture sinks or sources by the sign of P-E. As the moisture budget equation shows. P-E exactly equals the vertical integrated moisture convergence term (E-P equals the divergence term). The difference of P-E between future and current climate is shown in Fig.6c. Area with negative P-E changes indicates that the area will lose moisture. In general, it has the similar pattern as the precipitation difference in Fig.6b. However, when examined carefully, it can be found that the region with the precipitation increase in Fig. 6b has shrinked dramatically. The Red Sea and the Persian Gulf region show a negative value which can not be seen from the P difference chart, suggesting that these two water bodies also become drier, though the precipitation in this area has no clear index to change, but the evaporation field changed significantly. A completed "Fertile Crescent" strip, clearer than that of the P difference chart ,further proved the drying tendency in the future of this region.

CONCLUSIONS

The main conclusions can be summarized as follows:

1) JMA's 20km GCM shows its high capability in simulating the current two main moisture budget components - precipitation and evaporation - in the research region.

2) Both precipitation and evaporation are underestimated by the coarser resolution ERA-40 data, especially noticed in the relatively large errors for the estimation of the observed precipitation distribution in the research area.

3) The main three water bodies, EM, Red Sea and Persian Gulf are projected to be drier at the end of this century, i.e., reduced P-E.

4) The famous Fertile Crescent will become dramatically drier at the end of this century.

5) Most of the EM adjacent Middle East countries, such as the western part of Turkey, western part of Syria, entire Israel and Lebanon are projected to be drier; however, the east part of Iraq and part of Iran will become wetter by the end of this century.

6) The EM and ME topographic rainfall forcing as well as physiographical changes (like land-sea, land-use etc.) effects on rainfall are quite dominant. Therefore, high-resolution modeling plays a critical role in atmospheric processes. This seems to be true for the whole Mediterranean region, e.g., Lionello et. al. (2006).

7) A water crisis probably is an evitable challenge for the drier countries within the research region in the future.

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GLOBAL WARMING AND ITS IMPACTS ON WATER AVAILABILITY FOR CALIFORNIA AGRICULTURE

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ABSTRACT

Climate change in the western US is predicted to produce significant changes in temperature, precipitation amount and their spatial/temporal distributions. These changes will have profound affects on California's water resources and on both natural and agricultural ecosystems. California, with its limited water supply and the reliance of the State's economy on agriculture, faces enormous challenges in the near future, to analyze and to forecast climate change impacts. We present results that were based on three GHG scenarios using 2 different Global Climate Models (GCM's), in conjunction with a recently developed hydrosalinity model, and summarize impacts of climate change on irrigation water availability, crop water requirement (ET) and soil salinity for a 1,400 km^2 irrigated area in the San Joaquin Valley with 13 water districts. This model couples subsurface hydrology with climate change and will provide for an integrated approach towards understanding the impact of climate change on CA's irrigated agriculture, including the forecasting of the effect of various climate change scenarios on potential crop ET for typical crops in the SJV; and the impact of climate change on irrigation water availability, crop water requirement and soil salinity in the 21st century.

INTRODUCTION

Potential impacts of global climate change on food production need to be considered to ensure food security for the world's growing population. Impact assessment is especially important for irrigated agriculture, as it supports a large part of the world's food supply, while being vulnerable to water scarcity. Specifically, irrigated lands produce more than 40% of the world's food and account for almost 90% of global water consumption (Döll and Siebert, 2002). Climate change in the 21st century is expected to affect crop productivity (Rosenzweig and Hillel, 1998), irrigation water demand (Döll, 2002), and water supply. A recent study by Cline (2007) projects an overall negative effect of climate change on global crop production, with more severe production losses in the warm climates of Africa, India, and South America. Döll (2002) projected an increase in water demand for half of the world's irrigated areas, due to increased crop transpiration at higher temperatures and decreased precipitation in some areas. However, two additional factors that may affect water demand were not considered.

Salinization affects about 20-30 million ha of the world's current 260 million ha of irrigated land (Ghassemi et al., 1995), and limits world food production. Salinity reduces water availability to plants by the accumulation of dissolved mineral salts in waters and soils due to evaporation, transpiration, and mineral dissolution. Subsequent salt leaching leads to salt buildup in both shallow groundwater below the plant root-zone and aquifers. The San Joaquin Valley, which makes up the southern portion of California's Central Valley, is among the most productive farming areas in the United States. However, salt buildup in the soils and groundwater is threatening its productivity and sustainability. Innovative predictive tools are needed that can be applied at the regional scale and at the long term, so that the sustainability of alternative management strategies can be evaluated. For this purpose, an integrated regional-scale hydro-salinity model was developed (Schoups et al., 2005) to fully couple the hydrology and salt chemistry of the vadose zone with the groundwater system.

In a comprehensive review by Hayhoe et al. (2004), projections from various climate models for a range of emission scenarios were downscaled to evaluate potential hydrological and agricultural impacts in California. Though it is generally believed that warming will increase crop transpiration, few studies have quantified climate change impacts on water demand for California's irrigated agriculture within a broad hydrologic context, considering soil and groundwater salinity and groundwater pumping effects to balance expected reduced surface water supplies. This paper presents a quantitative analysis of the potential effects of 21st century climate change on the sustainability of irrigated agriculture in California's Central Valley, focusing on a 1,400 km2 study area located in the western San Joaquin Valley. We calculate changes in irrigation water demand, water supply, and groundwater pumping, and evaluate hydrologic responses such as groundwater levels and salinity, with implications for land subsidence and reduced crop yields due to increased soil salinity. A full description of the climate impact analysis is in progress (Schoups et al. 2009).

METHODS

Historical Context

The study area represents a 1,400 km^2 irrigated agricultural region in western Fresno County on the west side of the San Joaquin Valley (Fig. 1), where irrigation water is managed by water districts for water distribution and drainage management. Early irrigation in the valley, starting at the end of the nineteenth century, was limited to gravity diversions from the San Joaquin river and developed into intense groundwater pumping starting in the twenties, leading to an increase in irrigated acreage westwards and upslope. After completion of the Central Valley Project and the State Water Project, in 1953 and 1967, respectively, the whole study area was irrigated with high quality imported water from the Sacramento Valley. The salinity problem on the west side of the San Joaquin Valley is partly attributed to the continuous presence of a low permeability Corcoran clay layer, ranging in depths from about 30 m near the San Joaquin river in the east to a depth of about 250 m in the west, thereby largely defining the regional hydrology. To lower the water tables, subsurface drainage systems were installed to intercept and collect the shallow groundwater. However, for irrigated agriculture to remain sustainable, a soil salt balance must be maintained that allows for productive cropping systems.

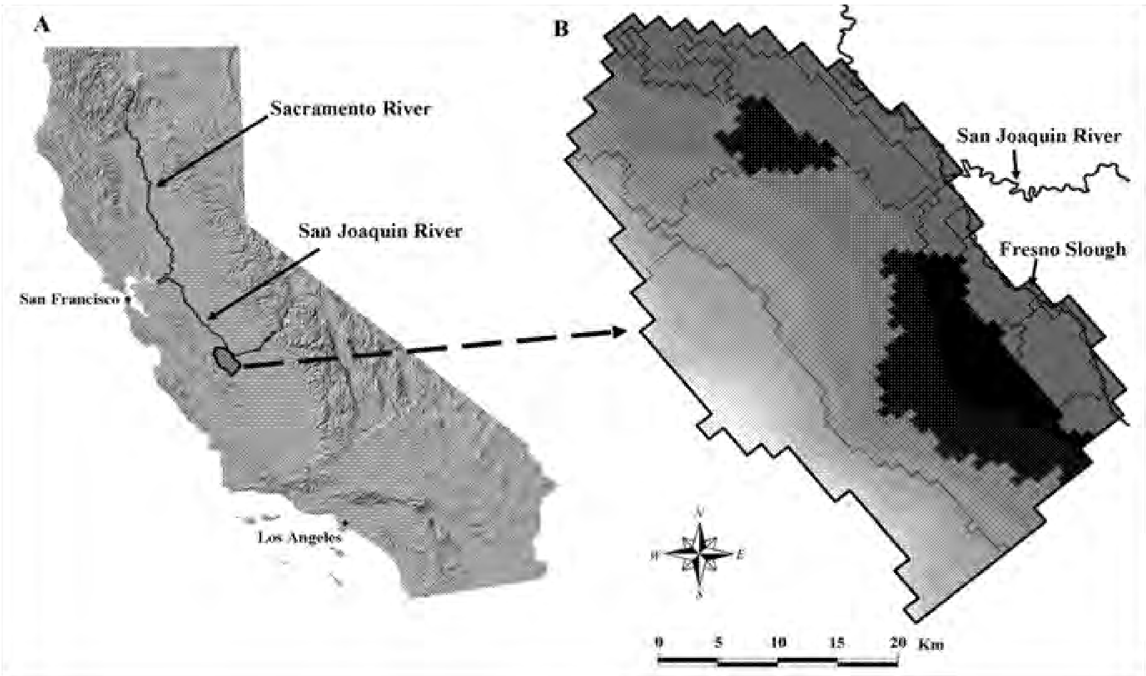

Figure 1: (A) Location of study area and model domain in the western San Joaquin Valley, California; (B) Detailed view of model domain, showing irrigation districts (as jagged lines) and two dark areas where land is retired from agricultural production as of 2006. Grey shades indicate land elevation, with lighter shades having higher elevation.

Model Environment

Schoups et al. (2005) developed and calibrated a hydro-salinity model for the study area (Fig. 1), using historical data from 1940 to 1997. The model solves three-dimensional variable saturated subsurface flow and salt transport, and accounts for chemical reactions, in particular gypsum dissolution-precipitation. Numerical solutions were obtained with the MODHMS code (Schoups et al., 2005). The horizontal boundaries of the model domain coincided with the hydrologic boundaries of an earlier regional groundwater flow model (Belitz and Phillips, 1995). The model domain was discretized into a regular finite difference grid of 2,960 square cells of 805 m (0.5 mi) side length and 64 ha area, corresponding to a typical field size. In the vertical direction, the model domain extended from the land surface to the top of the Corcoran clay, using 17 layers of increasing thickness from the surface downwards. Using historical crop acreage and water delivery records for each water district, crops and irrigation amounts were randomly distributed, leading to the annual assignment of a single crop to each grid cell. Spatially distributed water flow and salinity reaction and transport parameters were obtained from soil survey data and well logs. Hydrological parameter values were either optimized or obtained from existing information.

We used the final simulation results of 1997 as the initial condition, to perform simulations for each climate change scenario during 1998-2099, with a focus on changes in groundwater levels, soil and groundwater salinity, and impacts on crop yield and land subsidence. To simulate effects of pumping on groundwater levels, we extended the original model of Schoups et al. (2005) to include the Corcoran clay and the confined aquifer beneath it, from which most groundwater is extracted.

To quantify potential climate change impacts, we consider three greenhouse gas (GHG) emission scenarios, namely SRES B1 (low), A2 (mid-to-high) and A1fi (high). These scenarios largely bracket the range of IPCC's nonintervention future emissions projections, with atmospheric CO_2 concentrations for B1, A2, and A1fi reaching 550, 850, and 970 ppm, respectively by 2100 (IPCC, 2007). Following Hayhoe et al. (2004), we used the output of two General Circulation Models (GCMs), i.e. the National Center for Atmospheric Research-Department of Energy Parallel Climate Model (PCM, Washington et al., 2000), and the U.K. Met Office Hadley Center Climate Model version three (HadCM3, Gordon et al., 2002).

Because the spatial resolution of GCM output is large relative to the study area (~30 km across, Fig. 1), we employed empirical statistical downscaling method of Wood et al. (2002) to develop irrigation district scale climate projections to a 1/8 degree (~12 km) spatial scale (Maurer, 2007; Cayan et al, 2008). Starting from these climate scenarios, our regional impact study analyzes future changes in (1) irrigation water demand and (2) irrigation water supply, and (3) evaluates impacts of these changes on the regional hydrology.

Irrigation water demand and supply

Climate directly and indirectly affects crop ET (ET_c). First, evaporative demand changes as a function of atmospheric conditions such as temperature, relative humidity, net radiation, and wind speed. We quantify this by estimating reference ET (ET_{ref}), based on downscaled GCM projections of temperature and precipitation for California. Climate also indirectly affects crop development by changing growing conditions, of ambient CO_2 levels and air temperature. We assumed no effect of CO_2 on crop development, and used daily crop coefficients from Snyder et al. (1989) to calculate ET_c as a function of projected ET_{ref}. In addition, GCM-based temperature projections were used to evaluate temperature effects on crop development and ET_c, using the degree-days (*DD*) concept (Ritchie and NeSmith, 1991).

We considered three types of land use (A_c) change, namely (i) changes in cropping patterns, (ii) land fallowing, and (iii) land retirement. For each water district in the study area, we used a linear regression relation between land fallowing acreage and surface water supplies for the 1988-1997 period to project future land fallowing for the range of climate change scenarios, assuming no future investment in additional groundwater pumping capacity. Lastly, land degradation by soil salinization may result in permanent land retirement, as almost 100,000 acres of agricultural land was retired in 2006 in the western SJV.

Irrigation water requirement or demand, *IR,* can be met by two main sources, namely (i) imported surface water supply, and (ii) local groundwater supply. Given projections in surface water supply, annual groundwater supply was computed from this water budget. Possible implications of excessive groundwater pumping, such as land subsidence and soil salinization were assessed by simulating hydrologic system responses. Surface water supplies were estimated based on the results of Vicuna et al. (2007).

RESULTS

Historical Simulations

Simulation model results included historical spatial maps of the groundwater table, root zone and groundwater salinity. The hydrologic component simulated the dynamics of the regional variation in water table depths well, reconstructing the gradual increase in shallow water table area from the fifties to the nineties due to increased recharge from irrigated agriculture compared to pre-development conditions, and the shift in irrigation water supply from locally pumped groundwater to imported surface water in the early seventies. Much of the spatial and temporal dynamics in root-zone and groundwater salinity were adequately described with the hydro-salinity model (Fig. 2). The salinity dynamics in the shallow groundwater generally followed that of the root-zone, indicating that the two systems were closely connected. The relatively slow movement of salts to larger depths indicates that it takes a long time for salts to move into the deeper groundwater. Our model simulations demonstrated that a significant portion of the soil salinity dynamics was controlled by the cycling of soil gypsum through dissolution and precipitation, as caused by changes in salt leaching with time and soil depth, and soil cation exchange. We concluded that the salinization issues are critical to the sustainability of irrigated agriculture in the San Joaquin Valley, and similarly probably to many other areas of the world with relatively closed groundwater systems.

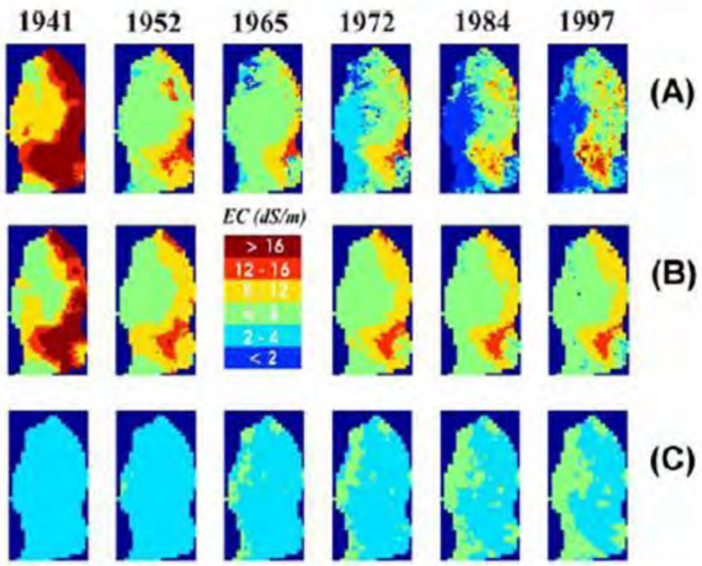

Figure 2: Temporal changes in the spatial distribution of dissolved salts, expressed by the electrical conductivity (*EC*, dS/m) of (A) the average root-zone (0-2 m below the land surface), (B) the shallow groundwater system (6 m below the land surface) and (C) the deep groundwater system (20-40 m below the land surface).

Climate Scenario Results

In the following, we discuss results for computed changes in irrigation water demand, irrigation water supply, and hydrologic response. All scenarios accounted for retired land, i.e. land permanently taken out of production. We forecasted a general decrease in ET_c that contradicts the general belief that global warming will lead to an increase in crop transpiration in California. The annual decrease in ET_c is a result of the accelerated crop development by the projected increased air temperatures. In addition to the projected climate change impacts, the recent land retirement in our study area of about 60,000 acres caused a 16% decrease in irrigation water demand for our study area, irrespective of climate change.

Projections of surface water and groundwater supply also differentiate between wet and dry scenarios, and are largely determined by the correlation between annual precipitation and surface water supplies Projected surface water supplies range from an increase of 14% for the wettest scenario to a decrease of -26% for the driest scenario, relative to a no-climate-change scenario Groundwater use for irrigation follows the opposite trend of surface water supplies, as most pumping will occur in the driest scenarios, to compensate for reduced surface water supplies. The model assumes that farmers will avoid water stress of all cropped lands, thereby supplementing available surface water supplies with groundwater pumping to satisfy all water demands. As one would expect, improvements in irrigation efficiency reduced the need for groundwater pumping.

We evaluate climate change impacts of water and land use changes on the hydrologic system by simulating shallow water table extent, soil salinity, salt-affected crop yields, groundwater salinity, and land subsidence. Using the modified hydro-salinity model of Schoups et al. (2005), we first reconstructed historical changes starting in 1940, and extended simulations through the 21st century for each climate change scenario. We only show forecasted impacts on shallow water table extend and tomato crop yield.

Figure 3a shows historical and projected changes in the area affected by shallow water tables, less than 2 m below land surface. As irrigated area increased during mid-century and imported surface water replaced locally-pumped groundwater as the main irrigation water source, groundwater levels rose throughout the 20th century (Fig. 4 and Schoups et al., 2005). Shallow water tables mainly developed in downslope, low-lying areas (see Fig. 1). The dry scenario results are caused by the decrease in surface water supplies, thereby causing increased groundwater pumping and lower groundwater levels by induced downward hydraulic gradients. The shallow groundwater level extent for the D4-IE scenario (fractional area of 0.16 in Fig. 3a) was much smaller than any of the others because of the assumed high irrigation efficiency of 90% and the relatively high pumping rate. Shallow groundwater table is one of the most important hydrologic variables, as it enhances the contribution of capillary rise to soil evaporation, leading to soil and groundwater salinization in downslope areas.

Historical simulations by Schoups et al. (2005) showed the large decrease in soil salinity in the San Joaquin Valley, with saline soils decreasing from a fractional area of about 0.5 to about 0.3, as the alluvial soils contained high salt content originally and were reclaimed by irrigation. Soil salinization increased in the late 1990's because of excess application of surface water, leading to rising water tables and drainage problems. We found that salinity projections were much less variable between climate scenarios. There appears to be an upper limit of the areal extent of salt-affected soils, geographically constrained to the low-lying areas with clayey deposits in the north-eastern part of the study area, leading to poorly drained conditions.

Apart from changes in salt-affected areas, we also considered the impact of soil salinity on crop production, as crop salt tolerance varies among crops and is not limited to 4 dS/m. Here, we present simulated yields for tomato (salt-sensitive), as affected by soil salinity, using the Maas-Hoffman function that relates relative yield to average root zone salinity (Maas, 1990). As expected, the wet scenarios with limited groundwater pumping predict the widest extend of yield reduction, and the scenario with technological adaptation projects (D4-IE) is the least affected. Our simulation results confirm that soil salinization will continue unless higher irrigation water efficiency management practices are widely used.. As many high-valued crops such as vegetables and fruit (melons, in particular) are also salt sensitive, the anticipated increase in future demand for such crops may require improved water and salt management practices in the study area.

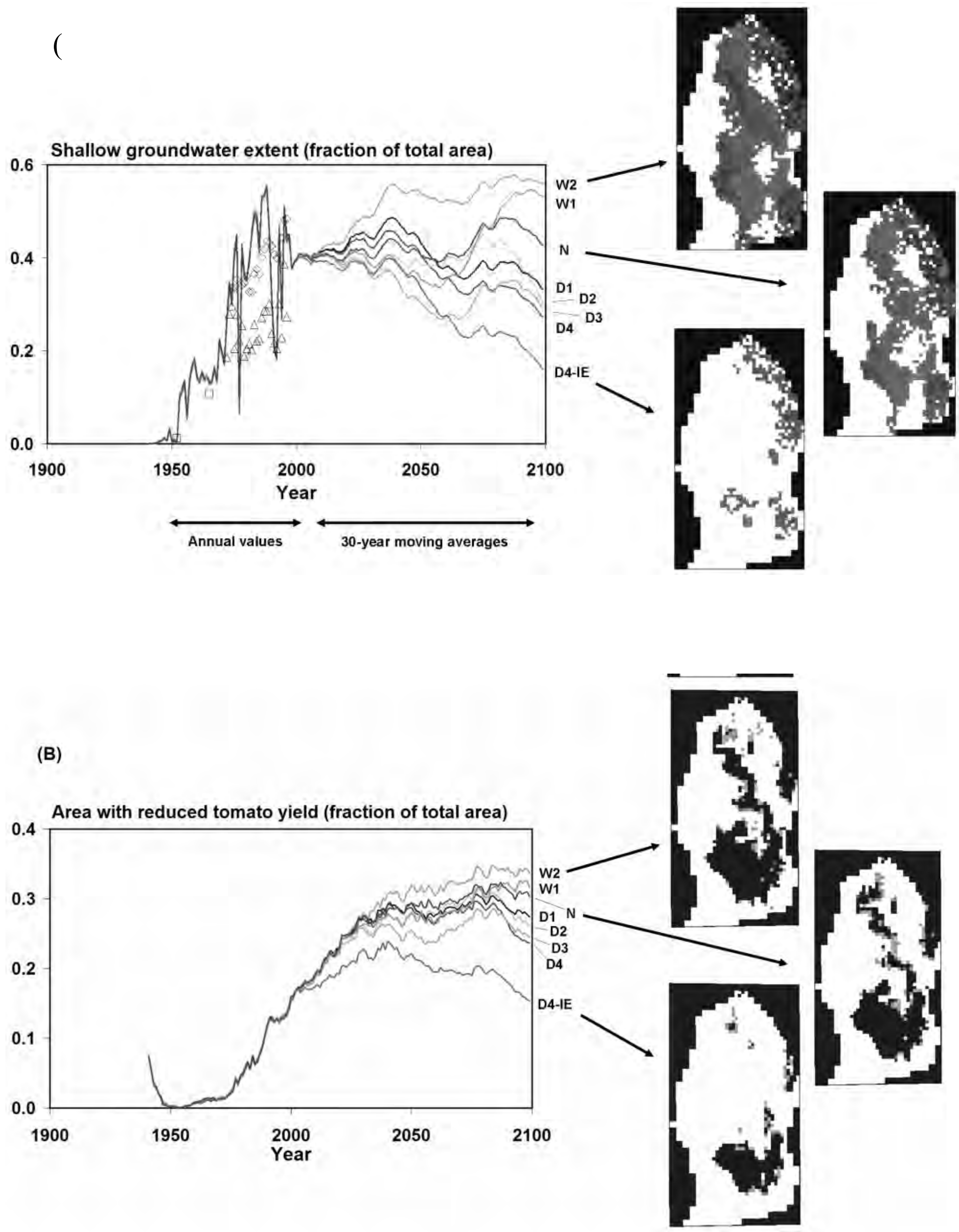

Figure 3: Historical and projected extent of shallow groundwater (a) and tomato yield reduction areas (b) with time-series and spatial maps for wet (W) and dry (D) climate change.=. N (no climate change), W2 (wettest scenario), and D4-IE (driest scenario). Shallow water tables are less than 2 m below land surface.

CONCLUSIONS

Our simulations showed that an increase in ET_{ref} for a warming climate is offset by a decrease in seasonal crop ET due to faster crop development. Though climate warming unexpectedly projected reduced seasonal crop water requirements, the resulting shorter growing seasons could make multiple cropping possible, thereby increasing annual irrigation water demand, perhaps beyond what can be supplied. Despite the large variation in the spatial extent of projected shallow water tables, the total salt-affected area is predicted to remain fairly constant in the 21st century, irrespective of climate scenario. High soil salinity is limited to the eastern half of the study area that is flat and poorly drained. The western half of the study area contains topographic gradients and coarse alluvial soil deposits, which is why salinization due to rising water tables is unlikely to occur in those areas, irrespective of climate scenario.

All scenarios project an increase in soil salinity in downslope areas (eastern portion of the study area), resulting in reduction of both tomato and cotton yields. Although already a significant fraction of the low-lying areas has been retired from agricultural production, model simulations indicated that additional upslope areas could be affected. Therefore, if these additional lands will not be drained in the future, additional land retirement may be required. Model results show that salinization will continue to occur, regardless of climate change. This is especially significant, realizing that economic analysis has shown that farmers will likely switch from salt tolerant crops (such as cotton) to high-value, salt-sensitive crops (such as tomato and melons), in the future. Salt leaching to deeper groundwater is most significant for the dry climate change scenarios, for which groundwater use is greatest. Groundwater irrigation generates the highest groundwater salinity, as salinity increases by recycling of already salinized groundwater, combined with gypsum dissolution. Hence, although groundwater pumping may reduce shallow groundwater extent, thereby preventing excessive soil salinization, irrigation with saline groundwater accelerates groundwater salinization.

Among the simulated scenarios, we considered a technological adaptation by improving irrigation efficiency to 90%. Such an adaptation could effectively mitigate many projected adverse effects. Increasing irrigation efficiency would reduce groundwater pumping, irrigation water demand, groundwater recharge, and soil salinity (both extent and level of salinity), thereby decreasing the need for land retirement.

In conclusion, the greatest threat to agricultural sustainability in the study area appears to be the continued salinization of downslope areas, jeopardizing crop production and requiring future land retirement. Technological adaptations, such as increasing irrigation efficiency, may mitigate these effects. The sensitivity results presented provide insights into impacts of climate change on irrigated agriculture. Our analysis does not only apply to California, but can be extended to other irrigated regions in the world, as many have similar constraints regarding water supply and land degradation.

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SATELLITE-DERIVED DROUGHT ASSESSMENT: MERITS AND LIMITATIONS

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ABSTRACT

A large number of water- and climate-related applications, such as drought monitoring, are based on spaceborne-derived relationships between land surface temperature (LST) and the *Normalized Difference* Vegetation Index (NDVI). The majority of these applications rely on the existence of a negative slope between the two variables found from site- and time-specific studies. The current paper investigates the generality of the LST-NDVI relationship over a wide range of moisture and climatic/radiation regimes encountered over the North American continent (up to 60° N) during the summer growing season (April – September). Information on LST and NDVI comes from long-term (21-year) datasets obtained by the Advanced Very High Resolution Radiometer (AVHRR). It was found that when water is the limiting factor for vegetation growth (typical situation for low latitudes of the study area and during the mid-season), the LST-NDVI correlation is negative. However, when energy is the limiting factor for vegetation growth (in higher latitudes and elevations, especially at the beginning of the growing season), a positive correlation exists between LST and NDVI. Forward multiple regression analysis revealed that during the beginning and the end of the growing season, solar radiation is the predominant factor driving the correlation between LST and NDVI, while other biophysical variables play a lesser role. Air temperature is the primary factor in mid summer. It is concluded that there is a need to use the LST-NDVI relationship with caution and to restrict its applications as a drought index to areas and periods where negative correlations are observed.

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INTRODUCTION

At Issue

Periods of persistent abnormally dry weather, known as droughts, can produce a serious agricultural, ecological, or hydrological imbalance. Drought harshness depends upon the degree of moisture deficiency, duration, and the size of the affected area (Wilhite and Glantz, 1985). The major effect of drought on human life has led to increasing efforts to develop and implement various quantitative measures of drought extent and severity.

Several drought indices use only ground-based measurements, some are based on energy-balance models, while others use spaceborne data, solely or in combination with the previous two (Heim, 2002; Quiring and Papakryiakou, 2003). Satellite-derived drought indices use observations in multiple spectral bands, each providing different information about surface conditions. Since droughts are naturally associated with vegetation state and cover, vegetation indices (VIs) are commonly used for this purpose (e.g. Tucker and Choudhury, 1987), mainly utilizing data in the visible red (R), near-infrared (NIR), and the short wave infrared bands. Other drought indices are based on data from the thermal infrared (TIR) spectral region, which provides information about vegetation health and soil moisture status.

NDVI as an Indicator of Drought

The most commonly used VI is the *Normalized Difference Vegetation Index* (NDVI, Eq. 1), which is based on the difference between the maximum absorption of radiation in R (due to the chlorophyll pigments) and the maximum reflectance in NIR spectral region (due to the leaf cellular structure) (Tucker 1979):

$$NDVI = (\rho_R - \rho_{NIR})/(\rho_R + \rho_{NIR}) \quad (1)$$

where ρ is reflectance in the respective spectral bands. The soil spectrum typically does not show such dramatic spectral difference between these bands, and thus the NDVI allows separation of the vegetation from the soil background.

Tucker and Choudhury (1987) found that NDVI could be used as a response variable to identify and quantify drought disturbance in semi-arid and arid lands, with low values corresponding to stressed vegetation. More recently, Ji and Peters (2003) found that NDVI is an effective indicator of vegetation response to drought in the Great Plains of the USA, based on the relationships between NDVI and a meteorologically based drought index. The *Vegetation Condition Index* (VCI; Eq. 2) developed by Kogan (1995, 1997, 2002), normalizes NDVI on a pixel-by-pixel basis, scaling between minimum and maximum values of NDVI (NDVImin and NDVImax, respectively) as observed at each pixel over a long temporal record since 1981:

$$VCI = \frac{NDVI' - NDV\,Im\,in}{NDV\,Im\,ax - MDV\,Im\,in} \qquad (2)$$

where NDVI' is the average NDVI over a composite period of interest (which can be a week, decade, month, growing season, or a year). The normalization serves to emphasize relative changes in the local NDVI signal through time, while reducing the influence of variability in NDVI phenology between different land-cover types and climatic conditions.

LST as an Indicator of Drought

In addition to vegetation indices based on the visible and near infrared (VNIR) bands, land surface temperature (LST), derived from TIR-band data, is found to provide vital and useful information on the state of the land surface and is widely implemented in formulating the energy and water budgets at the surface-atmosphere interface (Gutman, 1990). In this sense, LST serves as a proxy for assessing evapotranspiration, vegetation water stress, soil moisture, and thermal inertia (e.g. Anderson et al., 2007; Ottle and Vidalmadjar, 1994; Sobrino et al., 1998).

On the presumption that the LST provides complementary information about vegetation condition, Kogan (1995, 2000) adapted the VCI normalization approach (Eq. 3) to LST and developed the *Temperature Condition Index* (TCI) based on brightness temperature (BT) values:

$$TCI = \frac{BT\,max - BT'}{BT\,max - BT\,min} \qquad (3)$$

where the BT' is the average BT value for a composite period of interest. Note that in order to apply the TCI for determining temperature-related vegetation stress, it is formulated as a reverse ratio to the VCI. While the VCI increases with NDVI, the TCI decreases with LST based on the hypothesis that higher land-surface temperatures indicate soil moisture deficiencies and therefore stress in the vegetation canopy.

LST-NDVI as an Indicator of Drought

Both VNIR and TIR data have advantages and disadvantages in terms of drought detection utility. While LST-based assessments of land-surface conditions have shown a better performance over low vegetation cover (Friedl and Davis, 1994), VNIR-based indices are more reliable in assessing the condition and dynamics of vegetation over intermediate levels of vegetation cover (about 50%) (Huete et al., 1985). Therefore, extensive work has been devoted to combining these variables into a unified drought indicator, based on the assumption that complementary information in these wavebands may provide a more robust characterization for different phenomena at the land surface. Many studies have revealed a strong negative correlation between NDVI and LST (e.g. Goward et al., 1985; Nemani et al., 1993), resulting from the cooling effects of canopy transpiration. These early studies were typically limited to relatively small areas and based on a single or on few images. To date, the large-scale spatio-temporal variability of the LST-NDVI relationship has not been investigated.

Considerable attention has been given to the inverse relation between LST and NDVI with respect to drought monitoring. During drought periods, NDVI at a given pixel will typically be relatively low while LST is expected to be relatively high due to both vegetation deterioration and higher contribution of a soil signal (Kogan, 2000). McVicar and Bierwirth (2001), for example, used a simple ratio between LST and NDVI. The Vegetation Health Index (VHI) developed by Kogan (1995) combines two indicators of comparable magnitude, using the VCI and TCI described above (Eqs. 2 and 3):

$$VHI=\alpha VCI+(1-\alpha)TCI \tag{4}$$

where, α and 1-α define the relative contributions of each index. Due to lack of more accurate information, α has been usually assigned a value of 0.5, assuming an equal contribution of both variables to the combined index (Kogan, 2000). The VHI has been applied in a range of applications, mainly drought detection, at global, regional, and national scales, in many parts of the world. The VHI is a standard product for drought monitoring, provided weekly by NOAA.

To conclude, positive relationships between LST and NDVI tend to develop in areas where vegetation growth is energy or temperature limited. Therefore, in high latitudes increasing LST should not be interpreted as a signal of vegetation stress and specifically drought.

Objectives

Wide and diverse evidence regarding the LST-NDVI relationship is found in the literature. In general, prior studies suggest that the sign of the LST-NDVI slope may be governed by whether vegetation growth is water limited (negative slope) or energy/temperature limited (positive). The latter condition is prevalent at high latitudes or in the evergreen tropical forests, while the former might occur in lower latitudes and especially in drylands (Karnieli et al., 2006; Lambin and Ehrlich, 1996; Nemani et al., 1993; Nemani and Running, 1989).

In view of the extensive use of LST-NDVI relationship in drought monitoring and assessment, the objective of this paper is to investigate the generality of the of LST-NDVI relationship. The research was conducted over a wide range of moisture and climatic/radiation regimes encountered over the North American continent (up to 60° N) during the summer growing season (April – September) using long-term (21-year) datasets from the Advanced Very High Resolution Radiometer (AVHRR). Over this study domain, it was hypothesized that slope of LST vs. NDVI increases with latitude, and that the sign of the slope is related to the locally prevalent factor limiting vegetation growth: energy vs. moisture. The goal is to identify times and areas where simple empirical drought indices like the VHI, which assume a negative slope, should work well, and where their application may be problematic.

DATA AND METHODOLOGY

A wide range of physical variables affect NDVI, LST, and the relationship between cover and temperature. Primary among these are solar radiation, air temperature close to the earth's surface, and rainfall. Secondary biophysical variables of interest, which are closely related to these primary climatic factors, include soil moisture, and evapotranspiration. This study focuses on a domain including the United States and Canada (up to 60^{o} N), given the comprehensive set of ancillary data available over this area.

In this study, twenty-one years of NOAA-AVHRR data (July 1981 – December 2001) from the NOAA/NASA PAL dataset were used. Specifically, the AVHRR data used here include monthly composites of calibrated reflectances from bands 1 and 2, and brightness temperatures from bands 4 and 5, at 8 km resolution. Brightness temperatures were used to compute LST following a split window algorithm (Coll et al., 1994; Jang et al., 2006). Monthly LST and NDVI data over the study area were downloaded for a 6-month period – April to September for each year. The data were averaged for two months, representing sub-periods of the vegetation growing season – beginning (April-May), middle (June-July), and end (August-September). Long-term averages of NDVI and LST were also computed from the bi-monthly data. In total, for each bi-monthly period, one long-term average field and 21 yearly images were derived for both NDVI and LST.

Gridded data on long-term monthly mean air temperature at 2 m above ground level are based on the NCEP/NARR results (Mesinger et al., 2006). Gridded long-term averages of monthly precipitation data for North America at 0.25^{o} spatial resolution were obtained from monthly precipitation datasets prepared at NOAA's CPC using gage observations from 1948 to present. Radiances data were produced from an amalgamation of observations from five geostationary satellites as well as from the AVHRR instrument onboard the polar orbiting satellites.

Soil moisture and evapotranspiration reanalysis data were retrieved from the NCEP/NARR dataset (Mesinger et al. 2006) at 32 km grid. Soil moisture data were obtained in two layers – at the uppermost 10 cm and at the root zone (an integrated value for the 0-200 cm). The 10 cm soil moisture is more closely related to surface temperature under low vegetation cover conditions, while the deeper moisture content should be better correlated under high cover.

ANALYSIS AND DISCUSSION

Spatial Relationships between LST and NDVI

In the triangle/trapezoid approach to assess regional soil moisture availability, the LST-NDVI relationship is typically evaluated spatially at one instant in time – plotting snapshots of LST vs. NDVI, mapped over the spatial domain of interest. Long-term (1981-2001) averages of NDVI and LST for each of three bi-monthly sub-periods: April-May, June-July, and August-September (Fig. 1a-f), were used to create respective density scatterplots (Fig. 1g-i). In these scatterplots, yellow and red colors represent higher concentrations of pixels. In each sub-period, two distinct populations of points can be identified: one with the typical negative slope, indicative of moisture-limited vegetation growth, and a second with a small positive slope, showing little variability in LST over a wide range in NDVI. Two areas of interest (AOI) were identified on these feature spaces, as demonstrated for the April-May plot (Fig. 2a); one AOI for the positive branch and the other for the negative one. These AOIs were used as non-parametric signatures for supervised classification (Fig. 2b). The latter product identifies where these populations tend to cluster over the North America domain for the April-May sub-period. Similar patterns are found for the summer and fall seasons. Points comprising population with positive slope are primarily located at northern latitudes or at high elevations where energy-limiting growth conditions are expected.

Temporal Relationships between LST and NDVI

To ascertain whether the slope of LST vs. NDVI gradually varies with latitude (similarly to the trend identified in Mongolia (Karnieli et al., 2006)), eight points along a north-south transect over the Great Plains were selected at approximately 5° intervals (Fig. 3). For each point, the April and May monthly LST and NDVI averages were extracted for each of the 21 years of available data, resulting in 42 data pairs (21 years times 2 months) per point (sufficient for statistical analysis). Fig. 4 shows plots of LST vs. NDVI for the eight points along the transect. As expected, the slope gradually increases from negative to positive from the south northward. Along this transect, the reversal in slope sign occurs around 35-40° N, where the correlation between LST and NDVI is insignificant.

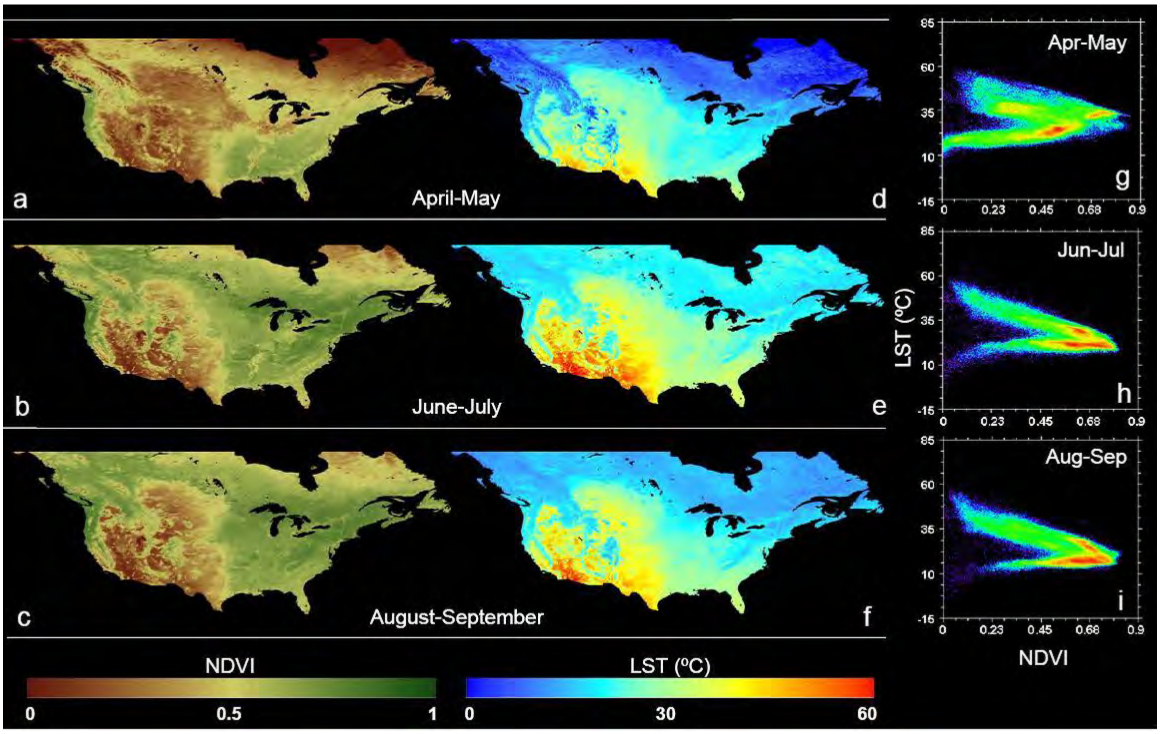

Fig. 1: Long-term averages of Normalized Difference Vegetation Index (NDVI) for the three sub-periods of the growing seasons – April-May (a), June-July (b), and August-September (c). Long-term averages of land surface temperature (LST) for the same sub-periods (d-f). Density scatterplots of LST vs. NDVI for the same sub-periods (g-i). Note that in the density plots, in each sub-period, one branch of the correlation is negative while the other is positive or insignificant. Yellow and red colors represent higher concentration of pixels.

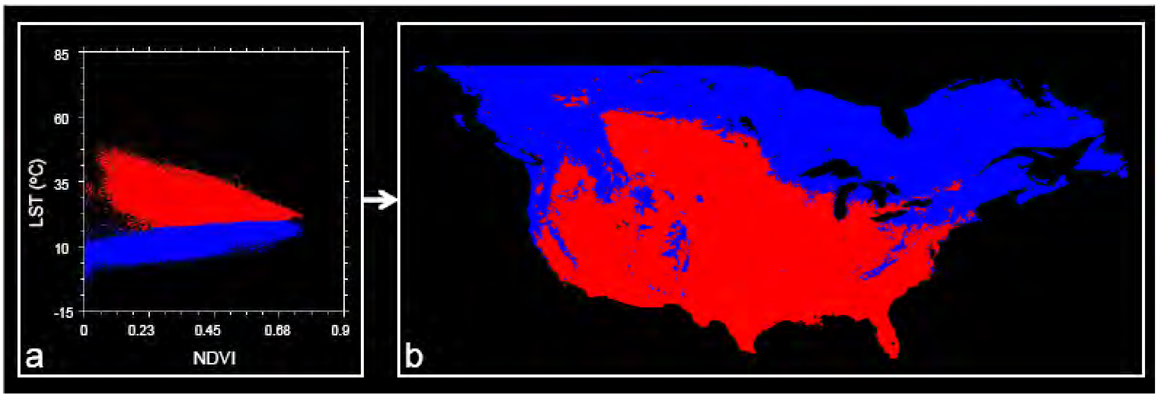

Fig. 2: Two areas of interest as identified on the LST-NDVI scatterplot for the April-May sub-period (a); supervise classification of the study area based on the non-parametric signatures (b). The map shows negative correlation in the southern part and positive correlation in the northern part of the North America continent.

To study the spatial patterns of temporal correlations between LST and NDVI, the correlation coefficient (r) was computed for each pixel in the study area, stratified by season (Fig. 5a-c). In these maps, the blue areas show negative correlation coefficients, indicative of moisture-limiting vegetation growth where the VHI may work well. The red areas have positive correlation and are likely energy limited, and the TCI component of the VHI may give confusing information. The white areas show no significant correlation between LST and NDVI. Corresponding histograms of r values are also shown in Fig. 5d-f to highlight variations in the distributions of positive and negative slopes between the seasons. In the April-May image (Fig. 5a), representing pre-emergence of vegetation over most of the domain, r is largely stratified by latitude. Only the southernmost part of the study area exhibits a significant negative correlation in the temporal behavior of NDVI and LST. This is also reflected in the frequency histograms where negative skewness (γ = -0.79) in r distribution was computed for April-May (Fig. 5d). In comparison, significant positive skewness in r is found in the June-July and August-September distributions (γ = 0.35 and 0.13, respectively) (Fig. 5e,f). The June-July map shows strong negative correlations between LST and NDVI over most of the domain, with variations in r less clearly characterized by latitude (Fig. 5b). Over this period, the VHI has the potential for yielding useful vegetation stress information over much of North America. The forested areas in western Canada and in the Rockies still exhibit, however, energy-limiting conditions in the summer months. Towards the end of the growing season (August-September), a north-to-south gradient reappears, with much of the area having insignificant correlation between LST and NDVI (Fig. 5e).

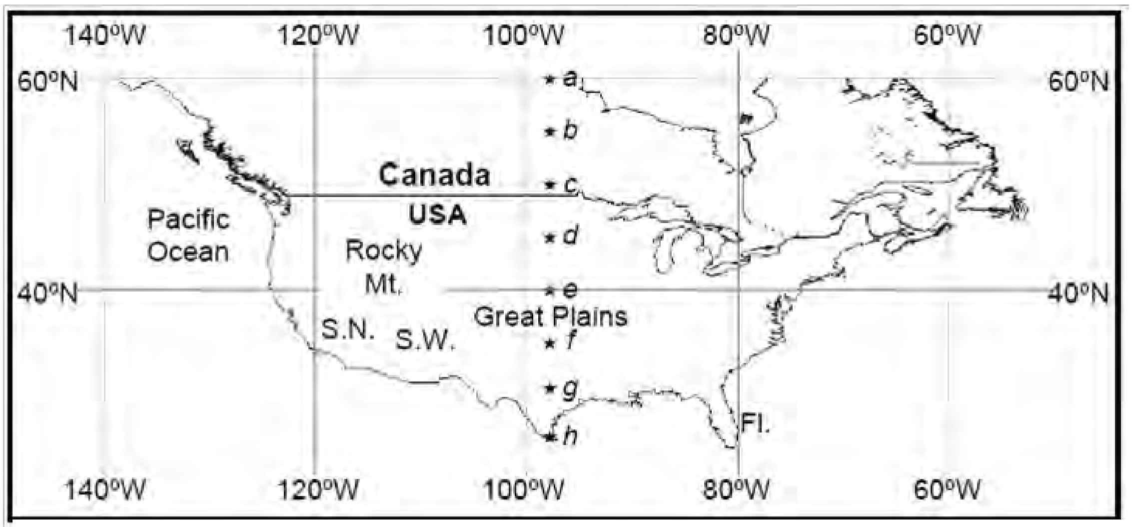

Fig. 3: Map of the study area. Stars mark locations along longitude 40.18' W where long-term (1981-2001) LST-NDVI relationships for April-May were examined (Figure 4). Relevant geographic locations are marked. Abbreviations: South-West (S.W.); Sierra Nevada (S.N.); Florida (Fl.).

Climatic Factors Driving LST-NDVI Correlations

The seasonal variability in the spatial distribution of the LST-NDVI correlation coefficient over the North America domain implies that different physical variables govern the correlation at different times of the year. The apparent seasonal shifts between energy- and moisture-limiting vegetation growth conditions suggests that solar radiation and near-surface (2-m) air temperature may be important factors in spring and fall, while precipitation could be expected to play a major role during the summer (growing) season. To identify which climatic factors are most strongly related to spatial distributions of r in different seasons, a forward stepwise multiple linear regression was performed for each sub-period, with the correlation coefficient (r) as the dependent variable, and the above-listed variable, averaged over long-term periods, as independent variables. The regression results are summarized in Table 1. Correlation coefficients derived through simple linear regression between these three primary climatic variables, r and the secondary biophysical variables fractional vegetation cover, soil moisture at the uppermost 10 cm, mean soil moisture at 0-200 cm, evapotranspiration, and fraction of tree cover are listed in Table 2 to highlight interrelations between these various factors.

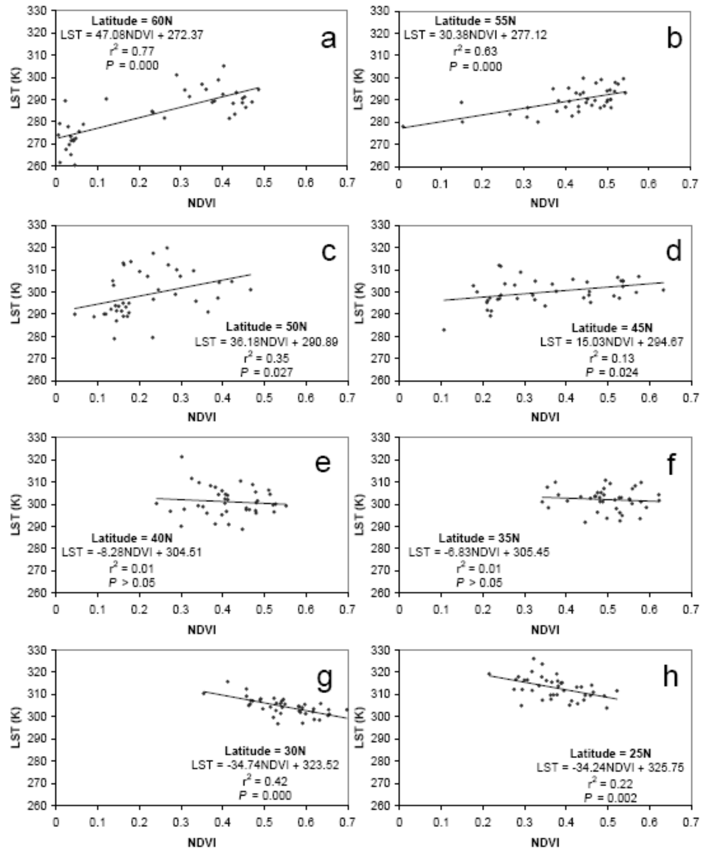

Fig. 4: LST-NDVI colorations at 5º increments along north-south transect (Figure 3). Note the gradual change of the slope from negative to positive proceeding north.

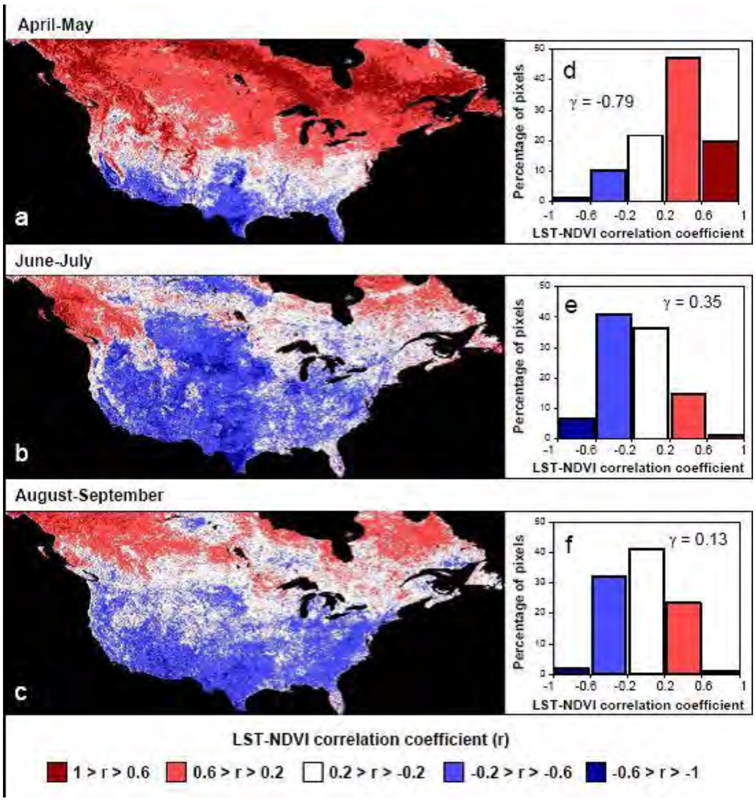

Fig. 5:

Spatial distribution of pixels with positive ($r > 0.2$), negative ($r < -0.2$), or insignificant ($-0.2 < r < 0.2$) values for the three sub-periods of the growing seasons (a, b, c) and their respective frequency histograms (d, e, f). Histograms and skewness values (γ) show that at the beginning of the growing season the majority of the area was characterized by positive correlation, at the middle of the growing season by negative correlation, and at the end of the season by insignificant correlation.

Table 1. Forward stepwise multiple regressions for three sub-periods. Variables are listed according to their contribution to the correlation. Bold numbers refer to the total explained variance.

	Multiple R^2	Marginal R^2
April-May		
Radiation [W m^{-2}]	0.643	0.643
Air temperature [^{o}C]	0.666	0.023
Precipitation [mm day^{-1}]	0.689	0.023
June-July		
Air temperature [^{o}C]	0.460	0.460
Precipitation [mm day^{-1}]	0.506	0.045
Radiation [W m^{-2}]	0.507	0.002
August-September		
Radiation [W m^{-2}]	0.591	0.591
Air temperature [^{o}C]	0.599	0.007
Precipitation [mm day^{-1}]	0.605	0.006

The total explained variance (coefficient of determination, R^2) resulting from the multiple regression is 0.69, 0.51, and 0.61, for the beginning, middle, and end of the growing season sub-periods, respectively. Solar radiation appears to be the most dominant driver for the LST-NDVI correlations at the beginning and the end of the growing season. At the beginning of the season, radiation accounts for 64% of the variation in r (out of the total 69% explained by all the three variables) with air temperature and precipitation contributing only ~2% each. At the end of the growing season, air temperature and precipitation contribute less than 1% each to the total explained variance. Note, however, that air temperature and solar radiation are themselves highly correlated ($|R|>0.8$ in each season; Table 2). The strong dependency of the correlation coefficient (and especially its sign) on radiation in spring and fall supports the hypothesis that the slope of the LST-NDVI relationship (positive vs. negative) reflects the dominant growth limiting condition. Where insolation and air temperature are typically low (energy limiting conditions), higher LST (reflecting warmer monthly conditions, or lower cloud cover and therefore higher intercepted photosynthetically active radiation - PAR) is associated with an increase in biomass production, and therefore a positive correlation is expected in these regions.

During the summer season, air temperature explains most of the variance. Due to the inclination angle of the Earth, radiation level throughout the entire study area is higher during this period, and even in the northernmost part of the study area radiation is most likely not a limiting factor for vegetation growth. This is also reflected in the map of correlation coefficient for June-July (Fig. 5b), where, in contrast to the other sub-periods, the spatial distribution of r is not strongly stratified by latitude. Cooler air temperatures in the NE and NW portions of the domain, as well as in the Rockies (due to elevation) correlate with areas of positive r, indicative of thermal limits on vegetation growth. In the multiple regression, precipitation ranks second in explaining patterns in r during this period. Note that in June-July the overall variance explained by air temperature, radiation, and precipitation, is lower than in the other two sub-periods (Table 1). This suggests that when radiation is limiting plant growth, it strongly affects the LST-NDVI relationship, while in non-radiation limiting conditions the nature of LST-NDVI correlations is more complex and not easily explained by simple linear relationships.

Multiple stepwise regressions were also performed with the full set of biophysical variables listed in Table 2. Note that while solar radiation, precipitation, and air temperature are the driving forces in the soil-biosphere-atmosphere system, the other variables reflect more the response of the system. Including all 8 variables resulted in a similar ranking of the three primary factors explaining the overall variance in r.

Table 2. Mean and standard deviation (STD) of variables examined for influence on LST-NDVI relationship and the correlation coefficient matrix for each of the three sub-periods. The following notations are used: Precip. (precipitation); Rad. (solar radiation); fc (fractional vegetation cover);

SM_10 (soil moisture at the uppermost 10 cm); SM_200 (mean soil moisture at 0-200 cm); ET (evapotranspiration); % tree (fraction of tree cover); and T air (air temperature at 2 m). VF stands for volumetric fraction. All correlations are highly significant ($P<0.001$).

	Means	STD	r [-]	Precip. [mm/day]	Rad. [W/m^2]	fc [-]	SM_10 [VF]	SM_200 [VF]	ET [Kg/m^2]	% trees [%]	T air [°C]
April-May											
r	0.29	0.35	1								
Precip.	55.65	32.12	-0.14	1							
Rad.	224.85	22.71	-0.80	0.32	1						
fc	0.32	0.16	-0.23	0.60	0.39	1					
SM_10	0.25	0.06	-0.02	0.51	0.16	0.58	1				
SM_200	0.23	0.08	-0.25	0.54	0.44	0.56	0.88	1			
ET	0.27	0.13	-0.33	0.75	0.50	0.83	0.70	0.69	1		
% trees	29.58	27.40	0.37	0.18	-0.26	0.41	0.15	0.06	0.16	1	
T air	8.73	6.91	-0.76	0.35	0.85	0.51	0.28	0.45	0.58	-0.26	1
June-July											
r	-0.15	0.32	1								
Precip.	71.94	31.93	0.13	1							
Rad.	255.97	24.79	-0.55	-0.11	1						
fc	0.50	0.17	0.20	0.54	-0.30	1					
SM_10	0.23	0.05	0.39	0.45	-0.24	0.43	1				
SM_200	0.24	0.05	0.21	0.18	0.08	0.25	0.75	1			
ET	0.41	0.16	0.02	0.67	-0.03	0.81	0.52	0.39	1		
% trees	29.58	27.40	0.42	0.31	-0.33	0.59	0.41	0.22	0.42	1	
T air	18.62	5.77	-0.68	0.12	0.78	-0.14	-0.31	-0.13	0.13	-0.32	1
August-September											
r	-0.05	0.31	1								
Precip.	64.05	31.24	0.09	1							
Rad.	206.14	35.68	-0.77	-0.01	1						
fc	0.50	0.18	0.24	0.50	-0.21	1					
SM_10	0.22	0.05	0.27	0.48	-0.25	0.41	1				
SM_200	0.22	0.05	0.16	0.31	-0.14	0.08	0.73	1			
ET	0.26	0.11	-0.13	0.64	0.24	0.74	0.48	0.18	1		
% trees	29.58	27.40	0.26	0.31	-0.31	0.65	0.38	0.08	0.44	1	
T air	17.01	5.98	-0.72	-0.05	0.89	-0.26	-0.36	-0.28	0.15	-0.33	1

SUMMARY AND CONCLUSIONS

This paper explores the spatial and temporal relationship between LST and NDVI over the North American continent during the summer growing season (April – September) in the context of the usefulness to monitor droughts. It is shown that in contrast to the common perception that LST-NDVI has a universally negative correlation, this relationship varies with location, time, and vegetation type. Many attempts have been made to interpret this relationship in terms of numerous biophysical and geographical variables (e.g., land-use and land-cover, fractional vegetation cover, moisture conditions, topography, etc.). This study revealed that during the beginning and the end of the growing season, solar radiation is the predominant factor driving the correlation between LST and NDVI, while other biophysical variables play a lesser role. This behavior has often been missed in earlier studies of more limited scope, typically conducted over the central U.S. during the growing season.

It was found that when energy is the limiting factor for vegetation growth, as is the case at higher latitudes and elevations in the study area, a positive correlation exists between LST and NDVI. On the other hand, during the mid-season, the radiative flux over most of the study area was high enough not to limit vegetation growth, and solar radiation plays a smaller role in determining the nature of the LST-NDVI correlation. In this sub-period, except for the northernmost areas, the LST-NDVI correlations were generally negative.

Since droughts occur mostly in low latitudes, several vegetation health and drought indices (e.g., the LST-NDVI ratio and the VHI) were developed based on the assumption that a strong negative correlation between NDVI and LST exists. In such areas, water is ultimately the limiting factor for vegetation growth throughout the year, making this assumption correct. Subsequently, these indices were applied globally assuming universality. Based on the current study, there is a need to re-examine this assumption and restrict applications of such an approach to areas and periods where negative correlations are observed.

It is concluded that over North America, spaceborne monitoring of vegetation health and droughts based on the LST-NDVI relationship is valid primarily over the Great Plains and the South-West regions, and during the middle of the growing season. Similar and complementary research should be conducted over other continents to assess the global distribution of the LST-NDVI relationship and its temporal variation. Global/annual assessments of the VHI and other related indices should be used with caution. An alternative approach for monitoring vegetation health might be to incorporate physical understanding of the important driving physical variables and their impact on NDVI and LST (e.g., through physically based surface energy balance models; Anderson et al., 2007).

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GROUNDWATER AND ENERGY: THE PERFECT STORM

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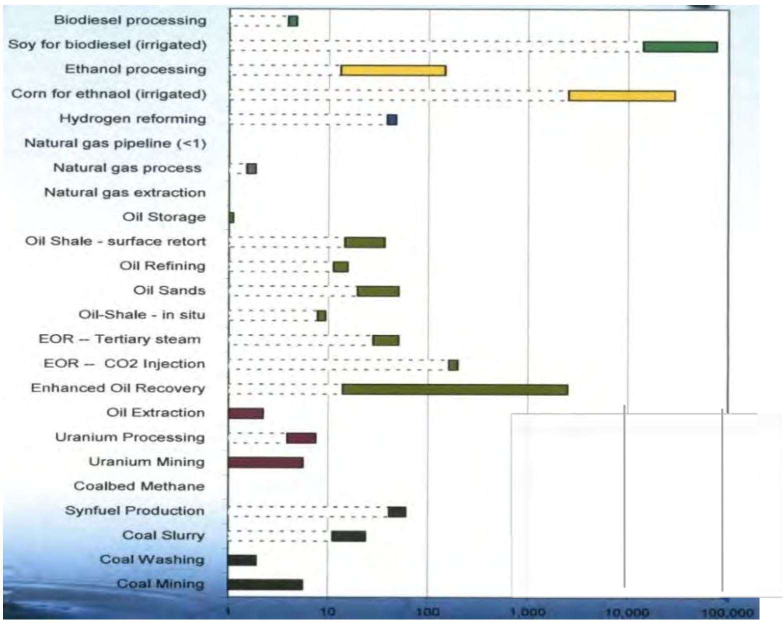
ABSTRACT

Groundwater use in agriculture constitutes a major portion of present day worldwide water usage. While subsidized electricity has given a boost to agricultural development in many countries, it has also resulted in severe groundwater depletion. In the US, the depletion rates of the Ogallala aquifer have been slowed down by the removal of subsidies, increased pumping costs, improved technologies and incorporation of important policy and legislative changes. Subsidized energy has also been very successfully used to encourage rural development in India but, unlike the US, efforts to remove the subsidies have often been unsuccessful resulting in risk to the economic viability of the electric power sector and rapidly declining ground water tables. In India, flat-rate subsidized electricity makes pumping costs very low or free causing massive groundwater overdraft. Due to the high cost to implement electric metering on large numbers of very small farms and due to political reasons, it has often not been possible to use metering to charge for electrical usage for irrigation pumping. The "rational flat tariff" has been proposed to provide high quality three-phase electric power for crop stress periods, with a commitment to gradually increase the flat rate tariff for electricity, and, if necessary, provide a reasoned partial subsidy to maintain viability of the electric power companies.

INTRODUCTION

Agriculture has and will likely continue to be the primary consumptive user of the world's fresh water, but water is also widely used for many domestic purposes and by most other industries. Historically, water has often been viewed as an abundant and cheap resource and is often grossly misused in the sense that rather than using an appropriate technology that conserves this critical natural resource, the cheap solution, relying on excessive quantities of water, often contaminating if not completely consuming it, is used. One industry that has become very dependent on water is energy. In the US, thermoelectric power plants withdraw as much water as that used for irrigation, in both cases about 40 percent of total water withdrawals (Hightower 2006). A major difference, however, is that most of the water used for irrigation is "consumptive" - evaporated or transpired - while most of the water withdrawals for thermoelectric plants is returned. Not only are irrigation and energy the dominant uses of water, but, as our life styles and technologies have developed, the interdependence that has emerged between energy and water has become critical, requiring management based on strategically coordinated plans.

Today's modern technologies for energy production are *increasingly* dependent on use of water. For example, in the US (as well as much of the rest of the world) there is a heated debate about the potential impact of biofuels on food supplies because of the direct competition for raw products (e.g. soy, corn) now used for food. But the debate also centers on the potential need for more water for irrigation to produce the biomass needed to produce biofuels. Figure 1 shows estimates of the demands that various types of energy development put on water in the US. According to these estimates, irrigation to produce biomass for biodiesel and ethanol is by far the most water intensive use of any energy production. Although the projections in Figure 1 were made as recently as 2004, many scientists do not believe corn ethanol or soy biodiesel have long term futures as biofuel feed stocks in part because of the potential high use of water. The message of Figure 1, however, is that nearly all sources of energy used today require water for their production. Furthermore, the newer technologies for energy production seem to be more water intensive than those of the past. The issue is not just that water is withdrawn to produce energy, or even used consumptively, it is also that the water used for energy production is often returned to the environment in a fouled state. For example, water used in gas and oil extraction, coal mining, or for emission control is often seriously contaminated after its use.



Source:

Hightower 2006

Gallons/MMBTU

Figure 1: Water used for energy production in USA

Water use has become dependent on energy just as energy production has become dependent on water. Energy is used to pump, transport, and distribute water but is also a critically important input to water treatment. Technologies for desalinization are continually being improved in terms of the amount of energy and cost required per unit of freshwater produced and are set to bring in radical changes in how we address the water crisis situation.

Our modern civilizations have developed in ways that have made the inter-dependence of water and energy essential. Economic and human population growth throughout the world will continue and, therefore, demand for both water and energy will increase. Not only are these two resources intrinsically connected but both will have major influence on future climate change. The importance of policies for energy and water (and even climate) being coordinated at the global scale seems obvious. Even more apparent is the local need within communities, states, countries or regions to find ways to work together in developing laws, policies, and appropriate technologies so that use of both water and energy are managed to sustain and protect the health of both resources.

DISCUSSION

Groundwater-Energy Nexus

Cornell University has had PhD students doing field studies of groundwater use for irrigation in India, Pakistan, China, and Mexico starting in the mid-1970s. These studies have not been comprehensive or even necessarily coordinated. But they did directly expose us to some of the critical issues in countries which are among the world's largest users of groundwater for agriculture (see Table 1). The groundwater problems in each country have their own uniquenesses as well as opportunities for common solutions. The size of farms is one critical variable unique to each area that impacts technologies for using groundwater as well as approaches for recovering associated energy costs for pumping. But there are many similarities as well. All of these countries are facing growing energy crises. Many of them have used subsidized energy as a means to stimulate rural development through irrigation. While there are many water-energy nexuses, we focus in this paper on the nexus of groundwater and energy.

Table 1. Groundwater usage by different countries

Country/province	Annual groundwater usage (km^2)	No. of pumps	Extraction per pump (m^3/yr)	Population (%) dependent on groundwater
Pakistan Punjab	45	0.5	90,000	60-65
India	150	21.28	7,900	55-60
China	75	3.5	21,500	22-25
Mexico	29	0.07	414,285	5-6
USA	100	0.2	500,000	<1-2

Source: Shah *et al* 2003

Highly Developed Country: Example

One of the similarities for many countries has been the use of irrigation as a means for agricultural economic development. Rural development often included systems for delivery of publically-funded rural electric power. In drier areas electric-powered pumps often become the method of choice for farmers to lift groundwater for irrigation. The so called “high plains” of central US span one such region, from nearly Mexico to Canada. Under much of this region, which covers portions of eight states, lays the Ogallala aquifer, the largest freshwater aquifer in the US. As a result of an unusually dry weather cycle farmers in the high plains were devastated in the 1930s, in what has become to be known as the Dust Bowl. Although this region is situated on top of the huge aquifer, farmers in the 1930s and even 1940s had no appropriate technology to draw water for irrigation resulting in many of them abandoning their farms.

With the advent of pump technology appropriate for lifting groundwater for irrigation and available, often subsidized, energy for operation the situation changed radically after about 1950 such that the Dust Bowl became one of the world’s most productive agricultural regions. Even in the 1950’s and 1960’s the extent and robustness of the Ogallala aquifer was not known, but farmers were rapidly developing irrigation wells in a manner as if the aquifer was inexhaustible. In a very real sense rural electrification and other cheap forms of energy were critical links that drove the agricultural development of the high plains because it encouraged affordable crop irrigation[1]. Reasonable people knew that the low rainfall of the region could not replenish the aquifer at the rate at which water was being withdrawn but practically nothing was done to control groundwater use until well into the 1970s. Due to its size the Ogallala aquifer is not uniform nor is water drawn from it at a uniform rate. But on an average the water table for the Ogallala fell at a rate of over 0.4 meters per year through the 1970s, with some areas dropping by well over one meter per year.

Through the 1960s the agricultural growth in the high plains was a model of success driven by groundwater irrigation from tube wells with pumps using low cost power. During this time no one thought much about the sustainability of the groundwater-dependent agricultural system that had developed. But as better data on the aquifer were collected and it was recognized that the water table was dropping fairly rapidly, interest grew in finding tools that could be used to manage the region’s groundwater resource. The water laws in this area basically allowed land owners to take as much water as they wanted; this is sometimes referred to as the law of capture. Over time the major subsidies for rural electricity were removed, but even so as long as the value of the water to the farmers was greater than the pumping costs they were able to optimize their profits by

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[1] Subsidized natural gas was also made available to many farmers. Much of the first information about the Ogallala aquifer was actually learned through the early natural gas exploration in the region. Hutson *et al,* 2000

drawing all the water they could beneficially use.[2] The water of the Ogallala is a common resource that is still being used at an unsustainable rate.

Fortunately, while the water table of the Ogallala continues to fall the average annual rate of decline slowed from 0.43m to .25m to 0.17m through the 1970s, 80s, and 90s respectively (Kansas Geological Survey, 2007). The rate of pumping slowed partly because as the water table dropped, pumping cost increased (Shipley and Goss, 1978), improved irrigation technology made irrigation more efficient needing less water (Kromm and White, 2007), and as subsidies were removed from electricity the cost to pump water increased, slowing pumping to the market rate for electricity. This improvement in slowing the drop in water table might have also resulted in part because of new policies issued by the States, the unit of government that generally controls water rights in the US. For example, several states adopted a policy of denying any permit for a new tube well if it could significantly reduce the availability of water to surrounding wells. Some states have local groundwater management districts, which have exerted efforts to slow the amount of pumping from the aquifer. These new policies are a move away from those policies in place when agricultural economic development was being aggressively encouraged using relatively abundant water and cheap energy as catalysts.

A relatively recent idea being promoted in Kansas takes the view that groundwater is a resource for all people of the state, including future generations (Peterson et al., 2003). The idea of sustainability is taken more seriously in the sense that pumping should be managed such that withdrawals beyond a fixed volume of water (which some people think should be zero) should be no greater than the natural recharge[3]. Whether this policy will make its way into law or even make a difference in farmers' actions is yet to be seen.

What are the lessons to be learned from Ogallala experience that *might* transfer to other countries that are less developed but growing their economies? One is that access to relatively inexpensive ground water can serve to significantly stimulate agricultural development. Also, while access to

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[2] Experience has shown that when a common resource, such as an aquifer, is basically free and unregulated it is over used. This is sometimes referred to as the tragedy of the commons. However, lateral flow of water in the Ogallala aquifer is slow, on the order of a few feet per year, so there is the possibility of a farmer with hundreds of hectares of land to conserve the water for later use. For this aquifer other farmers cannot easily access the water under a neighbor farmer's land. On the other hand there is no legal reason for the water users to conserve water in a sustainable way such that future generations will have access to the aquifers water.(Hightower 2006)

[3] In theory the way this management scheme might work is to allocate a user a fixed amount of water, say a 1000 ha -m, to be used on 100 hectare farm. Just like a bank account the farmer could draw from the 1000 ha-m but the allotment would go down by the amount used. So if he/she used 100 ha-m the balance to be used later would be 900 ha-m. The natural recharge to the aquifer would act like a deposit to the back account. So if the 100 hectare farm had a natural recharge of 50 hectare meters the balance to be used would be 950 ha-m. Such a management approach would give the farmers incentives to manage groundwater more carefully.

water facilitated by subsidized energy was a key to the agricultural development of the Ogallala region, other necessary inputs such as infrastructure and markets were available to create relatively large commercial farms. Also as agricultural economic growth took place, development subsidies were removed. The individual power use was easily measured, farmers had the ability to pay, and there was no particular political pressure to leave the initial economic development subsidies in place. The overuse of groundwater from a sustainable view can be slowed and perhaps will someday be stopped, although that has not been yet accomplished.[4] The basic laws governing groundwater rights and ownership relating to individuals who own the property above the aquifer have not changed significantly for decades. Even though there seems little opportunity for changing the water law there are ongoing efforts to implement policies to assure the water in the aquifer is used in a sustainable way.

Developing Countries and an India Example

Cornell was working with various international research organizations on irrigation in India for much of the period since 1984. Starting in the 1980s one of the leading groundwater experts in the world, Tushar Shah, was finding that crop yields for unit of water from groundwater irrigation were significantly more productive than government-managed surface water irrigation systems. The primary reason that groundwater was more productive was that it could typically be taken by the farmers *on-demand*, while surface water often required working with the irrigation bureaucracy resulting in untimely or irregular deliveries. Typically the cost to the Indian farmer for lifting groundwater for irrigation is more than offset when compared to government-run surface irrigation systems which typically provide water to farmers at little or no cost.[5] This is because of the increased reliability of having water on-demand when crops are water stressed and because much of electricity is typically heavily subsidized by the government, or is, in some cases, even free.

Crop area in India irrigated by both groundwater and surface water increased significantly over the last half century as shown in Figure 2.

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[4] Perhaps the most controversial current activity in the Ogallala region is the purchase of tens of thousands of hectares of land by T. Boone Pickens, a wealthy entrepreneur who made his fortune in oil. Mr. Pickens sees water as the new oil. His plan is to buy up water rights in the Texas Panhandle so that when cities such as Dallas, Fort Worth and others are short on water they will have little choice but to buy it from him. For some the idea that water is just another commodity to be bought and sold is difficult to accept.

[5] This statement is primarily accurate for subsidized electric powered pumps. In some Indian states such as Gujarat subsidies are slowly being removed. Diesel-based irrigation is typically much more expensive than electricity-based irrigation and is getting more so each year. Currently about 40% of India's groundwater irrigation is diesel powered but that percentage is much lower in the drier states.

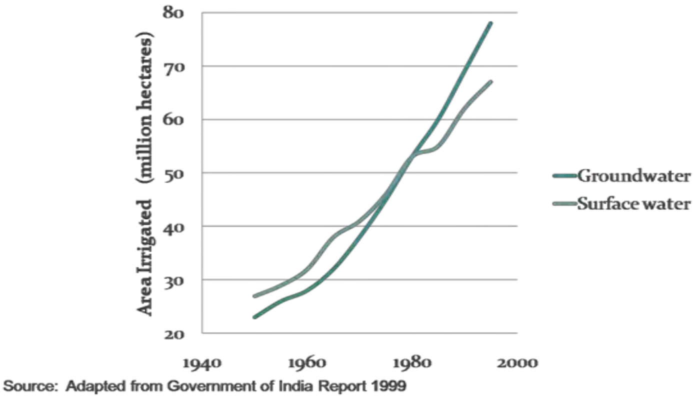

Figure 2: Crop area irrigated by surface water and groundwater in India

What has changed is the relative importance of surface water to groundwater as an irrigation source. Irrigation from surface water sources has increased at a steady rate while groundwater use has increased at an accelerated rate especially since the end of the Green Revolution when major government investments in surface water storage facilities slowed. Since the energy required by farmers to lift groundwater is far greater than energy needs of surface gravity systems, energy use can be expected to also follow the groundwater curve in Figure 2[6]. India, like the US and many other countries, used subsidized electrification as a means to accelerate agricultural development. In drier rural areas of India this encouraged installation of tube wells for irrigation which provide the needed catalysis for agricultural growth. The growth of private tube wells for groundwater irrigation in much of South Asia made the Green Revolution more successful than it would have otherwise been. Where groundwater was available, irrigation often became dependent on electricity, and farmers became hooked to cheap subsidized electricity. Figure 3 is illustrative of the problem electric subsidies to agriculture put on selected Indian states. Electricity for groundwater irrigation in India accounts for up to 20% of the country's total use of electricity (Shah, *et. al.*, 2003). This is a significant enough piece of the total electric power use so as to impact the stability of the electric industry of the country if the costs of electric power for irrigation are not recovered.

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[6] The values given in Figure 3 are not precise because groundwater and surface water are often used conjunctively if both sources are available to a farmer. It is also worth noting that "over irrigation" or irrigation canal leakage from surface water irrigation systems often result as the recharge to groundwater aquifers, so in some cases this situation is an unintended conjunctive use of sorts.

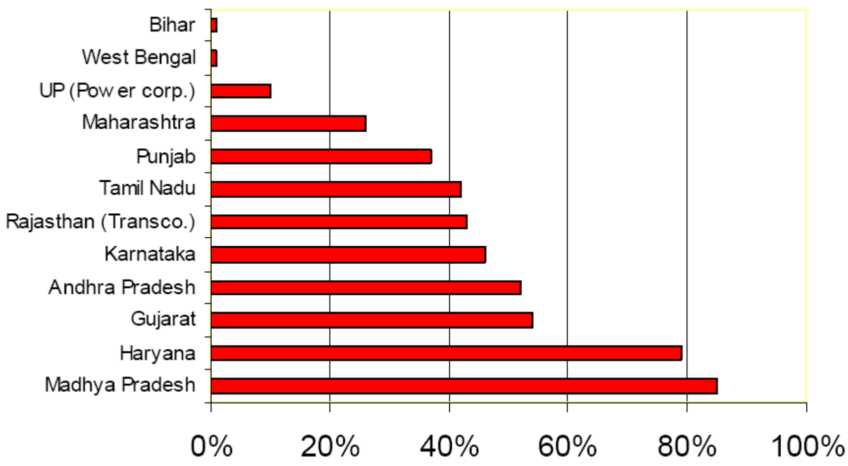

Figure 3: Electricity Subsidy to Agriculture as Percent of Gross Fiscal Deficit 2000-01
Source: Bhatia, 2005

Unlike the US and even China, efforts to increase the price of electricity to farmers to meet the real cost have failed in much of India for technical and political reasons. As the number of electric powered tube well pumps increased, the transaction costs associated with metering them for cost recovery became a significant part of the total cost of delivering power.[7] To overcome the metering problem some states moved to flat rate tariffs based not on actual electrical use but on the size (e.g. horsepower) of the pumps. However, this flat rate approach has at least two problems. First, with a flat rate there was little incentive to pump only the irrigation water actually needed since the incremental cost per unit of "over" pumping water is small. And second, once farmers became accustomed to subsidized electricity, politicians found they could win votes by promising to keep the price of electricity low, or stated more bluntly politicians in irrigation-rich states who said they would significantly raise electric power rates would not be elected. In any case, probably many poor farmers would have difficulty paying real (unsubsidized) energy cost, without the flat rate system

For the protection of both the groundwater resource as well as the power sector in some Indian states, the real cost of groundwater pumping must be reclaimed from the farmers or society broadly. In the US Ogallala aquifer case, the real costs, at least to the electric companies, are being paid by farmers because the farms are large and electric metering is accepted.[8] Generally, metered power at an appropriate tariff results in the cultivation of less water intensive crops and

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[7] India is the largest user of irrigation of any country in the world so it is a rather significant example of the irrigation-energy connection but similar situations can be found throughout South Asia. The US or even Mexico use on average much larger pumps for much larger farms than do farmers in South Asia. Average farm size in the US is 187 hectares and Mexico 40 hectares while in Pakistan farm size is 3.8 hectares and in India only 1.6 hectares (FAO, 2000).

[8] Even on China's North Plain where farms are relatively small metering seems to work in large measure because the government that manages the electrical system is not concerned about elections.

reducing overdraft. However in the Indian case, experts are of the opinion that the impact of metering and tariff rationalization may be small. This is because water is usually not the limitation for increasing farm returns. It is land which is the main constraint, as land holdings are extremely small. Hence, cost of power might not impact the water use or cropping patterns in a big way (GOI 2007). Therefore, while electrical energy metering might become a viable alternative even in India in the long term, to protect the groundwater and the energy industry a different method of controlling power usage must be found in the short term.

Just as in the US, in India the Union does not have any law to deal with groundwater. Most of the constituent states of India have groundwater acts, established in the form of 'State Acts'. Water-scarce states including Tamil Nadu, Andhra Pradesh, Kerala, Maharashtra, and Gujarat have comprehensive legislation addressing groundwater protection. Some key features of these Acts are notification of areas for regulation of groundwater abstraction, issuance of permits for new construction, upgrading or energizing wells/bore wells, registration of wells/tube wells, and non-supply of power from state electricity boards to wells sunk in contravention of the Acts. However, what is lacking is legislation which regulates the use of groundwater in such a way that depletion in the ground water levels and the similar rights of the adjoining land owners and public at large are not encroached upon (GOI, 2007). Therefore, there might be a need of an "Act" at the State level to monitor the ground water levels under the advisory guidance of Central Ground Water Board, instituted by Union Government. The awaited Supreme Court ruling in the Plachimada case in Kerala in which a Coca-cola factory is being charged with draining vast amounts of groundwater and also polluting groundwater by the Village Panchayat (local self Government), supported by affected villagers, is hoped to be able to incorporate sustainability issues in groundwater abstraction laws. At the policy level, the recommendations in the National Water Policy (revised 2002) and the National Environment Policy (2004) both instituted by the Union government serve as the cornerstone of ground water development and regulation in India.

One alternative proposed that would not require changing the law is to use a "rational flat tariff" (Shah et. al., 2003). One of the authors of this proposal is Tushar Shah, who was mentioned for his pioneer groundwater work earlier in this paper. The current flat rate tariff used to charge farmers for electricity for pumping groundwater in much of India is inefficient and inequitable. In fact the current flat rate tariff also puts both the sustainability of groundwater and country's electric power industry at risk of failure. Its primary attribute, however, is the ease with which it is implemented. The proposed rational flat tariff would be a sophisticated tool for managing electric power use and thus water use but retaining the simplicity not offered by metering at the farm gate.[9]

A rational flat tariff system must a) maintain the benefits of on-demand irrigation that groundwater provides, b) result in a high quality electrical service, c) sell electric power at a cost affordable to farmers, and d) generate enough revenue so as not to be a drag on the electric power industry.

Generally electric power is made available to rural communities year round for domestic and non-irrigation uses. But irrigation is required for only those periods when crops are water stressed. It cannot be known well in advance when these stress periods would occur but in drier parts of India they might occur about 50 days during the dry season. So if electric power could be delivered for irrigation for only 10 or 15 percent of the days of the year (on the stress days) most farmers would have something approaching water on-demand. Their situation would certainly be at least as good as the average farmer that uses water from a large surface irrigation canal. The second requirement of the rational flat tariff is that the electricity be of high quality, which for most electric irrigation pumps means stable three-phase power in sufficient quantity to operate pumps of a size needed to provide the quantity of irrigation water needed during the days of operation. Both of the requirements a) and b) above can be met by providing a 3-phase transmission line beyond the feeder line that is separate from the 2-phase domestic electric line. The 2-phase power will continue to be delivered year round and the 3-phase only during stress periods (Shah et al., 2007).

Requirements c) and d) of the system address issues of cost and cost recovery. The low flat rate currently charged will likely have to remain until farmers gain confidence in the new system. Then these rates charged to farmers need to be gradually adjusted upward but there needs to be an explicit subsidy wherein tariff rates increase in accordance with annual government subsidies provided the agricultural sector. Since the government continues to provide a subsidy for surface irrigation systems where essentially all costs are paid by the government there seems a justification to also support groundwater irrigation as well. Such a system would take time to

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[9] The proponents of the rational flat tariff sight surface irrigation as an example of a government service that typically does not charge individual farmers on a volumetric water use basis. This is because just as farm gate electrical use is extraordinarily difficult to monitor so is water use from large canal irrigation systems. A comprehensive evaluation of large surface irrigation in South Asia by Charles Perry (2001) showed that even with extraordinary efforts to construct devices to monitor flow to individual users, flow measurements were seldom taken and farmers rarely paid for irrigation on a volumetric basis. Transaction costs of monitoring irrigation water flow to a large number of small farms and unwillingness of farmers to pay was too high to allow the monitoring system to be used. Volumetric irrigation water monitoring can be successfully used in countries such as the US because as noted earlier the size of farms are orders of magnitude larger than in most of South Asia.

develop, particularly in regard to cost saving from off peak power use and so on as well as improvements to power delivery to match better the individual crop stress periods.

A well running rational flat tariff regime can cut wasteful use of groundwater on one hand and electricity losses on the other hand. Power supply for restricted periods will provide an impetus to farmers for undertaking water saving measures. During the non farming season, only 2-3 hrs of power supply will lead to the creation of on-farm storage tanks for manifold use. Also, with a hike in tariff rate, farmers will increasingly use smaller capacity pumps and hence reduce groundwater abstraction. Moreover as rural electricity transmission infrastructure is not very efficient, restricted periods of power supply will cause a reduction in technical and commercial losses of power. This approach is not just theoretical, 90% of the villages in Gujarat are following this system (Shah and Verma, 2007).

In fact a deviation from the flat tariff system currently followed in Pakistan is the Flat-*cum*-Metered tariff. It was primarily introduced to contain the power thefts and illegal power usage during the flat rate regime in the country. In this system, in addition to the cost of the units consumed, the government also charges a flat rate of approximately Rs. 400, Rs.700, and Rs.1050 in Pakistani money per month for 5, 7 and 10 horsepower motors, respectively. This system seems to be suitable for small farmers as they can control the electricity bill by restricting the operational hours in case of metered tariff (Qureshi, 2003).

Water markets existing in India are informal, limited to localized water trading between neighbors and are not regulated by any legal framework. Groundwater trading promotes efficient use of ground water and provides poor farmers unable to afford wells, an access to water. There is however, some evidence of decline in groundwater table caused by competitive water withdrawal due to intense water marketing activities. In the case of water markets it has been observed that with metered supply, high electricity price will restrict water markets. In Gujarat, it is seen that farmers with metered supply charge 30% to 60% more for water compared to farmers with flat tariff (Shah and Verma, 2007). So, a difficult situation exists. If the tariff is high, farmers will cut down on groundwater extraction and marginal farmers will end up paying more or having much less access to water. And on the other hand if tariff is low, then groundwater extraction will be higher, but marginal farmers will have better access to water.

The other major energy source for groundwater pumping in many developing countries is diesel. According to estimates, India, Pakistan, Bangladesh and Nepal together use about 21-23 million pumps, of which about 13-14 million are electric and around 8-9 million are powered by diesel engines (Shah et al., 2003). Electric tube well owners subject to a flat tariff regime use their pumps for much more horsepower hours compared to diesel tube well owners, as seen in Figure 4. So default waste of water and power is much lower in the latter case. In India, due to poor electrification, many parts of eastern India (Bihar, West Bengal, eastern Uttar Pradesh) are mostly dependent on diesel run pumps. In these groundwater abundant regions of the Gangetic basin, small diesel pumps have been mostly adequate. However, in the last 10 years, removal of subsidies on diesel have led to inordinately high costs for pumping groundwater which in turn has resulted in serious negative impacts on crop production and farm incomes (Mukherji, 2007). In order to cope, farmers have responded by changing cropping pattern from field crops to orchards and vegetables, increasing use of fuel efficient pumps, mixing kerosene with diesel to bring down fuel costs, etc. (Moench and Burke, 2002).

In present day Pakistan the shift towards diesel run tube wells is due to steep initial installation costs of electric tube wells and intermittent power supply for the electric tube wells (Qureshi, 2003). Though total withdrawal per diesel tube well is much less compared to an electric tube well, long term studies are needed to determine their impact on the groundwater levels.

Apart from tariff and legal modifications, a host of institutional, management and technical changes are needed to minimize waste in water and power and increase equity among consumers in India. Cooperative and user group management of groundwater, augmenting available ground water through recharge and watershed programs, upgrading of skill sets and competence of power utility companies to serve the agriculture sector, rectification programs for pump sets, etc. are some of the changes needed.

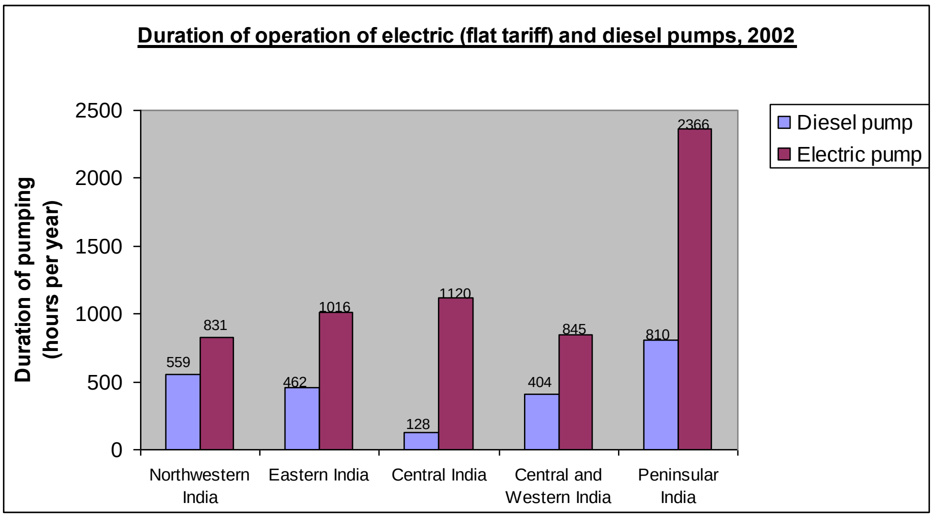

Figure 4: Annual duration of operation of electric and diesel pumps in India. Source: Shah et al. (2003)

CONCLUSIONS

This paper broadly reviews some aspects of the existing nexus of water and energy and the need to develop coordinated strategies for using these resources. The focus of the paper is on the growing problem of declining groundwater tables due to over pumping, a problem that is exacerbated by heavily subsidized rural electric power in water scarce regions of South Asia, like in parts of India. This is also causing a serious problem to the financial viability of the electrical power sector there. Experiences which have been successful in the industrial agriculture system in US pumping water from the Ogallala aquifer have been discussed in the context of India which has a developing economy and small holder farming systems. In India subsidized electricity at a flat rate is no longer economically viable for the power sector and because of logistic and political reasons, metering is not a workable solution. The proposed "rational flat tariff" system providing high quality three-phase electric power during crop stress periods is working well in many parts of the state of Gujarat. This system is also committed to increasing the flat rate tariff for electricity gradually for better cost recovery. Water markets which have flourished in India in the flat rate tariff regime and provided accessibility of groundwater to marginal farmers face a threat of shrinkage from metering with a high tariff. Due to poor electrification in some areas of eastern India, diesel based water pumping proves a reliable yet expensive alternative. Extensive studies are needed for understanding the contribution of diesel run pumps to the water-energy nexus. Legislative, institutional, management and technical changes are also required in this sector.

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Session 2: Agriculture and Global Changes

USING DIVERSITY IN TIMES OF GLOBAL CHANGES: PRODUCTIVITY, NUTRIENTS AND WATER USE

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ABSTRACT

To support a growing human population under conditions of climate change, it is essential to increase agricultural production and its efficiency in terms of land, nutrients and water. Plant diversity has in several studies been found to be positively related with biomass production. Coexisting plant species can preferentially use distinct nutrient pools. Therefore, competition between them may be smaller than intra-specific competition, stimulating biomass production in diverse swards. Species root in different depths, thus leading to a better use of available nutrients and water. This may also increase the resilience to climatic changes, which can be further improved in more species-rich systems because of a larger probability of presence of species that can deal with the changed conditions.

Besides stimulating productivity, an increased use of nutrients may lead to less losses of nitrogenous species such as nitrous oxide (N_2O). Agriculturally managed soils are the main sources of this greenhouse gas, with agriculture accounting for 84% of global anthropogenic N_2O emissions. However, there is also evidence for an uptake and further reduction of N_2O from the atmosphere into the soil, so that soils may act as a sink for N_2O. The influencing factors for this net N_2O consumption are not understood yet, but lower soil N contents due to increased plant uptake may stimulate the soils' sink strength for N_2O.

So far, the relationship between productivity, efficiency and species richness has mainly been studied in experimental grassland plots sown and weeded several times per year to yield different species numbers. Such management is unrelated to agricultural situations. However, first studies show that the benefits of plant diversity are also valid and relevant for agricultural grassland and cropping systems. Thus, the use of plant and crop diversity may be a tool to improve the sustainability, resilience and productivity of agriculture in times of climate change and at the same time protect diversity.

INTRODUCTION

To support a growing human population, it is essential to increase agricultural production and the efficiency of this production in terms of land, nutrients and water. In many regions, this has to occurr in deteriorating environmental conditions due to climatic changes. According to the Fourth Assessment Report (IPCC, 2007), the likelihood that heat waves and heavy precipitation events will become more frequent is more than 90 %, leading to drought and heat stress for plants and animals and increasing the risk of soil erosion.

The main agricultural land-use form worldwide is grassland, with permanent pastures covering approximately 40% of the world's land surface (White et al., 2000a) and two thirds of the total global agricultural land surface (FAO, 2006). Grasslands, including rangelands, contribute to the livelihoods of over 800 million people, many of which are smallholder farmers (Reynolds et al., 2005). Grassland soils are estimated to store 34% of the global terrestrial carbon stocks (White et al., 2000a). Furthermore, they provide an important reserve of biodiversity, especially for plants and birds (White et al., 2000a).

The role of biodiversity is often limited to that of a victim of both climate change and agriculture. While it is true that the spatial distribution of species changes and many are threatened by extinction (Parmesan et al., 1999; Walther, 2003), I want to emphasize in this paper that plant diversity may also be a tool in our efforts to adapt agricultural production to a changing environment. To this end, I will present results of studies investigating relationships between plant diversity, biomass production, nutrient and water use efficiency. I will discuss the results critically and outline further research needs. Most studies have been carried out on grassland, so that I will concentrate on this in the first part of the paper. Options for agricultural production in general will be outlined in the discussion.

PHYTODIVERSITY AND PRODUCTIVITY

The relationship between diversity and productivity is still highly debated. Higher plant diversity has often been found to be related to better productivity and nutrient use efficiency (Altieri, 1999; Bullock et al., 2001; Dodd et al., 2004; Hector et al., 1999; van Ruijven and Berendse, 2003; van Ruijven and Berendse, 2005). Thus, Bai et al. (2007) measured linear productivity-diversity relationships on 854 field sites in the Eurasian Steppe in Inner Mongolia. Coexisting plant species can preferentially use distinct nutrient pools, e.g., nitrogen (Bret-Harte et al., 2004; Weigelt et al., 2005). Therefore, competition between them may be smaller than intra-specific competition, stimulating biomass production in diverse swards. Species may also root in different depths, thus increasing the root zone, leading to a better use of available nutrients and water. Furthermore, phytodiverse grassland offers habitat and food for different animals, including pollinators and antagonists of pests (Braman et al., 2002; Meyer et al., 2007; Steffan-Dewenter and Tscharntke, 1999). Without this habitat, these organisms, which are highly beneficial for agricultural production, may become scarce.

Besides positive or hump-backed relationships between diversity and productivity, also negative, u-shaped or insignificant relations have been found (Mittelbach et al., 2001; Waide et al., 1999). In a meta-analysis of previously published results, Waide et al. (1999) found that for studies of plants, at large scales (> 4000 km) a positive relationship was most common, while at smaller scales, especially at the local scale (< 20 km), unimodal or insignificant relationships were usually found. In terrestrial systems, positive relations between species richness and productivity were more common at all scales than in aquatic systems (Waide et al., 1999). De Lafontaine and Houle (2007) cautioned that pooling of data across production ranges and community types may confound factors determining the diversity-productivity relationship.

Does productivity determine species richness or vice versa? On the one hand, for grassland, increasing fertilization has usually been found to increase productivity, but diminish plant diversity (Hejcman et al., 2007; Janssens et al., 1998). The effect depends not only on the amount, but also on the type of fertilizer used. Thus, organic fertilizers seem to affect plant diversity less than mineral fertilizers (Jones and Haggar, 1997). Plant diversity is usually largest in soils with intermediate to low nutrient contents (e.g. Critchley et al., 2002). In nutrient-rich soils, competition for light limits diversity to the most competitive species (Tilman, 1990), while in very nutrient-poor conditions, only few specialized species can grow, leading to the hump-backed relation between productivity and species numbers. On the other hand, controlled experiments with treatments differing in the number of sown species suggest that it is species richness that determines productivity (Hector et al., 2007; Hector et al., 1999; Tilman et al., 1997), of course within the constraints given by the location and resources (Dodd et al., 2004). He et al. (2002) have shown that the relation between species numbers and biomass production also depends on the amount of nutrients in the soil. Thus, the site characteristics and management determine the range of species able to grow and within these limits, the number of species actually growing and their diversity influence productivity.

PHYTODIVERSITY AND NUTRIENT USE

One measure applied to recreate grassland diversity in Europe is the depletion of soil nutrients (Berendse et al., 1992; Isselstein, 2005). Low-input grazing systems have been suggested as a management option helping to reduce nutrient contents, combining the recreation of diverse grassland with economic benefit for the landowner (Bakker et al., 2003; Dahlin et al., 2005; Rook et al., 2004). However, although the observed relation between soil nutrient contents and biodiversity is negative, extensive management aiming at a depletion of nutrients is not always successful in restoring biodiversity in the short term (Berendse et al., 1992; Marriott et al., 2005; Marriott et al., 2004). Obviously, depletion is a time consuming process (Bakker and Berendse, 1999; Critchley et al., 2002; Loiseau et al., 2005). It is not yet fully understood, especially not in complex systems such as grazed pastures, where the temporal and spatial variation in nutrient fluxes is large.

Productivity may be increased in more diverse swards due to more efficient use of nutrients. More efficient use of available nutrients in more diverse swards may decrease leaching and gaseous N losses (Niklaus et al., 2006; Scherer-Lorenzen et al., 2003). Agriculturally managed soils are the main sources of the greenhouse gas nitrous oxide (N_2O), with agriculture accounting for 84% of global anthropogenic N_2O emissions (Smith et al., 2008). N_2O has due to its long atmospheric lifetime of 114 years a 100-year global warming potential that is about 298 times as strong as that of carbon dioxide (CO_2, IPCC, 2001). Plant diversity has been found to increase soil mineralisation (Zak et al., 2003). This does not necessarily result in increased N_2O production, as the plant N uptake is also increased by higher diversity (Niklaus et al., 2006; Zak et al., 2003).

There is also evidence for an uptake and further reduction of N_2O from the atmosphere into the soil, so that soils may act as a sink for N_2O (Chapuis-Lardy et al., 2007; Wrage et al., 2004). The influencing factors for this net N_2O consumption, measured as negative fluxes (from atmosphere to soil) are not known yet (Chapuis-Lardy et al., 2007), but lower soil N contents due to increased plant uptake may stimulate the soils' sink strength for N_2O.

Thus, increased plant diversity may increase productivity within the lines set by management and site characteristics, increase nutrient use and decrease losses of the greenhouse gas N_2O. This leads to the next topic, the relation between plant diversity and water use or stresses caused by climate change.

PHYTODIVERSITY AND RESILIENCE TO CLIMATIC STRESSES

Can increased plant diversity in grasslands serve as insurance for productivity in a changing climate? A positive relationship between diversity and production stability has first been suggested by MacArthur (1955). This was based on the idea that species-rich systems have a higher probability of containing species that are tolerant against a specific disturbance. Thus, species or functional groups that might be redundant in normal conditions might provide insurance in times of change (Yachi and Loreau, 1999). In line with this, Tilman et al. (2006) found a higher temporal stability of the annual aboveground productivity with larger numbers of plant species in a decade-long grassland experiment. They suggested that the reliable, sustainable and efficient production of livestock fodder and biofuels can be enhanced by making use of biodiversity (Tilman et al., 2006).

In line with this, different rooting depths of coexisting species have been found to increase the water use of more diverse systems (Caldeira et al., 2001), thus potentially increasing the vegetation's resilience to water stress. However, experimental simulations of climate change have also indicated shifts in the proportion of functional groups, usually reducing diversity. After extreme heating events, White et al. (2000b) found a larger surface cover of C_4 species in grassland. Three years of elevated temperatures increased forb production in another experiment, without significantly changing overall diversity (Zavaleta et al., 2003). Kahmen et al. (2005) did not find changed species numbers, but observed an increased below-ground production in more species-rich plots after simulated drought, which may affect the recovery of the vegetation, thus potentially also increasing resilience to drought.

We may conclude that more diverse plant communities may cope with climatic stresses better for two reasons: 1) they have a larger probability of containing species able to deal with the changed conditions, and 2) they may have a better partitioning of resources, including water. As climate change also affects the distribution of species and the relative proportion of functional groups in swards, it is essential to have a large diversity to begin with and to be aware of possible changes in fodder quality.

DISCUSSION

Plant diversity may increase biomass production per unit of nutrient and water available and make it more sustainable also in terms of decreased nutrient losses and greenhouse gas production. In the following, I want to discuss 1) whether the results from ecological studies described above are applicable for agricultural grasslands, 2) whether the outlined relationships may also apply to agricultural situations other than grassland farming, and 3) where major research needs are.

So far, the relationship between productivity, efficiency and species richness has mainly been studied in experimental grassland plots sown and weeded several times per year to yield different species numbers (e.g. Hector et al., 1999; Tilman et al., 2006). After weeding was terminated, Pfisterer et al. (2004) reported similar numbers of species in treatments with originally 1, 2, 4, 8 or 32 species within two years. Harvest management was very extensive in the Cedar Creek experiment, consisting of annual burning (Tilman et al., 2006). While this may be comparable to some extensively used rangelands, it is very different from more intensively used meadows or pastures. Kirwan et al. (2007) adapted the plot management more to agricultural practices, but worked with mixtures with very few species (up to four). While these experiments allow the investigation of ecological questions, such experimental conditions make it difficult to draw conclusions for agricultural grassland management, especially for permanent grassland (Hofmann and Isselstein, 2005; Sanderson et al., 2004; Soder et al., 2007). The set-up of the experiments, with initial burning, tilling, use of herbicides and sowing of target species, means a major disturbance for the system, with changes in soil processes and nutrient dynamics that may also influence the results. However, results from e.g. Bai et al. (2007) suggest that also permanent grassland with grazing intensity from low (hayfields) to high (summer grazing with very high stocking rates) show positive relationships between species richness and productivity. This nourishes the hope that plant diversity can be used to improve productivity, resilience and sustainability of grasslands.

Other agricultural systems that might profit from increased diversity reach from traditional cropping to agroforestry systems. The latter already benefit from increased diversity as part of the system. In traditional cropping systems, a higher diversity of crops in a landscape has been shown to be related with larger productivity (Di Falco and Chavas, 2008). As well, a higher on-farm phytodiversity (Omer et al., 2007) or variety richness (Di Falco et al., 2007) could be shown to increase production. Thus, it is not in all cases necessary to change the diversity per field, although an increased genetic diversity on rice fields has also been shown to decrease the risk of illness and increase production (Zhu et al., 2000). The use of cover crops can be a further means of increasing both diversity and productivity.

Research needs can be identified both in the agricultural and ecological field. For agricultural researchers, it is essential to investigate how the ecological findings can be transferred to agricultural situations. Some of the services provided by phytodiversity are substituted in agriculture by management, e.g. by fertilization or use of pesticides. However, if diversity decreases losses of nutrients, it may also improve sustainability of intensively managed systems and reduce the use of increasingly expensive fertilizers. From an ecological point of view, it is still necessary to get better insight into the reasons for the observed relationships between diversity and productivity, nutrient use and resilience to stresses, and into connections between above- and belowground diversity and their consequences. The combination of agricultural and ecological research and application of the findings in agricultural management should not only help to conserve biodiversity, but also to develop a more sustainable agricultural system to produce the food for a growing human population.

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THE IMPACT OF GLOBAL CHANGE ON N_2O EMISSION RATES BY CHANGE IN ENVIRONMENTAL CONDITIONS AND IN MICROBIAL COMMUNITY STRUCTURE

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ABSTRACT

The response of nitrous oxide (N_2O) emission rates and β-Proteobacterial ammonia-oxidizing (AOB) communities to changes of temperature, soil moisture and nitrogenous fertilizer concentration were studied for 16-20 weeks in a multi-factorial laboratory experiment using a California meadow soil. Interactions among these three environmental factors influenced the N_2O emission rates, and two patterns of N_2O emission rates due to nitrification ($NitN_2O$) were observed: (1) in soils receiving low or moderate amounts of fertilizer the rates decreased sharply in response to increasing soil moisture and temperature. (2) in soils receiving high amounts of fertilizer, the rates were influenced by an interaction between soil moisture and temperature. At 20°C increasing soil moisture resulted in an increase in the rates, and at 30°C the highest rate was observed at moderate soil moisture. We used path analysis to identify the inter-relationships that best explain these two patterns. Path analysis revealed that in the high fertilizer treatment the major path by which ammonia influenced $NitN_2O$ rates was indirect through an influence on the abundance of one particular phylogenetic group (AOB "cluster 10"). In contrast, in the low and moderate fertilizer treatments soil moisture influenced the rates both directly (the major path) and indirectly through AOB community structure. This study thus demonstrates the potential contribution of change in environmental factors to variability in N_2O emission rates indirectly by AOB community shifts.

INTRODUCTION

Nitrous oxide (N_2O) emission to the atmosphere is a major environmental concern due to its contribution to global warming (12), and to destruction of the stratospheric ozone layer (10). N_2O is a by-product of the first step of nitrification (that is, oxidation of ammonia to nitrite by AOB), as well as an intermediate product of denitrification by denitrifiers (8). N_2O emission rates are influenced by change in various environmental factors among them temperature (9, 18, 34) soil moisture (18, 22, 27), and N fertilization (28, 33). The contribution of nitrification to total N_2O emission has been observed to be influenced by ammonium concentration, soil moisture (29, 31) and temperatures (4, 27). The response of N_2O emission rates to these various components of global environmental change is particularly important since temperature, soil moisture, and nitrogen deposition have increased in many regions (38, 40), and are predicted to increase further in the future. The community structure of AOB in soil has been widely studied, and has been shown to be influenced by various factors, including ammonia concentration (23), pH (11, 24, 25), temperature (2, 3) and soil moisture (17), the same factors affecting N_2O emission rates. Furthermore, variation in N_2O emission rates has been demonstrated for different pure cultures of *Nitrosospira* and *Nitrosomonas europaea* strains incubated under similar conditions (21, 32), suggesting a potential impact of community structure on N_2O emission rates. However, a relationship between community structure and N_2O emission rates under natural environment conditions has not yet been demonstrated.

In the present work we examined the effects of changes in environmental factors involved in global change (i.e. temperature, soil moisture and nitrogen inputs) on N_2O emission rates from Jasper Ridge soil after incubation of 16-20 weeks. We explored by statistical analysis the two different patterns of $NitN_2O$ emission rates observed, testing the hypothesis that community structure plays an important role in determining $NitN_2O$ emission rates along with other biotic and abiotic parameters.

METHODS

Soil sampling, Experimental Set-Up and Measurment Of Nitrous Oxide Emission Rates

A soil sample was taken from the upper 10-cm of a grassland in the Jasper Ridge Biological Preserve (1), and was sieved to < 2 mm aggregate size. The laboratory experiment was set up in a full factorial design, including 2 temperatures typical of winter and summer (20°C and 30°C), 3 soil moisture levels commonly experienced in this soil (30, 45 or 60% of maximum water holding capacity (WHC)) and 3 fertilizer concentrations that span a wide range of nitrogen inputs (between 0.05 to 0.3% w/w of the slow releasing N source Methylaneurea), resulting in 18 different treatment combinations in duplicates. Samples of low and moderate concentrations (i.e. 0.05 and 0.1% w/w; denoted as LF and MF treatments, respectively) were incubated for 20 weeks, while samples of high fertilizer concentration (i.e. 0.3% w/w; denoted as HF treatment) were incubated for 16 weeks. Samples for estimation of ammonium and nitrate concentrations were taken from all treatments at the end of the experiment (i.e., after either 16 or 20 weeks of incubation). Ammonium and nitrate concentrations were determined after extraction of soil samples with 1M KCl. Soil extractions were frozen at –20°C before analysis. The pH was determined after suspension of the soil both in 0.01M $CaCl_2$ and in water.

N_2O emission rates were measured as described previously (4). The contribution of nitrification to nitrous oxide (N_2O) release was estimated by comparing the N_2O released from samples amended with 10Pa acetylene to that released from samples without addition of acetylene (i.e.

estimation of N_2O emission due to denitrification and due to total emission, respectively) as described previously (15).

Community Analyses

DNA was extracted from a 500 mg (wet weight) subsample using the Fast DNA® SPIN® Kit for Soil (BIO 101, Carlsbad, CA), in accordance with the manufacturer's instructions. DNA was cleaned of possible PCR inhibitors using the Wizard DNA clean up kit (Promega, Madison, Wis.). The samples were amplified in triplicate using *amoA* primers and protocols identical to those described previously (1). Fingerprinting analysis using T-RFLP was conducted, and resulting data analyzed as described previously (1). PCR products which exhibited different fingerprint patterns were cloned, using a TOPO cloning kit (pCR 2.1 vector for *Escherichia coli* TOP 10F'; Invitrogen, Leek, The Netherlands) following the manufacturer's instructions. Clones were sequenced (DNA Sequencing Facility, Genaissance Pharmaceuticals, Inc), analyzed by FinchTV1.3.1 (http://www.geospiza.com/finchtv) and the ARB program package (http://www.arb-home.de) as described previously (4). All sequences of *amoA* genes retrieved in this work have been deposited in the GenBank nucleotide sequence database under accession no. DQ396811 through DQ396858 (1). Real time PCR (aka Quantitative PCR or qPCR) amplification was performed using the same primer sets and protocols as described previously (1, 19). In order to estimate the abundance of each cluster separately, we multiplied the total abundance of the *amoA* gene (estimated by qPCR) by the proportion of each cluster (estimated via T-RFLP). This product is presented below as the "scaled abundance" as described previously (1).

Statistical Analysis

All statistical analyses were performed in SAS version 9.1 (SAS Institute Inc., Cary, NC). The data were transformed to achieve normality. For each dataset, the transformation that resulted in the best fit of the dataset to a normal distribution was chosen. For most datasets a log-transformation was best, with the exception of the N_2O emission rates due to nitrification ($NitN_2O$) and ammonium concentration data (square root-transformed), the scaled abundance of AOB cluster 3a, 9 and 10 data (log followed by additional log transformation). ANOVA was performed using both the GLM and MIXED procedures in SAS. The relationship of community structure, total abundance and environmental parameters to $NitN_2O$ emission rates was analyzed with multiple regression performed using the REG procedure in SAS 9.1. We used path analysis, an extension of multiple regression (35), to further explore the interrelationships among those variables significantly related to $NitN_2O$ emission rates.

RESULTS

Nitrous Oxide Emission Rates

The rates of total N_2O emission and $NitN_2O$ emission resulted in similar patterns (Fig 1). Given that nitrification was the major contributor to N_2O emissions in most treatments, all further analyses were done on the $NitN_2O$ rate data. Overall, the $NitN_2O$ emission rates were influenced by the interaction between the three treatments ($F_{4,18}$=6.09, p=0.0028), indicating that the effects of the three treatments are not additive. The pattern in the HF treatment was influenced by the interaction between soil moisture and temperature ($F_{2,6}$=13.68, p=0.0058), such that at 20°C elevated soil moisture resulted in an increase in $NitN_2O$ emission rates, and at 30°C the highest rate was observed at moderate soil moisture (i.e. 45% of maximum water holding capacity, WHC; Fig 1). Strikingly different pattern was observed in the LF and MF treatments, where the rates were influenced by soil moisture ($F_{2,12}$=62.24, p<0.0001) and by temperature ($F_{1,12}$=14.76, p=0.0023), such that both elevated soil moisture and elevated temperature resulted in a decrease in $NitN_2O$ emission rates with no interaction between these factors (Fig 1).

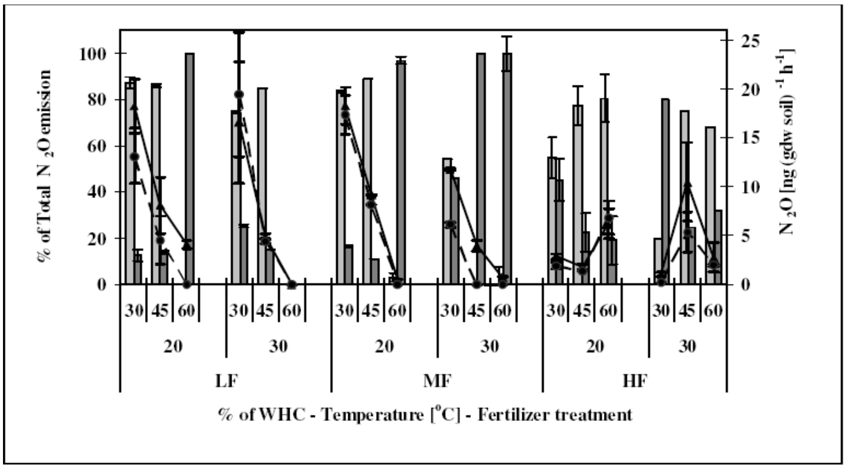


Figure 1: Effect of temperature, soil moisture and fertilizer concentration on total nitrous oxide emission rates (▲) and the rates due to nitrification (●). The percentage of nitrification (weak gray) and denitrification (dark gray) are displayed as bars. Key: % of WHC represents the percent of the soil's maximum water holding capacity. Fertilizer treatments are denoted as LF, MF and HF and represent low, moderate and high fertilizer concentrations (0.05, 0.1 and 0.3% of fertilizer, respectively). Rates were calculated per gram dry soil (gds). Error bars are 95% confidence limits.

Ammonia Concentration

We calculated ammonia concentrations at the end of the experiment from our measurements of ammonium concentration, pH and temperature (using the formula in (13)). Ammonia concentration in the HF treatments was influenced by an interaction between soil moisture and temperature ($F_{2,6}$=8.73, p=0.0167), such that an increase in soil moisture resulted in a decrease in ammonia, and the effect was stronger at higher temperature.

AOB Community Structure

The community structure of most samples incubated under the LF and MF treatments was dominated by AmoA cluster 10, ((4), with *Nitrosospira* sp. AF as a representative pure culture - 93-100%). However, the relative abundance of cluster 10 was influenced by an interaction between temperature, soil moisture and fertilizer treatments ($F_{2,12}$=4.85, p=0.0285), such that it was decreasing with increasing soil moisture, and the effect was stronger at a combination of 30°C and the MF treatment (decreasing to 65.2%).

The community structure of soil samples incubated at a combination of the HF and 45-60% WHC treatments for 16 weeks changed strikingly. Cluster 10 dominated (95.7 ±1.6%) under the 20°C and HF treatment combination, with no significant differences among the soil moisture treatments. Cluster 9 dominated (73.5±5.4%) under the 30°C, either 45 or 60% WHC and HF treatment combinations; cluster 3a was in highest relative abundance (19.4±7.4%) in this treatment combination as well.

Total Abundance and Scaled Abundance of AOB

Total abundance in soil samples incubated for 16 weeks at 20°C increased with increased soil moisture in the HF treatment, but at 30°C the highest total abundance was measured under moderate soil moisture (i.e. 45% WHC). Total abundance in the LF and MF treatments was not related to NitN_2O emission rates. An interaction between temperature and soil moisture influenced the scaled abundance of cluster 9 and 3a in the HF treatment ($F_{2,6}$=10.33, p=0.0114; $F_{2,6}$=17.59, p=0.0031, respectively, Fig 2) in a similar manner as total abundance, while scaled abundance of cluster 10 was influenced by temperature ($F_{1,6}$=15.49, p=0.0077) and by soil moisture ($F_{2,6}$=34.49, p=0.0005), such that its values were decreasing with increasing temperature and increasing with increasing soil moisture.

The Relationship between Scaled Abundance and NitN_2O Emission Rates

(1) In the HF treatment

The best fit multiple regression model was one that included the following predictor variables: ammonia concentration, scaled abundance of cluster 10, scaled abundance of cluster 3a, and scaled abundance of cluster 9 ($F_{4,7}$=8.24 , p=0.0088). This model could explain 83% of the variance in NitN_2O emission rates (r^2=0.825, r^2_{adj}=0.725). For path analysis, we hypothesized a causal model that related ammonia concentration both directly and indirectly to NitN_2O emission rates (Fig. 3a). The strongest causal path was the indirect effect of ammonia through the scaled abundance of cluster 10 to NitN_2O emission rates (path coefficient = -0.90).

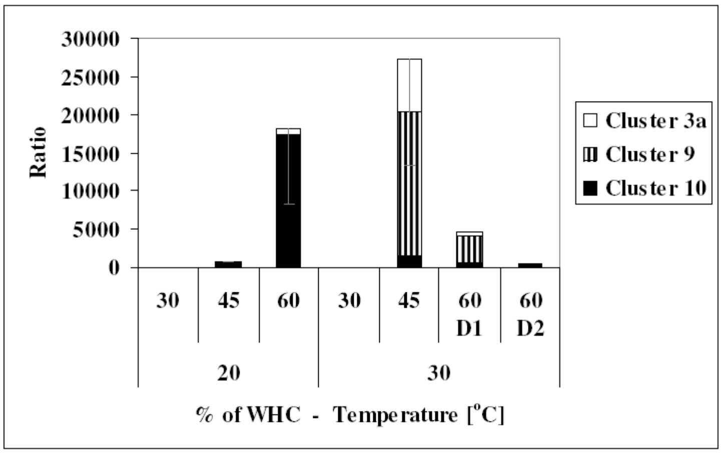


Figure 2: Effect of the interaction among temperature and soil moisture on total abundance of ammonia-oxidizers in high fertilizer (HF) treatment. The total abundance has been normalized to a standard sample. The stacked bars represent the contribution of each phylogenetic group to the total abundance. Key: % of WHC represents the percent of the soil's maximum water holding capacity. The duplicates incubated at 30°C and 60% WHC are displayed separately due to major differences in their community structures (D1 denotes duplicate 1 and D2 denotes duplicate 2). Error bars are 95% confidence limits of the total abundance.

(2) In the LF and MF treatments

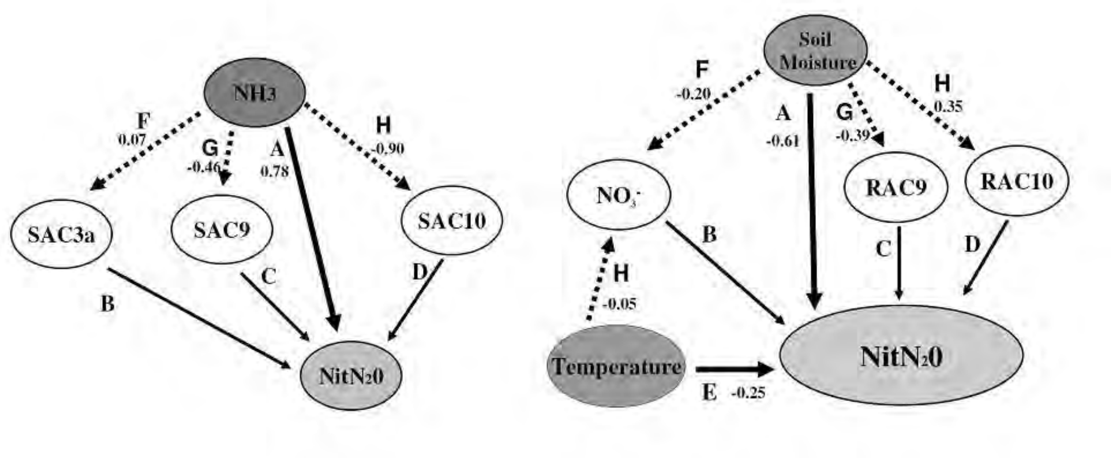
The best fit multiple regression model was one that included the following predictor variables: soil moisture, temperature, nitrate concentration, relative abundance of cluster 9 and of cluster 10 ($F_{5,18}$=23.16, p<0.0001). This model could explain 87% of the variance in NitN_2O emission rates (r^2=0.866, r^2_{adj}=0.828).

For path analysis, we hypothesized a causal model that related soil moisture and temperature both directly and indirectly to NitN_2O emission rates (Fig. 3b). The strongest causal path was the direct effect of soil moisture (path coefficient = -0.61), followed by the indirect effect of soil moisture through the relative abundance of cluster 9 and of cluster 10 to NitN_2O emission rates (path coefficient = -0.39 and 0.35, respectively).

DISCUSSION

In this work we addressed the potential ecosystem consequences of changes in environmental conditions and in the abundance and community structure of AOB. One of the ecosystem consequences of nitrification activity is the emission of nitrous oxide, a greenhouse gas with approximately 300 times the global warming potential of carbon dioxide (20) and a lifetime of about 150 years (39). To address this topic we manipulated temperature, soil moisture and fertilizer concentration in a meadow soil incubated in the laboratory for 16 – 20 weeks. Two distinct patterns of NitN_2O emission were observed in the laboratory experiment: (1) in the HF treatment at 20°C, elevated soil moisture resulted in an increase in the rates, and at 30°C the highest rate was observed in the moderate soil moisture treatment, and (2) in the LF and MF treatments, elevated soil moisture and elevated temperature resulted in a decrease in NitN_2O emission rates.

Figure 3a **3b**



Path diagram of the hypothesized models analyzed using path analysis for nitrous oxide emission rates due to nitrification (a) In high fertilizer treatment and (b) In low and moderate fertilizer treatments. Direct effects are designated as A, B, C, D and E indirect effects as F---B, G---C, H---D and H---B. Path coefficients for the latter are written on the first arrow and letter only, but represent the complete path. NH_3=ammonia concentration, NitN_20= nitrous oxide emission rates due to nitrification, SAC3a=scaled abundance of cluster 3a, SAC9=scaled abundance of cluster 9, SAC10=scaled abundance of cluster 10, NO_3^- =nitrate concentration, RAC9=relative abundance of cluster 9, RAC10=relative abundance of cluster 10.

We explored the interrelationships among the abiotic and biotic factors that could underlie the two patterns of NitN_2O emission. NitN_2O emission rates in the HF treatment were influenced by an interaction between temperature and soil moisture. This same interaction also influenced the pH, ammonia concentration (after 16 weeks of incubation), and the scaled abundances of clusters 9 and 3a. Path analysis suggested that the major path by which ammonia influenced NitN_2O emission rates was indirectly through its influence on the scaled abundance of cluster 10, but also through its influence on scaled abundance of cluster 9 (Fig 3). AmoA cluster 10 was the dominant population of AOB in the non-manipulated source soil (19), and after short-term incubation in the laboratory (1). To date, sequences closely related to *Nitrosospira* sp. AF (cluster 10) have only been detected in a slightly acidic soil (pH 5.5) from Tennessee incubated at 23-25°C (7, 37), similar conditions (in pH and temperature) to those of our incubation. Consistent with our study, sequences belong to AmoA cluster 9 (most closely related to *Nitrosospira* sp. Nsp.65) were detected in an Israeli irrigated soil (i.e. high temperature and nitrogen concentration) (30), and in German meadow soil incubated at 30°C and fertilizer concentration of 100-200 μg N-NH_4^+*gds^{-1} (values between our MF and HF treatments) (3). Previous studies indicated that ammonium concentration and availability can influence the community structure of AOB (6, 24, 25) and of nitrous oxide emission (29, 31). Previous work on our soil showed that these three environmental factors could interact to alter the potential nitrification activity (1, 5), abundance and community structure of AOB (1, 19). Nevertheless, a short period (i.e. 7 weeks) of environmental manipulation of this same soil in the laboratory did not reveal any significant relationship between potential nitrification activity and the community structure or abundance of AOB (1). In our current study (i.e. after 16-20 weeks of incubation) we observed a significant relationship between community structure of AOB and nitrous oxide emission rates and of PNA.

NitN_2O emission rates in the LF and MF treatments were influenced by temperature and soil moisture. In contrast to previous studies of temperate soils (22, 27), an increase in soil moisture caused a decrease in N_2O emission rates. However, potential nitrification activity increased in response to the increase in soil moisture (data not shown), which is consistent with previous reports (27). Differences in microbial community structure may help explain this discrepancy. It is known that temperate soils, characterized by a cold and wet climate, are dominated by AOB belonging to AmoA clusters 1, 2 and 4 (3). These types are not found in subtropical soils (2), nor are they present in Jasper Ridge (JR) soil, which was dominated by AOB from AmoA cluster 10 (*Nitrosospira* sp. AF-like) as noted above. Jasper Ridge is in a region with a Mediterranean-like climate (with long, hot, dry summers). We hypothesize that communities dominated by cluster 10 respond uniquely to hot dry conditions, perhaps as a stress response, as proposed below. However, more soils from various climatic regions would need to be surveyed for both NitN_2O emission rates and community composition to test this hypothesis.

The direct and indirect effects of temperature and soil moisture on NitN_2O emission rates in the LF and MF treatments were further studied. Path analysis indicated that the major path by which soil moisture influenced NitN_2O emission rates was directly, rather than indirectly through effects on community structure. Reduced water and ammonia resulted in a major increase in N_2O emission rates. Stark & Firestone (36) suggested that low soil moisture could lead to low ammonia concentrations and subsequent substrate limitation of ammonia oxidizers. We hypothesize that under such conditions the denitrification pathway of AOB might serve as a stress response, allowing the organisms to gain enough energy to survive, similar to that observed under oxygen limitation (16, 26). The denitrification pathway has been reported recently among *Nitrosopira* species (14, 32). Our observations of increased N_2O emission rates under low soil moisture are of potential environmental significance given the vast area of arid soils on Earth, soils characterized by long periods of dry conditions. Most studies of nitrous oxide flux have been performed in cold temperature soils and may present an inaccurate view of the response of N_2O flux to environmental change. Soil moisture also influenced NitN_2O emission rates indirectly through changes in the relative abundances of clusters 9 and 10, although to a lesser extent than its direct effects. These findings support previous reports of variation in N_2O emission rates of different pure cultures of AOB (21, 32), although pure cultures belonging to clusters 9 and 10 have never been tested.

CONCLUSIONS

It has long been debated how microbial community structure and ecosystem functions are linked. Our study suggests ways that this linkage can occur. For example, the striking shift in community structure and abundance observed in our HF treatment suggests that AmoA cluster 9 and 3a were outcompeted by AmoA cluster 10 under a wide range of conditions, with the exception of high temperature and nitrogen. The ecological consequences of this finding are that a community shift may play an important role in linking environmental change to nitrogen loss when ammonia is in excess, such as in agriculture soil, or in environments with high rates of mineralization such as those with frequent freeze-thaw cycles. Furthermore, community structure may play a role in determining feedbacks important in global change.

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ECONOMIC ANALYSIS OF CLIMATE-CHANGE IMPACTS ON AGRICULTURAL PROFITABILITY AND LAND USE: THE CASE OF ISRAEL

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ABSTRACT

We develop a regional scale economic model for analyzing climate-change impacts on agriculture. Non-linear production functions describing yield responses to land allocation, water application and water salinity are integrated into a mathematical programming model. The responses to water quantity and quality are estimated by the use of scientific-based models simulating equilibrium in the root zone among plant's water uptake, soil salinity and soil's water content. Internalization of land allocation among crops is based on Howitt's PMP calibration approach (1995). The model, therefore, enables assessment of climate-change impacts on optimal agricultural management, where adaptation is considered endogenously with respect to both the extensive and intensive margins.

The model is applied to the case of Israel. We divide the country into 14 regions and estimate regional future precipitation levels by implementing a climate-change down-scaling procedure. Then the model computes optimal agricultural managements under these projected rainfall levels. The results indicate a reduction of about 20% in statewide annual agricultural net-revenues by the year 2100 in comparison to 2002. Land allocated to field crops is increased on the expense of forages and vegetables. The shares of field crops and forages in the agricultural irrigation-water allotment are increased while that of vegetables declines.

INTRODUCTION

Evaluation of climate-change impacts on the economy is essential for setting mitigation programs in the regional and global scales. Integrated assessment models, frequently used for generating projections and designing long-run policies, need reliable information on expected climate-change damages, as well as on the efficiency of adaptation tools available in the private and public levels. This requires integration of economic principles with validated scientific knowledge on technologies and behavior of natural systems. In this work we present such integration for the case of evaluation of climate-change impacts on agriculture.

Our methodology is related to what is known as the production-function approach, under which yield-response functions are used to describe the impact of climate factors on agricultural productivity (e.g. Adams et al., 1990, 1999; Rosenzweig and Parry, 1994). The present work follows a series of two previous studies: a preliminary study by Yehoshua and Shechter (2003), who employed a simple production function model approach to assess the economic impact of climate change on the agricultural sector in Israel; and a more elaborated study, using the same production function approach, by Kadishi et al. (2005). Here we develop a non-linear mathematical programming model to mimic farmers' (optimal) behavior in the regional scale under various levels of precipitations. Precipitations contribute directly to crops' water availability in the fields through rain falling during the growing season, and may also indirectly influence the constrained amount of different types of irrigation-water sources. Farmers' adaptation tools include both the land allocation among crops and the per-dunam water application; these are also known as the extensive and intensive margins of substitution, respectively (Howitt et al., 2003; Schwabe et al., 2006). We utilize Howitt's (1995) PMP calibration approach to internalize land allocation as an endogenous decision. Accordingly, to account for unobserved factors such as land-quality variations, management constraints, risks, etc., the crop's per-dunam yield is assumed reducing as crop's area expands. Note that considering land allocation as an adjustment instrument reduces the likelihood of damage overestimation, as was claimed against the production-function approach (e.g. Mendelsohn et al., 1994, 1996). The effect of water application is integrated based on yield-water-salinity response functions developed in the scientific literature (Kan et al., 2002). This enables us to explore the effect of both water's quantity and quality; the latter plays a major role in arid zones, where brackish water and treated wastewater sources are extensively used for agricultural production. The model is calibrated for a base year, and then run under various levels of precipitations to simulate the associated impact on optimal agricultural management. Optimality is considered as maximization of regional net returns from agricultural production subject to land constraint and availability of water sources for irrigation.

We utilize the model to evaluate climate change impacts on agriculture in Israel. This country is characterized by a sharp spatial climate gradient, varying from arid conditions in the south to subtropical in the north (Dayan and Koch, 1999). Forecasts for the Middle East predict a worming of 3-5°C and a reduction of 3-35% in annual precipitation by the end of the 21st century (IPCC, 2001). Recent studies on Israel's climate show intensification of extreme temperatures, decreases in annual rainfall and increase in extreme weather events (Ben-Gai et al., 1999b; Alpert et al., 2001). Dayan and Koch (1999) predict a temperature increase of up to 1.8°C and a decrease of up to 8% in annual precipitation by the year 2100.

We divide the state of Israel into "natural" zones, and apply the model for each one of them separately. Calibration is based on 2002 data with respect to regional cropping patterns, prices, and annual rainfall levels typical for the period 1961-90 (Ben-Gai et al., 1999a). The model is then used to examine the influence of variations in regional precipitations estimated for the years 2020, 2050 and 2100 (based on Dayan and Koch, 1999), while all other parameters are kept unchanged.

The presentation continues as follows: Section II describes the programming model, the specification of production functions, the calibration method, and a procedure for down-scaling statewide predictions of future precipitations into a regional scale; Section III presents the results and Section IV concludes.

METHODOLOGY

The Model

Consider an area (the State of Israel) divided into J regions. Each region j, j=1,…,J, is characterized by exogenous climate factors. Our focus is on the precipitations level, r_{jt} (mm/dunam-yr), which may vary in time, t. Let $y_i(s_{jit}, x_{jit} \mid r_{jt})$ (ton/dunam-yr) be the per-dunam annual yield production of a specific crop i, i=1,…,I, in region j. The yield is a function of the water applied through irrigation, s_{jit} (mm/dunam-yr), and the area of land devoted to the crop, x_{jit} (dunam), both are decision variables. It is also affected by the effective rain, $\rho_{ji}r_{jt}$ (mm/dunam-yr), where ρ_{ji} is the fraction of rain falling during crop-i's growing season. With respect to water, this function represents responses to both the amount of water available to the crop, $w_{jit} = s_{jit} + \rho_{ji} r_{jt}$, and the associated average salinity, $c_{jit} = s_{jit} \chi_j w_{jit}^{-1}$ (dS/m), where χ_j (dS/m) is the salinity of the irrigation water; the salinity of the rain is considered zero. The effect of land on yields is integrated based on Howitt's approach, as will be specified in the next subsection. The regional net return from production by crop i is $\pi_{jit} = x_{jit}\left[p_i^y y_i\left(s_{jit}, x_{jit} \middle| r_{jt}\right) - g_i - p^s s_{jit}\right]$ (NIS/yr), where p_i^y (NIS/ton) is the output price, g_i (NIS/dunam) denotes non-water costs, and p^s (NIS/m3) is the irrigation-water price; all these parameters are considered similar for all regions and unchanged along time.

In each region there is an agricultural area of X_j dunams, and a regional irrigation-water constraint, S_{jt} (m^3/yr). Our analysis is static: given the regional rainfall level at time t, r_{jt}, the objective of the programming model is to set the vectors of decision variables $x_{jt} \equiv \{x_{jit},\ldots,x_{jit},\ldots,x_{jIt}\}$ and $s_{jt} \equiv \{s_{jit},\ldots,s_{jit},\ldots,s_{jIt}\}$ so as to maximize the regional net returns $\Pi_{jt} = \sum_{i=1}^{I} \pi_{jit}$, subject to the land constraint, $\sum_{i=1}^{I} x_{jit} \le X_j$, the irrigation-water limitation, $\sum_{i=1}^{I} x_{jit} s_{jit} \le S_{jt}$, and non-negativity of x_{jt} and s_{jt}. The model is run under future projected rainfalls to simulate the impact of precipitations on optimal agricultural management and net revenues.

Production Functions and Calibration

In the aforedescribed model yield level responses to cropland, water application and water salinity. We require that such a response function i) will reflect responses validated by well designed field experiments, ii) that when the model is run under rainfall conditions observed in a predetermined base year it will reproduce the values of the decision variables and yields observed at that year, and iii) that calibration will be based on regional aggregated data available from information sources open to the public. To this end we formulate and calibrate a production function, which is an integration of two response functions appearing in the economic literature:

$$y_i(s_{jit}, x_{jit} \mid r_{jt}) = (\delta_{ji} - \gamma_{ji} x_{jit})\psi_i(e_i(w_{jit}, c_{jit}))\hat{y}_i^{-1} \quad (1)$$

The first element, $\delta_{ji} - \gamma_{ji} x_{jit}$ (ton/dunam-yr), represents a linear reduction in the per-dunam yield as the crop's area increases, as suggested by Howitt (1995). The second component, $\psi_i(e_i(w_{jit}, c_{jit}))$ (ton/dunam-yr), describes yield responses to evapotranspiration (ET), $e_i(w_{jit}, c_{jit})$ (mm/dunam-yr), which in turn depends on water application and salinity. We multiply these two elements and divide by $\hat{y}_i$ (ton/dunam-yr), which denotes the base-year observed yield.[10]

Specification and calibration of the second element is as follows. We adopt the functional form developed by Kan et al. (2002), $e_i(w_{jit}, c_{jit}) = \dfrac{\bar{e}_i}{1 + \eta_{1i}\left(c_{jit} + \eta_{2i} w_{jit}^{\eta_{3i}}\right)^{\eta_{4i}}}$. Here $\bar{e}_i$ is crop-i's maximum ET and η_{1i}-η_{4i} are crop-specific parameters. These parameters are estimated based on data produced by agronomic models that simulate equilibrium in the root zone among plant-water uptake, soil-water salinity and soil-water content (Letey et al., 1985). The translation of ET into yield units is by the Cobb-Douglass function $\psi_i(e_i(w_{jit}, c_{jit})) = \phi_{1i} e_i(w_{jit}, c_{jit})^{\phi_{2i}}$, where ϕ_{1i} and ϕ_{2i} are coefficients. Given the base-year observed values of $\hat{\chi}_j$, $\hat{s}_{ji}$ and $\hat{r}_j$, these two parameters are calibrated such that the water-response function reproduces the base-year yield,

$$\hat{y}_i = \phi_{1i} e_i(\hat{w}_{ji}, \hat{c}_{ji})^{\phi_{2i}}, \quad (2)$$

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[10] One may consider the function $y_i(s_{ji}, x_{ji} \mid r_j) = (\delta_{ji} - \gamma_{ji} x_{ji}) + \psi_i(e_i(w_{ji}, c_{ji})) - \hat{y}_i$ as an alternative integration of the water and land effects; a sensitivity analysis has reviled a relatively minor impact of using this formulation.

as well as satisfying the condition for optimal irrigation-water application:

$$p_i^y \phi_{1i}\phi_{2i} e_i\left(\hat{w}_{ji}, \hat{c}_{ji}\right)^{\phi_{2i}-1}\left[\frac{\partial e_i}{\partial w_{ji}} + \frac{\partial e_i}{\partial c_{ji}}\frac{\partial c_{ji}}{\partial s_{ji}}\right] = p^s \quad (3)$$

.[11]

Separately, we calibrate the parameters of the land-response component, δ_{ji} and γ_{ji}, such that the model reproduces the base-year land allocation, $\hat{x}_j \equiv \{\hat{x}_{ji},\ldots,\hat{x}_{ji},\ldots,\hat{x}_{jI}\}$, and the base-year yield. The two PMP calibration conditions (see Howitt 1995) are

$$\delta_{ji} = \frac{\lambda_{ji}}{p_i^y \hat{x}_{ji}}, \quad (4) \quad \text{and} \quad \gamma_{ji} = \hat{y}_i - \delta_{ji}\hat{x}_{ji}, \quad (4)$$

where $\lambda_{ji} = p_i^y \hat{y}_i - g_i - p^s \hat{s}_{ji} - \left[p_I^y\left(\hat{y}_I - \Delta y_I\right) - g_I - p^s \hat{s}_{jI}\right]$ is the dual value of the land-calibration constraint, crop I is the one exhibiting the lowest value of average production of land in the discussed region, and Δy_I is the observed crop-I's lower bound of yield variation around the average, $\hat{y}_I$.

Data

The state of Israel was divided into 14 regions ($J = 14$) based on the natural-zones allocation used by the CBS. Figure 1 presents the regions on a map describing the distribution of annual rainfall throughout the country. This is the single exogenous variable representing regional climate changes in our analysis. Future forecasts for rainfall (r_t) in Israel were produced by Dayan and Koch (1999) for the years 2020, 2050 and 2100. They predict about 1-2%, 2-4% and 4-8% reduction relative to precipitations at the end of the 20 century. Kadishi et al. (2005) have used a down-scaling procedure for estimating regional precipitations (r_{jt}) based on compilation of Dayan-and-Koch's predictions with rainfall-monitoring-station data analyzed by Ben-Gai et al. (1999a). We apply this procedure to approximate average rainfall levels for each of the 14 regions for the years 1975, 2020, 2050 and 2100. The 1975 estimate was considered representative of the base year of our analysis, 2002. Figure 2 summarizes the resultant estimations. As shown, most of

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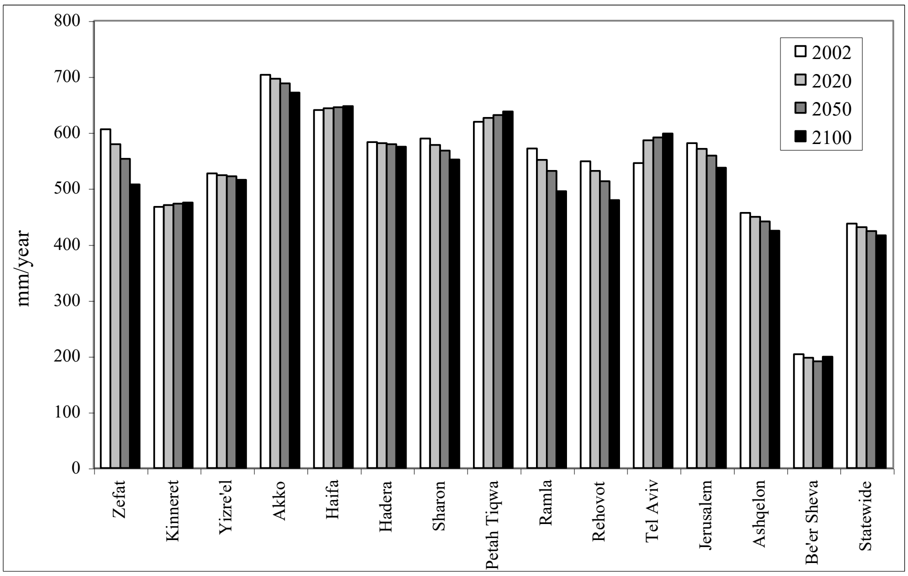
[11] It is worth stipulating two advantages associated with the formulation of yield's response to water as a composition of two functions. First, the responses to variations in water and salinity are dominated by the experimental estimates of their impacts on ET. Second, for a crop absent such experimental information, the influence on ET can be borrowed from another crop of the same botanic species, while the conversion to yield is by calibrating based on the original crop's data. For instance, the function $e_i\left(w_{jit}, c_{jit}\right)$ estimated for wheat may be used for oat, where the parameters ϕ_{1i} and ϕ_{2i} can be calibrated based on the observed oat's water application and yield.

the regions are expected face a reduction in average rainfall. Exceptional are the Tel-Aviv and Petah-Tikve regions in which precipitations are in a trend of increase.

Figure 1: Natural regions and rainfall distribution in Israel.

Figure 2:

Down-scaled regional estimates of annual precipitations.



In the herein application crop areas were aggregated into four groups (i.e., $I = 4$): field crops, cotton, vegetables and forages (plantations were left out of the analysis). For each group we select one representative crop to which a response function was estimated; the crops are wheat, cotton, tomato and vetch, for the aforementioned groups, respectively.

The relevant agro-economic parameters were collected from various publications of the Ministry of Agriculture and the Israeli Central Bureau of Statistics (CBS). Monetary values are reported in terms of 2002 New Israeli Shekel (NIS). The economic parameters and estimated production-function coefficients are reported in Table 1. Figure 3 shows the regional water and land allocations among the four groups of crops in 2002. Altogether our analysis covers an area of two million dunams and 367 million cubic meters of fresh water, which constitute about 50% and 70% of Israel's agricultural area and fresh water, respectively.

Table 1. Production-function coefficients and economic data*

Parameter	Wheat (Field crops)	Cotton	Vetch (Fodders)	Tomato (Vegetables)
Production function				
$\bar{e}$ - Maximum ET (mm/yr)	469	751	800	820
η_1	0.01343	0	0.00058	0.01742
η_2	6.70×10^{13}	1.30×10^{3}	2.20×10^{4}	2.70×10^{10}
η_3	-4.91	-0.53	-1.18	-3.42
η_4	1.13	4.18	2.56	1.45
ϕ_1	2.49×10^{-6}	1.31×10^{-7}	7.24×10^{-6}	1.70×10^{-6}
ϕ_2	2.06	2.45	1.8	2.36
General				
χ^s - Surface-water salinity (dS/m)	1			
ρ - Effective rain (%)	100	20	100	60
Prices and costs				
p^s - Surface water price (NIS/mm-dun)	1.10			
p^y - Output price (NIS/ton)	710.0	1,750.0	768.0	220.0
g - Non-water costs (NIS/dun-yr)	314.3	642.5	194.0	1,422.0

Due to lack in regional scale data the reported values are identical for all regions.

The programming model is built on an Excel worksheet and run by the Premium Solver Platform V5.5 instrument to locate global optimum using the Multistart Search strategy. The solving procedure applies a quasi-Newton method based on quadratic extrapolation, where central differencing is used to estimate partial derivatives.

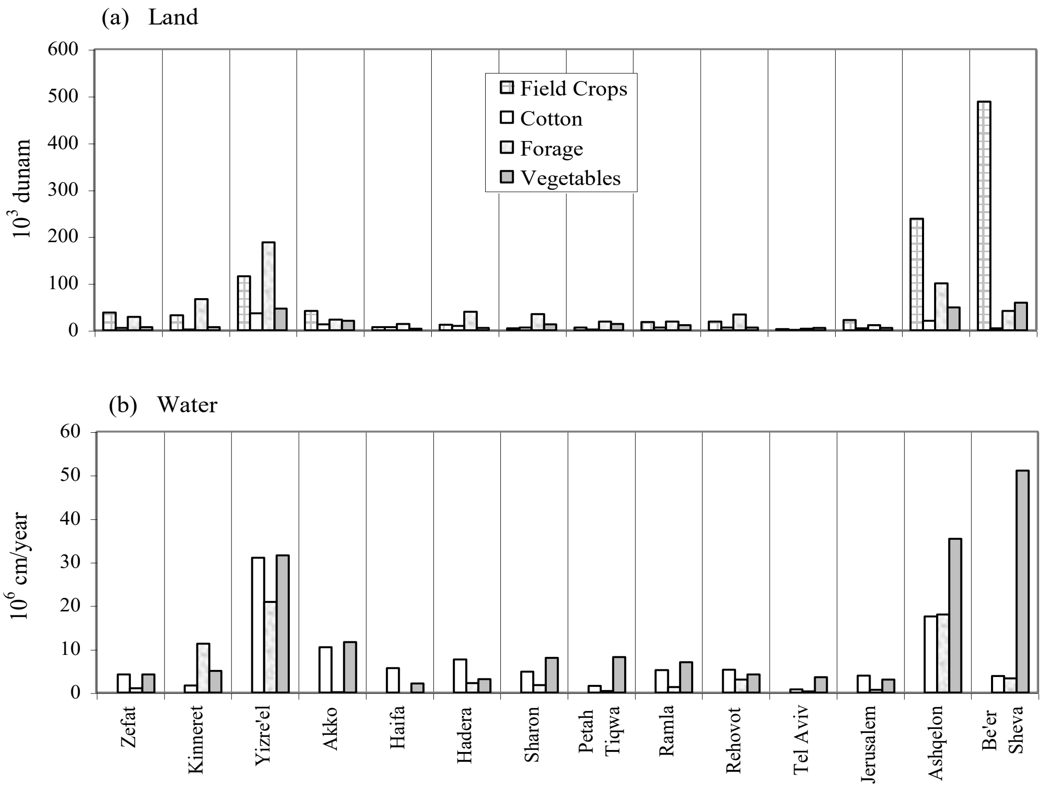


Figure 3: Regional (a) land and (b) surface-water allocations among crops in 2002.

RESULTS

In this paper we present results associated with a preliminary version of the model, in which rainfall is assumed to have only a direct impact on the water applied to each crop during the growing season. I.e., the changes are in the value of r_{jt}, whereas the indirect impacts on the regional surface-water availability, S_{jt}, and salinity, χ_{jt}, are ignored. Moreover, there is no differentiation among various sources of irrigation waters, and potential inter-regional water transfers are not considered.

Optimal land and surface-water allocations were computed by running the model for each of the 14 regions under the four rainfall levels. Figure 4a and 4b present, respectively, the percentage change in land and surface-water allocations in 2100 relative to 2002. In most regions there is an increase in the area of parcels allocated to field crops, mostly at the expense of forages, and to some extent on the account of vegetables. This trend is seen in regions where the rainfall declines, particularly in Zefat in the north of Israel, in Ramle and Rehovot at the coastal plain, and in Jerusalem. An opposite trend appears in the Tel-Aviv and Petah-Tiqwa regions, where rainfalls are increased.

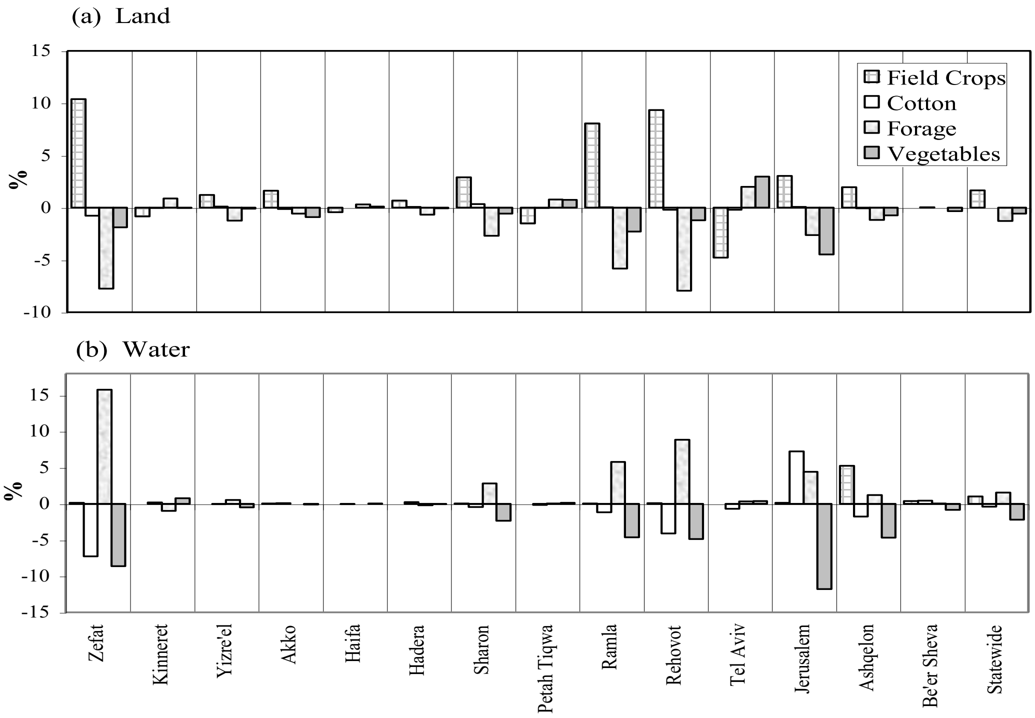


Figure 4: Regional changes in (a) land and (b) surface-water allocations among crops in 2100 relative to 2002.

The responses of optimal surface-water allocations to rainfall changes are characterized by an increase in allotments to forage crops on the account of cotton and vegetables. Noteworthy is the Ashkelon region, in which water allocation to field crops are also increased. These changes are noticed in regions at which forecasted rainfalls decline. On the other hand, at regions with increased precipitations changes in water allocations are minor.

Most of the crop production in Israel takes place in the Yisre'el valley, Ashkelon and Be'er-Sheva regions (Figure 3a). Some forages and cotton are grown in the north of Israel, in Akko and Kinneret. In all of these regions we found relatively slight changes in land allocations as a response to the projected rainfall variations. Changes in water distributions are minor as well. These 2002-2100 changes in optimal levels of the decision variables, while may seem insignificant, have considerable impacts on maximum regional net-revenues, as presented in Figure 5. Variations in net revenues are in the range of -50% in forage production at Zefat, to +30% in field crops at Hasharon. Average regional net-revenues are dramatically reduced in those regions where rainfall is sharply declined: Zefat, Ramle, Rehovot, Jerusalem and Ashkelon.

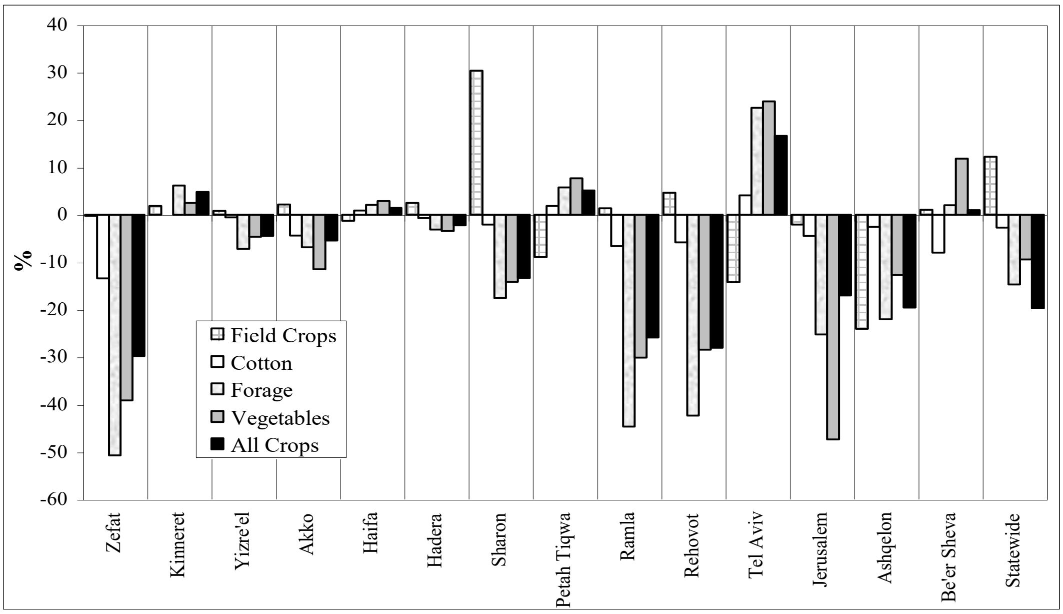


Figure 5: Changes in net revenues in the year 2100 in relation to 2002.

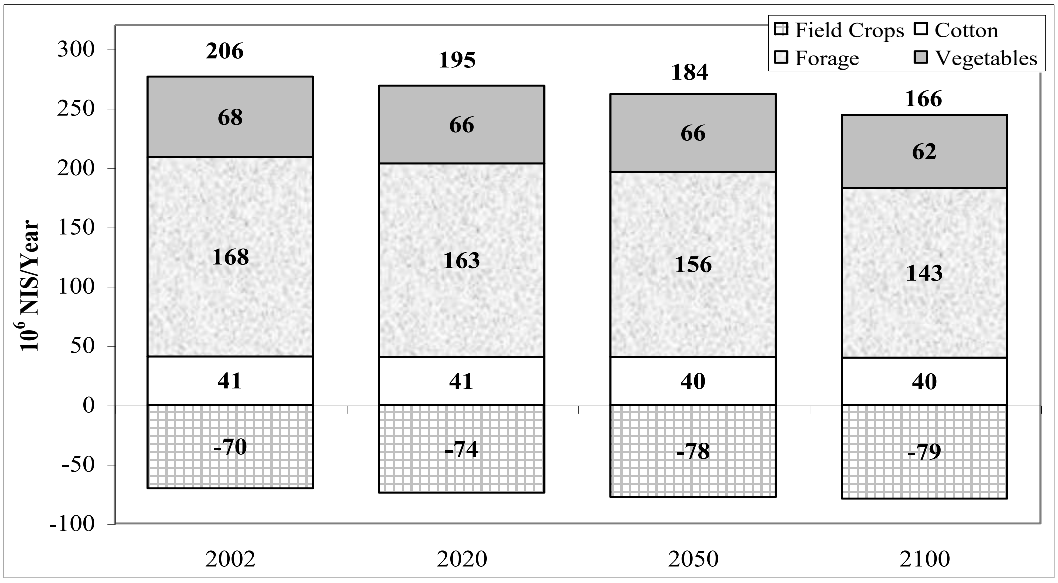


Figure 6: Variations in statewide agricultural net revenues induced by changes in precipitations.

The overall statewide change in agricultural net-returns is summarized in Figure 6 for the four analyzed years. It appears that, subject to the aforementioned assumptions, the agricultural sector in Israel is expected to face a reduction of about 20% in profits due to the projected decline in rainfall levels. The main contribution to these losses is by the forage production (12%), then by field crops (4.3%), vegetables (2.9%), and finally cotton (0.5%) (see also the right columns in Figure 5). Note that farmers are frequently reimbursed by the Israeli government for losses associated with wheat production, which stands here for field crops. Our analysis indicates that these subsidies are expected to increase in the future.

SUMMARY AND EXTENSIONS

In this study functions describing yield responses to land allocation, water quantity and water salinity are integrated into a mathematical programming model; the model is utilized for analyzing the impact of projected changes in annual rainfall levels on regional agricultural profitability in Israel.

The results indicate a reduction of about 20% in agricultural net-revenues in the year 2100 relative to 2002 conditions. This is, however, an output of a preliminary version of a more comprehensive model. In order to achieve more accurate and representative damage estimates we are currently in a process of upgrading this model along various directions. First, the set of crops represented by production functions is to be extended from four to about thirty, taking into account differences among regions with respect to climate and soil characteristics. Second, external benefits associated with the contribution of agriculture to landscape and open spaces (Fleisher and Tsur, 2004) will be incorporated. Finally, the advanced model will apply a multi-regional analysis, where inter-regional water transfers are considered endogenously. This implies that regional availability of water sources, the impacts of rainfall levels on the supply of these sources, demands for non-agricultural uses, and transference capacities and costs, should be all incorporated.

Such a model may constitute an efficient tool for analyzing impacts of changes in various exogenous parameters on the agricultural sector, in terms of agricultural water and land uses. It will be able to simulate optimal managements under scenarios with respect to climate conditions, agriculture's terms of trade, policies in the water economy, etc. The results, or the model itself, may be incorporated into an integrated assessment model to provide a better understanding of the mutual relationships between agriculture and other factors in the economy.

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Session 3: Irrigation, Plant Nutrition and Pollution

BEST AGRICULTURAL MANAGEMENT PRACTICES FOR REDUCING WATER POLLUTION AND HYPOXIA IN WATER BODIES

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ABSTRACT

Point and diffused source pollution of large water bodies (such as the lakes, reservoirs, rivers and oceans) are recognized as important environmental and ecological issues for the society to protect finite water resources to meet the needs of all species on this planet including plants, animals, and humans. In agricultural watersheds, intensive cropping systems were introduced in 1960's and 1970's to grow more food in meeting the increased need for food to feed the growing populations in the world. These increased uses of pesticides, and nitrogen fertilizers/animal manure resulting in surface and ground water contamination from agricultural chemicals. In particular increased leaching/transport of nitrogen and phosphorous to water bodies have resulted in reduced dissolved oxygen in some large surface water bodies and further enriched the supply of nutrients causing nuisance plant growth, especially algae. Large algae growth has occurred in local water bodies such as lakes and reservoirs as well as in the international water bodies, like the Gulf of Mexico and Black Sea, where "hypoxia zones" are drawing international attention. Agricultural and animal production systems in the USA, Europe, and many other countries have become highly intensive and are causing negative impacts on surface and groundwater quality. Because of these water quality concerns, several tillage and nutrient management studies were conducted at Iowa State University between 1990 and 2007 to develop best agricultural practices (cropping, tillage and nutrient management systems) to reduce nitrate and phosphorus transport leaching to surface and groundwater systems. The overall objective of this paper is to present brief summaries and outcomes of several Iowa studies on the development and use of best agricultural practices in watersheds to reduce hypoxia problems in large water bodies, such as the Gulf of Mexico. The farming systems developed and evaluated in these studies have shown that crop

farmers and livestock producers can maintain long-term sustainability of agriculture and enhance the quality and ecological health of water resources.

INTRODUCTION

Diffused nutrient pollution of large water bodies (such as the rivers and oceans) is recognized as an important environmental issue for several reasons. First, excessive use of nutrients from commercial fertilizers and animal manure for crop production can have serious negative impact on the quality of surface and ground water resources. Second, several states in the United States are in the process of creating rules and regulations to reduce nitrogen and phosphorus leaching/transport to water bodies from fertilizers and manure to soil and water resources. Third, pollution of water resources from nutrients applied agricultural fields will establish guiding principles for developing public policies on the management of natural resources, especially protecting the quality of water supplies for drinking. Organic and inorganic forms of leached N and P can reduce oxygen levels in surface water resources and further "enrich" the supply of nutrients. This, in turn, can cause nuisance aquatic plant growth in water bodies such as the Gulf of Mexico, where a "hypoxia zone" has become an international concern for the society. Alexander et al. (1995) reported that the upper Mississippi river basin contributed about 39% of the nitrogen delivered to the Gulf of Mexico, which has become the second largest hypoxic zone in the world. Several studies have shown connectivity of hypoxic zone to the NO_3-N loadings from the Mississippi river basin (Rabalais et al., 2002; Randall and Vetsch, 2005; Kanwar et al., 2005).

Rapid growth in swine production facilities in Iowa has resulted in the concentrated production of animal waste, with manure production ranging from 1 to 10 kg/day/hog. About 28.4 million tons of liquid swine manure is stored in pits annually in Iowa (Iowa Agricultural Statistics, 1996). This necessitates that farmers apply manure on agricultural lands. Year after year application of liquid manure at higher rates to a field results in the accumulation of more nutrients in the root zone than crops may need. Gupta et al. (1997) investigated the effects of liquid swine manure on the quality of surface runoff. Jongbloed and Lenis (1998) reported that negative effects of swine production on the environment have already led to new legislation that limits the use of animal manure or localization of swine production facilities in some counties. Nitrate contamination of groundwater is a major concern in crop and swine -producing areas, and additional information on the best agricultural practices is needed to reduce the leaching of nitrate to surface and groundwater resources (Bakhsh et al., 2005; Gupta et al., 1997; Kanwar et al., 1995, 1997). However, only limited field data are available on the environmental effects from use of best agricultural practices (Kanwar et al., 1995; 1999). Kanwar et al. (1999) reported that six year (1993-98) average NO_3-N concentrations in tile water from manure applied plots were 19.0 mg/L under continuous-corn and 14.2 mg/L under corn-soybean rotation. These results clearly show that application of swine manure to croplands can increase NO_3-N concentrations in the shallow groundwater at significantly higher levels. The objective of this paper is to examine the results of several long-term studies conducted at Iowa State University and evaluate the potential impacts of cropping systems, and fertilizer and manure application rates on shallow groundwater contamination. These observations may help the development and use of environmentally friendly best agricultural practices in agriculturally intensive watersheds, allowing farmers to reduce the potential of water contamination and hypoxia of larger water bodies.

METHODS AND MATERIALS

Various experimental studies reported in this paper were conducted at a site located at Iowa State University's Northeast Research Farm near Nashua, Iowa. Three long-term studies were conducted between the period of 1979 and 2005 to develop best agricultural management practices, which could help farmers sustain their agricultural production by adopting environmentally friendly practices to reduce the leaching of nutrients to surface and ground water resources. A total of more than twenty good agricultural management practices were developed and evaluated in this study. The soils at this study site are moderately well to poorly drained and lie over loamy glacial till. This experimental site has 36, 58.5m by 67m plots with a fully documented tillage and cropping history of the past twenty eight years. In 1979, subsurface drains were installed in all the 36 plots at 29m spacing and approximately 1.2m deep. Each plot has a drain along the center and along the north-south borders. A 9.1m grass strip isolated the plots on the east and west sides. Center drains were intercepted at the end of plot and connected to sumps for monitoring subsurface drain flows, while border drains isolated plots on the north and south sides of each plot. Each sump contained a sump pump with a flow meter. Flow meters were read manually three times a week. Data on drain flows were collected from approximately mid-March to the beginning of December each year. Water samples were collected from the sumps for NO_3-N analyses when flow meters were read, again three times a week from 1990 to 1998 and once a week after 1999. For water sample collection, subsurface drain sumps were equipped with a state-of-the art sampling system which pumps about 0.02% of the water discharged by the sump pump into the sampling bottle through the orifice tube installed on the sump discharge line (Kanwar et al., 1995; 1999). Sampling bottles were removed after being filled with subsurface drain water. These bottles were immediately stored in the refrigerator at 4^oC. The N in the water and soil was analyzed using standard methods (APHA, 1995). Nitrate-nitrogen in water samples was analyzed spectrophotometrically using a Lachat Model AE ion analyzer. Data on corn yields were collected at harvest and converted to 15.5% moisture content level for determining corn yields.

Experimental Treatments for Study # 1 (1979-1992): The overall objectives of this study were to evaluate the effects of four tillage systems (no-till, chisel plow, ridge till, and moldboard plow) and two crop rotations (continuous corn and corn-soybean rotation) on surface and subsurface drain water quality. Experimental treatments were laid out on 36 plots using a randomized complete block design. Four tillage treatments and two crop rotation treatments were replicated three times using 36 plots (Kanwar et al., 1997). Each plot received the same treatment (in terms of tillage, crop rotation, fertilizer and pesticide application from 1979 to 2002 (Table 1). Continuous corn practice received 200 kg-N/ha every year, whereas corn-soybean rotation received 168 kg-N/ha every other year for corn plots only. Surface and ground water samples for water quality analyses were collected only from 1990 to 1992, so that effects of long-term tillage and crop rotations on water quality can be monitored in the last three years of the study period (from 1978-1992) and recommendations can be made to watershed farmers on which of these practices are environmental friendly and economically sustainable to maintain farmers' income if recommended production systems are adopted.

Experimental Treatments for Study # 2 (1993-1998): Study #1 was completed in November 1992 and a set of nine new N-management practices were implemented in 1993 on 36 plots plus four additional plots using only two tillage systems (chisel plow and no-till) under continuous corn and corn-soybean rotations with swine manure as one of the sources of N-fertilizer (Figure 1). This study, which was completed in 1998, included a unique N-free treatment of alfalfa inter-seeded with berseem and clover on two plots. This totally N free treatment consisted of three years of alfalfa then corn-soybean-oat rotation in the years 4, 5, and 6, respectively. The second innovative agricultural practice introduced was on the use of nitrogen fertilizer for only one third of the crop area (Kanwar et al., 2005). This treatment included strip cropping system (consisting of three strips of corn, soybean, and oats with only corn strip receiving the N-fertilizer every year). The third agricultural practice tested in this study was the corn-soybean rotation system with Late Spring Nitrate Test (LSNT) practice (Kanwar, 2003).

Experimental Treatments for Study # 3 (1999-2005): At the end of the completion of study #2 and after crop harvest in the late fall of 1998, a set of new agricultural practices were established on 36 plots with experimental treatments consisting of mix of P and N-management systems using UAN and swine manure as sources of nitrogen (Table 3). This resulted in using 12 of the 36 plots for the four innovative agricultural practices of the future as: a) corn after soybean with side dress urea ammonium nitrate (UAN) application with localized compaction doming (LCD) applicator (Baker et al., 1997), b) corn after soybean with single application of UAN fertilizer using spoke injector (Baker et al., 1989), c) soybean after corn with side dress UAN application using LCD and d) soybean after corn in plots with single spoke injected UAN application to corn year. The idea behind these best agricultural practices is to develop innovative systems to reduce the leaching of N and P to water bodies. Single application of UAN solution fertilizer was made using a spoke injector after planting. This injector injects at about 200-mm intervals and at 250-

mm from corn rows (Baker et al., 1989). Details on crop and chemical management activities are given in Table 3. Nitrogen was applied to corn plots at a rate of 168 kg-N//ha for both LCD and spoke injector methods.

RESULTS, DISCUSSION AND CONCLUSIONS

In the first study, the long-term effects of tillage and crop rotations (from 1979 to 1992) on water quality were evaluated using water quality data from 1990 to 1992. Table 1gives the yearly NO_3-N concentration and losses with subsurface drain water and data on crop yields. Three year average (1990-92) for NO_3-N losses with subsurface drain water ranged from 4.8 kg/ha in 1992 to 107.2 kg/ha in 1990 and were much higher under continuous corn in comparison with the corn-soybean rotation for all tillage systems. Although NO_3-N concentrations were greater under conventional tillage (moldboard plow + disking) in comparison with the no-till system, total NO_3-N losses with subsurface drain flow were higher under the no-till and chisel plow systems possibly due to greater volume of water flux moving through the soil because of the presence of higher percentage of macropores. The data on crop yields show that corn yields were much higher under corn-soybean rotation in comparison to continuous corn. These results clearly indicate that continuous corn production system, results in significantly higher NO_3-N leaching losses to groundwater and gives lower crop yields in comparison to corn-soybean rotation. Therefore, it is not a sustainable agricultural practice to be adopted.

Part of the results of the second study are summarized in Figure 1, which presents NO_3-N concentrations in subsurface drain water under three different agricultural production practices (strip cropping, alfalfa rotation, and corn-soybean rotation). Figure 1 clearly shows that in 1998 (the last year of second study), the six-year average NO_3-N concentrations for the corn-soybean rotation system resulted in the highest NO_3-N concentrations in the subsurface drain water in comparison with the other two treatments of strip cropping and alfalfa.

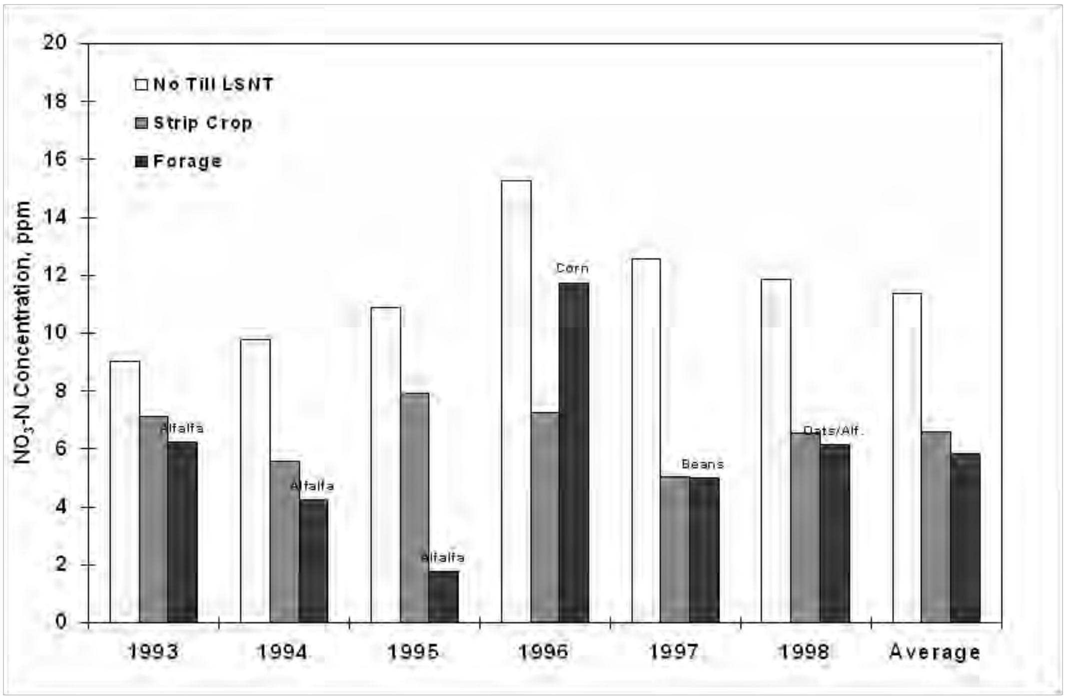

Figure 1: Yearly average NO_3-N concentrations from no-till LSNT rotation, strip cropping and alfalfa rotation plots (Kanwar , 2006).

Data on NO_3-N concentration in subsurface drain water indicate that with non-traditional production systems of strip cropping and alfalfa rotations, it is possible to reduce the leaching NO_3-N into the shallow groundwater and still meet the EPA drinking water standard of 10 mg/l.

The second objective of study #2 was to determine the optimum application rates of nitrogen fertilizer and swine manure to maximize crop yields and minimize nitrate leaching. Precise application rates of N from fertilizers or manure will help farmers to minimize the potential of water contamination. To study this objective, experimental treatments included reduced UAN fertilizer application of 112 kg-N/ha to corn plots grown in rotation with soybean and 135 kg-N/ha to continuous corn under chisel plow as the primary tillage practice. Alternate N-management strategies included the use of swine manure as the N source for both continuous corn and corn-soybean rotation to give N application rate similar to UAN applications. Table 2 gives the six-year average NO_3-N concentrations in the subsurface drainage water as a function of different N application rates from manure and UAN. Highest six-year average NO_3-N concentration of 19.0 mg/l in the drainage water was observed from manure plots under continuous-corn production and the lowest average NO_3-N concentrations of 10.2 mg/l was observed from plots with UAN applications under corn-soybean rotation.

Table1. Average yearly NO_3-N losses (kg-N/ha) with subsurface drainage water as a function of tillage and crop rotation (Kanwar et al., 1997)

Year	Cropping systems	Rainfall (mm)	Average NO_3-N conc. (mg/L)	Average NO_3-N loss (kg/ha)	Corn grain yield (Mg/ha)
1990	Continuous corn – chisel plow	1,040	54b	100.0a	11.09
	Continuous corn – moldboard		64a	58.1a	11.41
	Continuous corn –ridge tillage		44c	83.4a	10.59
	Continuous corn – no tillage		39c	107.2a	9.34
	Corn after soybean- chisel plow		28	52.4a	11.35
	Corn after soybean- moldboard		27	38.0a	11.10
	Corn after soybean-ridge tillage		22	30.3a	10.79
	Corn after soybean-no tillage		23	36.5a	11.22
	Continuous corn – chisel plow		28b	76.0a	8.78
	Continuous corn – moldboard		34a	62.7a	9.22
1991	Continuous corn –ridge tillage	965	21c	58.2a	7.96
	Continuous corn – no tillage		19c	61.7a	7.34
	Corn after soybean- chisel plow		21	36.3a	9.91
	Corn after soybean- moldboard		22	35.5a	9.53
	Corn after soybean-ridge tillage		18	29.4a	9.22
	Corn after soybean-no tillage		17	30.3a	8.97
	Continuous corn – chisel plow		15a	17.0a	9.16
	Continuous corn – moldboard		16a	16.6a	9.47
	Continuous corn –ridge tillage		11a	10.2a	8.96
	Continuous corn – no tillage		11a	14.9a	8.72
1992	Corn after soybean- chisel plow	742	10	15.3a	10.22
	Corn after soybean- moldboard		11	9.1a	9.84
	Corn after soybean-ridge tillage		10	11.2a	9.97
	Corn after soybean-no tillage		8	4.8a	10.03
	Continuous corn – chisel plow		32ab	64.3a	9.68a
	Continuous corn – moldboard		38a	45.8a	10.03b
	Continuous corn –ridge tillage		25c	50.6a	9.17c
	Continuous corn – no tillage		23bc	61.2a	8.47d
	Corn after soybean- chisel plow		20ab	32.1a	10.49a
	Corn after soybean- moldboard		20a	27.5a23.7a	10.16a
Avg.	Corn after soybean-ridge tillage	916	17ab	23.9a	9.99b
(1990-92)	Corn after soybean-no tillage		15b		10.07b

Continuous corn and corn after soybean received 200Kg-N/ha and 168 kg-N/ha, respectively.

Manure applied plots under corn-soybean rotation resulted in six average NO_3-N concentrations of 14.2 mg/l. These results indicate that the corn-soybean production system helps in reducing NO_3-N concentrations in shallow groundwater under both UAN and manure applications when compared to continuous-corn. Manure plots, under continuous corn, showed the greatest NO_3-N loss, possibly due to higher accumulation of N in the soil. Lowest NO_3-N loss of 13.7 kg/ha was obtained from plots receiving UAN applications under corn-soybean rotation. These results show clearly that higher N applications of manure resulted in significantly higher NO_3-N leaching losses to subsurface drain water in comparison with UAN fertilizer.

Table 2. Impact of agricultural practices (crop rotations, manure, and UAN applications)* on corn yields and NO_3-N concentrations and losses with subsurface drain water (Kanwar, 2006)

Year	Cropping systems	Rainfall (mm)	N-applications (kg/ha)	Avg. NO_3-N conc. (mg/L)	Avg. NO_3-N loss (kg/ha)	Corn yield (Mg/ha)
1993	CC-Manure	1,030	68	12.4a	48.3a	3.1c
	CS-Manure		82	12.9a	35.3a	6.3a
	CC-Fertilizer		135	12.2a	46.7a	4.6b
	CS-Fertilizer		110	9.3b	32.8a	5.1b
1994	CC-Manure	750	262	16.7a	10.1a	7.4b
	CS-Manure		235	11.0b	11.9a	8.4a
	CC-Fertilizer		135	11.0b	7.8a	5.8c
	CS-Fertilizer		110	9.3b,c	2.7a	7.9ab
1995	CC-Manure	800	260	31.9a	38.1a	5.4bc
	CS-Manure		206	18.2b	12.9b	6.5a
	CC-Fertilizer		135	14.4b	15.9b	4.6c
	CS-Fertilizer		110	15.5b	10.5b	6.0ab
1996	CC-Manure	680	102	24.3a	11.3a	7.9b
	CS-Manure		83	14.5b	12.7a	8.6a
	CC-Fertilizer		135	7.5c	3.7a	7.0c
	CS-Fertilizer		110	12.9b	6.3a	8.8a
1997	CC-Manure	750	103	7.6b	6.8a	7.6c
	CS-Manure		85	13.0a	7.5a	8.8b
	CC-Fertilizer		135	7.2b	3.8a	8.6b
	CS-Fertilizer		110	12.4a	6.3a	9.8a
1998	CC-Manure	980	164	21.2a	40.8a	7.2c
	CS-Manure		124	14.5b	39.6a	9.6a
	CC-Fertilizer		135	12.9b	23.3a	7.8b
	CS-Fertilizer		110	12.7b	23.6a	9.7a
Six yearly average (1993-98)	CC-Manure	830	163	19.0a	25.9a	6.4b
	CS-Manure		135	14.2b	19.9a	8.0a
	CC-Fertilizer		135	11.1c	16.8a	6.4b
	CS-Fertilizer		110	12.0c	13.7b	7.9a

***CC-Manure = continuous corn with liquid swine manure application**
CS-Manure = corn after soybean with liquid swine manure application
CC-Fertilizer = continuous corn with UAN-fertilizer application
CS-Fertilizer = corn after soybean with UAN-fertilizer application

Table 3 also gives yearly average corn yields for the six-year period. The data on corn yields indicate that lowest corn yields were obtained from continuous corn plots receiving either manure or UAN fertilizer and the highest corn yields were obtained from plots rotated with soybeans. Therefore, the continuous corn production system results in higher NO_3-N losses and lowest corn yields and is not a sustainable system.

Table 3. Average NO3-N concentrations (mg/l) in subsurface drainage water as a function of treatments*

Treatments	Years					Average
	2001	2002	2003	2004	2005	(2001-2005)
CLCD	12.6a	12.4b	19.4a	19.6b	20.1a	16.8a
CPSN	14.2a	11.4b	21.7a	30.3a	23.1a	20.1a
SLCD	18.4a	20.3a	20.5a	22.1b	19.7a	20.2a
SPSN	18.8a	18.8a	18.2a	18.6b	18.1a	18.5a

***CLCD = corn after soybean – side dress UAN application to corn with LCD**
CPSN = corn after soybean – spoke injected UAN application to corn
SLCD = soybean after corn – side dress UAN application with LCD to corn
SPSN = soybean after corn – spoke injected UAN application to corn

Table 4. Average corn and soybean yields as a function experimental (Mg/ha)

Treatments	Years					Average corn yield
	2001	2002	2003	2004	2005	
CLCD	9.97a	11.83a	9.33a	12.85a	11.90a	11.17a
CPSN	10.22a	12.01a	9.77a	12.85a	12.02a	11.37a
						Average soybean yield
SLCD	3.06a	3.60a	2.04a	3.97a	4.30a	3.39a
SPSN	3.08a	3.62a	2.07a	4.00a	4.45a	3.44a

Table 3 shows the effect of experimental treatments from the third study on NO_3-N concentrations in the subsurface drain water. The average NO_3-N concentrations for all treatments were found to be well above the US EPA drinking water quality standard of 10 mg/l. Also, corn plots treated with LCD N-applicator showed lower NO_3-N concentrations of 16.8 mg/l when compared with corn plots treated with spoke injected N-applicator of 20 mg/l. On the average, soybean plots resulted in slightly higher NO_3-N concentrations of 19.3 mg/ in comparison with corn plots of 18.4 mg/l. Treatment effects on corn-soybean yields were not significant (Table 4). Maximum average corn grain yield of 12.85 Mg/ha was observed in 2004 and minimum average of 10.09 Mg/ha in 2001. On the average, corn plots treated with LCD gave slightly lower corn grain yields of 11.17 Mg/ha in comparison with that of 11.37 Mg/ha with N-application using spoke injector. The overall results of the third study clearly indicate that although LCD N-applicator method can reduce NO_3-N leaching to groundwater but no benefits were observed on corn yields in comparison to spoke injector method of N-application. Therefore, the following conclusions can be drawn from various studies presented in this paper on the adoption of best agricultural practices in the agricultural watersheds to reduce nitrate leaching and hypoxia problems in major water bodies in the world.

The NO_3-N losses to subsurface drainage water were much higher under continuous corn in comparison with corn-soybean rotation for four tillage system evaluated in a long-term study. Continuous corn production systems cannot be considered good agricultural practice. Therefore, corn-soybean production system should be promoted with no-till and chisel plow systems.

Continuous corn plots receiving N from swine manure resulted in significantly higher NO_3-N concentrations in subsurface drain water in comparison with manure plots rotated with soybean. Also, highest corn yields were obtained from plots rotated with soybean under both manure and UAN fertilizer applications, whereas, continuous-corn plots resulted in lowest yields. Therefore, use of swine manure under corn-soybean rotation should be used as the best manure management practice in agricultural watersheds.

The non-traditional cropping systems of strip cropping and alfalfa rotation with corn, soybean and oats resulted in lowest NO_3-N concentrations in tile flow in comparison to all other systems evaluated and could be used as best agricultural practices to reduce dangers of hypoxia, provided some incentives are offered to farmers to stay financially sustainable.

Two innovative methods evaluated on the placement and application of N-fertilizer (LCD applicator and spoke injector) did not show significant differences between methods on NO_3-N leaching loss and crop yields, although average NO_3-N concentrations were about 16% lower for the LCD method in comparison to spoke injector method.

Overall results of various studies conducted in Iowa indicate that some of the best agricultural practices developed have the potential to significantly reduce NO_3-N concentrations in shallow ground water and surface water systems Iowa. Many of the agricultural practices developed in Iowa studies can be adopted by farmers to reduce hypoxia problems in the Gulf of Mexico with appropriate combination of tillage, crop rotation, and rate and method of N-application.

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PLANT NUTRITION CHALLENGES AND OPPORTUNITIES FOR THE GLOBAL FERTILIZER INDUSTRY

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ABSTRACT

Population growth, urbanization and advances in technology aimed at increasing productivity were the main driving forces affecting agriculture in the second half of the 20th century. More recently, additional driving factors have emerged, such as income growth and related changes in consumption patterns; greater attention to environmental and social concerns, and to food quality and safety; and the development of technologies aimed at optimizing resource use efficiency.

Fertilizer nutrients are important for crop growth and development; however, their misuse can impact the hydrosphere and the atmosphere through eutrophication of surface waters or emission of greenhouse gases. The fertilizer industry is challenged to supply the needed fertilizer products and help the farmers to apply them at the right rate, time and place, not only to increase production from a limited land area but also to ensure safe and high-quality food. In order to respond to these challenges and opportunities, the fertilizer industry has to innovate and adopt best available techniques in fertilizer production, and develop and promote site- and crop-specific fertilizer best management practices tailored to the socio-economic context of the farming systems.

INTRODUCTION

World population now stands at 6.7 billion people and all need food, fibre, housing and energy to survive. Agriculture is challenged to meet these needs, being a key driver of the global economy, a support of the livelihood and subsistence of the people, and vital to rural development and poverty alleviation. However, it is dependent on site-specific variables such as climate, geography, demography and standard of living, as well as man-made regulations.

Intensive agriculture rather than an extensive one is the best option if the impact of agriculture on the environment is to be minimized. Increasing agricultural output from a limited land area cannot be achieved without mineral fertilizers and other inputs. With the help of the fertilizer industry, agricultural productivity and food production can be improved in a sustainable manner to meet the needs of the population with limited negative impact on the environment.

This paper presents the agricultural production patterns, global fertilizer supply and demand, how fertilizer use impacts the environment and the initiatives taken by the industry to help mitigate climate change and contribute to sustainable agricultural productivity.

Driving Forces for Agriculture

World population is projected to reach 9 billion before 2050 (USCB, 2008) with the majority living in urban areas. While the rural population tends to stabilize, the additional people concentrate in cities, with more than half of the world's humanity now living in urban areas. Furthermore, it is projected that income will grow on average by some 4 percent annually in developing countries between 2007 and 2016 (OECD-FAO, 2007), resulting in diet diversification with greater consumption of meat, fish, sugar, fruits and vegetables, and less cereals and pulses. The production of agricultural commodities for food, feed, fibre and biofuels leads to competition for land, water and other natural resources. Currently, the opening up of new areas for agriculture is considered to be not environmentally friendly. Where fertilizer applications are already high, increasing fertilizer use efficiency rather than using larger amounts of fertilizer will put less stress on the environment. New varieties with stress tolerance, improved application techniques, better soil and crop management technologies, and the implementation of recommended practices, all contribute towards improvements in fertilizer use efficiency, especially nitrogen.

GLOBAL AGRICULTURAL SITUATION

World Cereal Production and Utilization

The 2008/09 global cereal harvest is expected to reach 2.2 billion tonnes (Bt), a 4.5 percent increase from the 2007/08 level of 2.1 Bt (USDA, 2009). Europe would improve production by 23 percent, reaching as high as 59 percent in Oceania. Thus, most of the recorded increase in production would come from developed countries (+10.3 percent) as shown in Table 1.

Table 1. Global/Regional Cereal Production (Mt): 2006 to 2008

Region	2006	2007(e)	2008(f)	change
Asia	912.6	950.5	945.4	-0.5%
Africa	142.7	133.5	144.4	+8.2%
Central America	37.2	39.9	40.6	+1.9%
South America	110.8	130.9	135.9	+3.9%
North America	384.5	462.1	452.5	-2.1%
Europe	404.7	388.7	478.6	+23.1%
Oceania	20.0	22.8	36.3	+59.1%
Developing	1 155.2	1 202.3	1 212.7	+0.9%
Developed	855.9	924.8	1 019.7	+10.3%

Source: FAO (2008)

However, for 2009/10, the International Grains Council (IGC) predicts a decline of 1 percent in the world's area planted to wheat, due to the current lower market prices and relatively higher input costs, which will likely result in lower wheat production at around 650 Mt, down by around 37 Mt from the record crop of 2008.

Global cereal utilization in 2008/09 is forecast to reach almost 2.2 billion tonnes, a 59 Mt or 2.7 percent increase from the previous campaign, driven by a strong demand from the US bioethanol industry. By the end of the 2008/09 marketing campaign, USDA predicts that the world stock-to-use ratio would be almost 23 percent for wheat, about 17 percent for coarse grains and nearly 20 percent for rice.

Table 2. World Cereal Production, Utilization and Stock-To-Use Ratio: 2006/07 to 2008/09

	2006/07	2007/08(e)	2008/09(f)	Change
Production (Total – Mt)	2 005.2	2 121.6	2 222.6	+4.5%
Wheat	596.1	610.9	682.8	+10.5%
Coarse grain	988.5	1 078.8	1 100.1	+1.9%
Rice (milled)	420.6	431.9	439.7	+1.8%
Utilization (Total – Mt)	2 052.6	2 106.5	2 165.4	+2.7%
Wheat	616.6	618.4	652.4	+5.2%
Coarse grain	1 015.1	1 059.8	1 078.9	+1.8%
Rice (milled)	420.9	428.3	434.1	+1.3%
Stock-to-Use Ratio (%)				
Wheat	20.6%	19.3%	22.9%	
Coarse grain	13.7%	14.9%	16.6%	
Rice (milled)	17.9%	18.4%	19.5%	

Source: USDA (2009)

Production and Utilization of Other Major Crops

World production of oilseeds is seen to increase by 6.7 percent and utilization by 3.0 percent in 2008/09. In view of the supply/demand situation, world ending stocks are seen to increase by 5 percent in 2008/09. For the same year, world sugar output is seen to decline by 3 percent to 164 Mt (ABARE, 2008), due to decreases in production in the EU and India but utilization is expected to increase by 2.3 percent, affecting world ending inventories and stock-to-use ratio, which would significantly decline by some 45 percent. Cotton output in 2008/09 is expected to decrease by 6.3 percent, driven by a 30 percent reduction in the US output as a result of the 26 percent reduction in cropped area. Utilization and ending stocks would decrease by some 3.3 percent and 6.5 percent respectively and the overall stock-to-use ratio is seen to decline by some 48 percent.

2008 has been a unique year because of the magnitude and speed of price changes for most commodities. Figure 1 shows that wheat, maize, rice, soybean and palm oil prices peaked during the first half of the year, well above levels registered since 1995 (used as base year) and dropped in the last quarter of the year, mostly in response to the world financial and economic downturn.

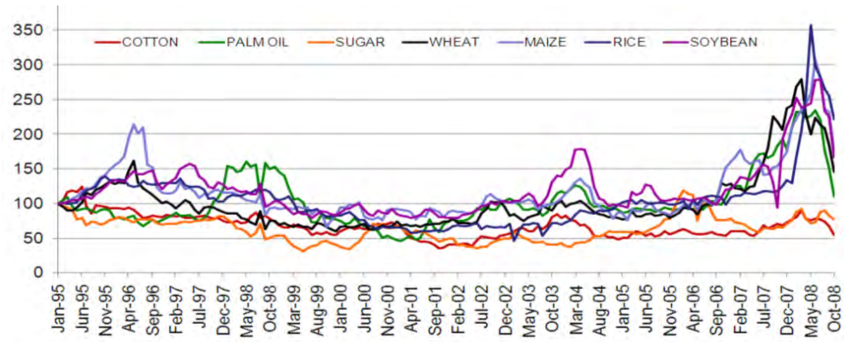

Figure 1: Relative Evolution of Selected Agricultural Commodity Prices (base 100 = January 1995)
Sources: Financial Times, IMF and MPOB

GLOBAL FERTILIZER SUPPLY AND DEMAND

Fertilizer Demand

Global fertilizer consumption increased by 7.5 Mt nutrients or by 4.7 percent in 2007/08 from the previous year level. Five regions in the world account for almost 90 percent of world fertilizer consumption. East and South Asia together account for 54 percent (37.5 and 16.9 percent, respectively), while North America accounts for 13.6 percent, Western and Central Europe for 11.4 percent and Latin America and the Caribbean for 10.2 percent. Fertilizer consumption is determined by the size of the population, the standard of living, the availability of fertile land and water, the connection to the world market and the climatic conditions, among others.

Table 3. Regional/World Fertilizer Consumption (Mt nutrients) 2006/07 to 2009/10

Region	2006/07	2007/08	2008/09e	2009/10f
Western and Central Europe	17.62	19.15	17.51	18.21
Eastern Europe and Central Asia	4.84	5.25	5.43	5.72
North America	23.38	23.03	22.79	23.33
Latin America and the Caribbean	15.24	17.28	16.18	16.41
Africa	4.47	4.39	4.35	4.61
West Asia	5.18	4.86	4.45	4.64
South Asia	27.33	28.60	29.74	30.84
East Asia	60.20	63.22	61.61	64.22
Oceania	2.96	2.97	2.97	2.90
World	161.22	168.73	165.04	170.88

Source: Heffer (2008) e=estimate f=forecast

Nitrogen, phosphorus and potassium remain the three most important macronutrients in agricultural production and are used on average in a 3:1:1 ratio, emphasizing the importance of nitrogen. Smil (2001) estimated that nitrogen fertilizers supply about 50 percent of the total nitrogen required for global food production and have contributed to an estimated 40 percent of the increase in per capita food production for the past 50 years. However, for 2008/09, it is estimated that world nutrient consumption will drop by 2.2 percent with a significant contraction in potash (-8.2 percent) and phosphate (-4.7 percent), while demand for nitrogen is likely to remain the same as in the previous year (+ 0.5 percent). World consumption is seen at some 165.0 Mt nutrients, broken down as 101.1 Mt of N, 37.5Mt of P_2O_5 and 26.5Mt of K_2O. During this campaign, only South Asia (+4.0 percent) and Eastern Europe and Central Asia (+3.5 percent) are expected to increase their fertilizer demand, as these two regions enjoy strong policy support for increasing fertilizer consumption.

Table 4. World Fertilizer Consumption, Fertilizer Year 2006/07 to 2009/10 (Mt nutrients)

	N	P_2O_5	K_2O	Total
2006/07	95.8	38.2	27.2	161.2
2007/08 (e)	100.5	39.3	28.9	168.7
Change	+4.9 %	+2.8 %	+6.3%	+4.7%
2008/09 (f)	101.1	37.5	26.5	165.0
Change	+0.5%	-4.7%	-8.2%	-2.2 % t
2009/10 (f)	104.5	38.8	27.5	170.9
Change	+3.4 %	+3.6 %	+3.9 %	+3.5 %

Source: Heffer and Prud'homme (2008) e = estimate f = forecast

Demand projections for 2009/10 are very speculative, but after a likely depressed period in the first semester of 2009, demand could possibly recover in the second half of the year. Global fertilizer demand is tentatively projected to grow by 3.5 percent with about the same growth rate for each of the three nutrients. Bulk of the increase in demand is expected to come from East and South Asia.

Fertilizer Use by Crop

Based on 2006/07 data, world fertilizer use on cereals contracted to 51 percent of the total, down from 60 percent, due to the increased consumption by the fruits and vegetables sector, which is estimated to consume more than 15 percent, similar to wheat, rice and maize. Oil crops account for 10 to 11 percent, cotton and sugar crops for less than 4 percent each and other crops use the remaining 15 percent.

On a per nutrient basis, cereals still consume bulk of the nutrients, accounting for some 56, 48 and 39 percent of total world consumption of nitrogen (N), phosphorus (P), and potassium (K), respectively. Wheat accounts for 19, 18 and 8 percent, while rice consumes 16, 18 and 13 percent, respectively. Maize accounts for 16 percent N, 18 percent P and 14 percent K. Oil crops, cotton and sugar crops represent some 7, 4 and 3 percent of total N use respectively. Fruits and vegetables account for 14 to 15 percent. For phosphorus (P) consumption, oil crops account for 14 percent, soybean for 8 percent and 4, 3 and 16 percent for cotton, sugar, and fruits and vegetables, respectively. Of the total potassium (K) fertilizer worldwide, wheat consumes 8 percent, rice 13 percent and maize 14 percent. Oil crops account for 17 percent, cotton for 3 percent, sugar crops for 8 percent and fruits and vegetables for 19 percent. Contrary to the other nutrients, K fertilizer use is strongly influenced by oil palm, sugar cane and fruits and vegetables, these crops together representing almost one third of world K fertilizer use.

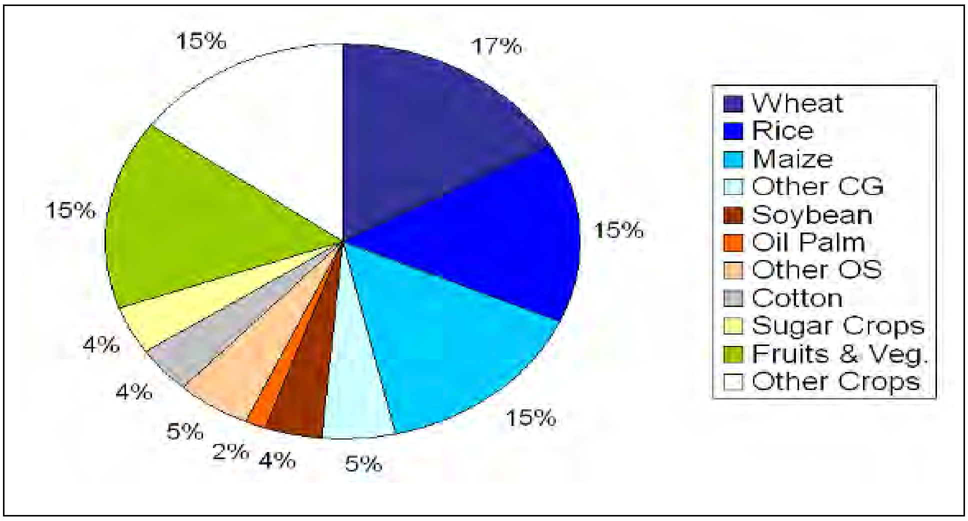

Figure 2: Fertilizer Use by Crop at the Global Level
Source: Heffer (2008)

Fertilizer Supply

The main basic product for all nitrogen fertilizers is ammonia; phosphate rock is the raw material for phosphate fertilizers, and for potassium fertilizers, potash deposits such as sylvinite and carnallite as well as potassium-rich brines are the main sources.

Ammonia is produced in 68 countries, with a majority in South and East Asia accounting for almost 50 percent of the world output. In China, two-thirds of the ammonia is produced using coal. Globally, about two-thirds of the ammonia is produced from natural gas and about a quarter using coal. Eighty percent of the ammonia produced is further processed in the region of origin and about 12 percent is traded. Urea remains the most popular nitrogen source, accounting for over half of the total nitrogen fertilizer produced, and responsible for three quarters of the international nitrogen trade. The predominance of urea is largely due to its relatively high nutrient concentration. In 2008, urea production was estimated at about 146.8 Mt product. China has emerged as the world's largest exporter of urea in 2007.

Approximately 70 percent of the mined phosphate rock is used to produce phosphoric acid, which is utilized for the manufacture of high analysis phosphate fertilizers and other industrial products. In 2008, world production of phosphate rock decreased to 174.1 Mt from 176.1Mt in 2007. IFA estimates that in 2007/08 all phosphate-based product outputs will be reduced, phosphate rock (-1 percent) down to 174.1Mt; phosphoric acid (-5.4 percent) to 35.2Mt; and processed phosphates (-5 percent) to 23.8Mt P_2O_5.

Despite record levels achieved during the first half of 2008, world potash production, sales and exports declined in 2008, as a result of stock carry-overs from 2007 and the severe financial and credit crisis worldwide, impacting demand and imports. Global potash capacity is, however, forecast to increase in 2009 to 42.3Mt from 40.9Mt K_2O in 2008, representing an additional 1.4 Mt of capacity, two-thirds of which will come from China along with additional capacity from Canada, Chile, Russia and Israel.

IMPACT OF NUTRIENT APPLICATIONS ON THE ENVIRONMENT

The increased use of nitrogen fertilizers has been essential in doubling global food production over the past 50 years (Smil, 2001). From an environmental perspective, however, nitrate can impact water quality, ammonia contributes to acidification of natural ecosystems, and nitrous oxide is a greenhouse gas with a strong global warming potential. In addition, most phosphate not taken up by the crop is retained in the soil. Small quantities may be lost through erosion and run-off into water bodies. Very small quantities are sufficient to promote algal growth and, in extreme cases, eutrophication. There may be a small loss of potash through dissolution in drainage waters, especially if the application is excessive, but it has no known adverse environmental impact.

At the global level, Galloway *et al*. (2004) estimated that agricultural production is responsible for about 75 percent of total ammonia emissions. Within agriculture, animal wastes account for more than 50 percent, manufactured fertilizer for 22 percent, direct emissions from crops for 9 percent and human wastes for 7 percent. The balance originates from the burning of agricultural wastes, forests and savannas.

More than 50 percent of the global emission of N_2O is considered to be "natural" (soils under natural vegetation, oceans, etc). About 30 percent is estimated to arise from agriculture, including N_2O emission from agricultural soils that would have occurred even if left undisturbed. Of the agricultural N_2O emissions, 44 percent is related to the management and application of animal manure, while manufactured fertilizers are estimated to account for about 14 percent. Nitrous oxide emissions induced by manufactured fertilizers are estimated to amount to about 1 percent of the fertilizer nitrogen applied (IFA, 2001).

Bouwman *et al*. (2002) (cited from Brentrup, 2008) developed generic emission factors for different N fertilizer types (Figure 3), which show that the higher the share of nitrate in the fertilizer the lower the N_2O emission. The use of a urea or ammonium based fertilizer often implies the nitrification to nitrate followed by a potential denitrification. Applying nitrates circumvents the nitrification step and implies only the risk of denitrification (Brentrup, 2008).

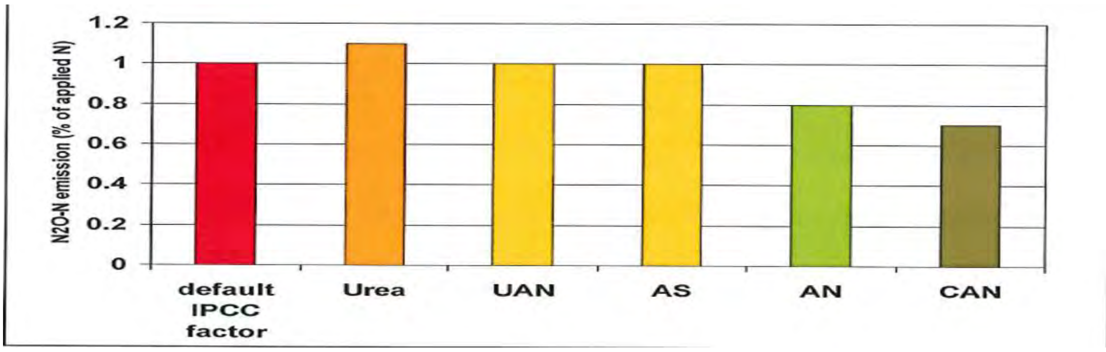

Figure 3: Average nitrous oxide emission factors for different N fertilizer products (Bouwman *et al.* 2002)

OPPORTUNITES FOR THE FERTILIZER INDUSTRY TO MEET THE CHALLENGES OF GLOBAL CHANGE

In order to meet the challenges of ensuring world food and nutrition security and, at the same time, mitigating the negative impacts on the environment, the global fertilizer industry has embarked on a number of initiatives.

Improved Efficiency of Manufacturing Plants

Technical innovation has changed the relative importance of fuel and feedstock gas in fertilizer manufacturing plants, thus modifying the amount of greenhouse gas emissions per tonne of ammonia produced. Theoretically, universal application of the best production techniques currently available could further reduce the fertilizer industry's GHG emissions by 60 percent and energy use by some 40 percent (Swaminathan and Sukalac, 2004). In addition, the move towards higher capacity plants has also helped implement more efficient technologies, as capacity upgrades offer a cost-effective opportunity to install better performing technology.

Improving the Efficiency of Mineral Fertilizer Use

In many developed countries, yields increased steadily during the past 20 years without significant increases in nitrogen fertilizer use. This is the case, for example, in Western Europe (cereals), North America (maize), Japan and the Republic of Korea (irrigated rice). Average cereal yields in these regions are 60 to 100 percent above the world average. These improvements can be attributed to better cultivation practices, better techniques of fertilizer application and improved crop varieties. Environmental regulations or incentives also have had an impact. In most developing regions, however, nitrogen use efficiency tends to decline.

Some of the most important means of improving fertilizer use efficiency are:

Balanced fertilization: If any plant nutrient (whether a macronutrient or a micronutrient) is deficient, crop growth is likely to be affected. One definition of balanced fertilization is “the nutrient mix which gives the optimum economic return.”

Site-specific fertilizer application: The efficiency of fertilization is improved by the implementation of fertilizer recommendations that take into account the specific agro-climatic and environmental conditions where the fertilizers are applied.

Fertigation: This technique enables growers to simultaneously maximize the use of water resources and increase the efficiency of fertilizer use.

Microbial inoculation: Inoculation with efficient strains of *Rhizobium* has proved to be beneficial for legumes. Free-living organisms such as *Azobacter* and *Azospirillum* have proved effective for rice and certain other crops. Certain microbial inoculants are also able to solubilize soil phosphorus. Vesicular-arbuscular mycorrhizae have favourable effects on phosphorus uptake, but more research and development is required.

Products with built-in enhanced-efficiency such as urease and nitrification inhibitors and slow- and controlled-release fertilizers.

Fertilizer Best Management Practices

The fertilizer industry recognizes that its efforts alone are not sufficient to ensure widespread adoption of fertilizer best management practices (FBMPs), yet it takes a pro-active stance on improving fertilizer use efficiency. For these reasons, IFA launched an initiative to foster the development and dissemination of FBMPs worldwide.

The main objective of FBMPs is to manage the flow of nutrients in such a way as to produce enough affordable and healthy food while sustaining soil fertility, protecting the environment, conserving natural resources and creating an atmosphere of trust with consumers and policy makers concerning food production.

The principle of fertilizer best management is simple: using the right product(s) at the right rate, time and place. Implementation, however, is more complicated because of the many considerations that must be taken into account. FMBPs bring together concepts such as balanced fertilization, site-specific nutrient management and “tea-spoon” feeding (enhanced-efficiency fertilizers, fertigation).

Another complexity of FBMPs involves answering the question “Best to achieve what: maximizing and stabilizing yields, reducing greenhouse gas emissions, limiting nutrient leaching, enhancing the nutrient density and balance of food products, or something else?” Ideally, enhanced practices would accomplish all of these things. In reality, there are trade-offs between two or more of the goals. The objective is, therefore, to determine the top priorities and achieve the greatest net benefit possible.

The purpose of IFA’s initiative is to encourage the spread of FBMPs that are developed and assessed within a scientifically valid framework. The initiative is particularly concerned with promoting FBMPs in developing-agriculture countries, where they are currently weakest. Nevertheless, even in some developed countries, much of the data underlying the best agricultural practices currently disseminated are outdated. One challenge will be to ensure that enough data is available to establish a scientific foundation for the recommendations.

Conclusion

The challenge for agriculture is to adapt fast enough to the changing climate and shift production practices to reduce and mitigate climate and other changes, at the same time meeting the food, feed, fiber and energy demand of the growing population.

Good Management Practices include:

- Maximizing on-farm recycling of nutrients;
- Matching nutrient/fertilizer applications to crop needs;
- Planting varieties that absorb nutrients efficiently;
- Creating physical or vegetative barriers to prevent the movement of nutrients out of the field; and
- Applying efficient plant nutrient products at the right place and time and in the right amounts.

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Session 4:

Carbon Sequestration and Soil Productivity

CONSERVATION TILLAGE AND COVER CROPPING: EFFECTS ON SOIL CARBON, NITROGEN AND CROP WATER USE IN THE COASTAL PLAIN OF GEORGIA

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ABSTRACT

Agriculture in the Southeastern Coastal Plain of the USA faces several challenges. Growing season temperatures, humidity, weed pressure, insect and disease all present significant challenges for producers. Soils in the region typically have sandy surface horizons that are low in carbon and nitrogen, have low water retention capacities, and are susceptible to erosion. These characteristics require intensive management of water, nutrients, and pesticides and may increase the potential for surface water pollution as well as competition with other sectors for water allocation. Although not typically thought of as a rainfall deficit region, rainfall during the growing season is highly variable and often in the form of locally-intense convective storms or tropical depressions. Irrigated acreage in southern Georgia has increased substantially since the 1970s. By the year 2000, the agricultural sector had become the largest water user in the state. In 2004, cotton, corn, and peanuts represented 85% of row crop production in Georgia, with nearly 90% of the acreage in the Coastal Plain. For the period 2000 – 2002, a study by the University of

Georgia reported that growing season monthly irrigation levels may vary from 2.5 – 41 mm per month during typical rainfall years and from 2.5 – 66 mm per month for drought years. Reduced tillage and surface residue retention has been demonstrated to increase infiltration, soil water content, and plant available water while decreasing runoff and erosion. Conservation tillage systems are currently in place on approximately 45% of the agricultural acreage in Georgia and approximately 45% of the acreage under conservation tillage is irrigated (about 21% of total agricultural acreage). Previous results from our team demonstrated: conservation tillage can reduce rainfall runoff and increase infiltration in these systems by 29% to 46%; decrease soil erosion by 350%; and decrease soil carbon loss associated with eroded sediments by 700%. Our work has also demonstrated the high potential for organic matter mineralization in these sandy soils by showing the depletion of NH4-N from poultry litter within 21 days of application followed by peak soil NO3-N concentrations within 28 days of application. Here we report preliminary data from several new projects that suggest a tight relationship between management (winter cover cropping and conservation tillage); patterns in soil physical properties (surface structure and depth to compacted layer); patterns in soil carbon and nitrogen; and patterns in crop nitrogen availability, water use, and resilience to water stress.

INTRODUCTION

The Little River Experimental Watershed (LREW) is located in south central Georgia in the western headwaters area of the Suwannee River Basin, centered at approximately N31.61o and W83.66 o (Figure 1). The USDA Agricultural Research Service's Southeast Watershed Research Laboratory (SEWRL) constructed a hydrologic monitoring network on the Little River between 1967 and 1971. Since that time, the SEWRL has collected hydrologic and water quality information intended to support research evaluating the impacts of agriculture and conservation management practices on landscape and watershed-scale processes affecting precipitation-runoff relationships, hydrograph characteristics, water quality, and the integrative effects of climate, vegetation, soils, and land use on agricultural production. Data are available at www.tiftonars.org. The 334 km^2 LREW originates approximately 9.6 km west of Ashburn, Georgia near the northwest corner of Turner County.

The watershed flows in a generally southerly direction to its confluence with the Withlacoochee River, eventually joining the Suwannee River which empties into the Gulf of Mexico west of Gainesville, Florida. Instrumentation on the LREW measures rainfall, stream flow, sediment, nitrogen and phosphorous flux from seven sub-watersheds in a paired and nested arrangement that facilitates testing of analytical formulas and modeling concepts. The precipitation network currently consists of 46 rain gauges and 3 climate stations installed throughout the LREW and the Upper Suwannee River Basin. Twenty nine of the rain gauge sites include soil moisture measurements in the top 300 mm of the soil profile. A seasonally dependent shallow aquifer exists throughout the watershed that drains into the stream network. Detailed descriptions of the LREW and its sampling networks can be found in Bosch et al. (2007a&b), Bosch and Sheridan (2007), and Sullivan et al. (2007).

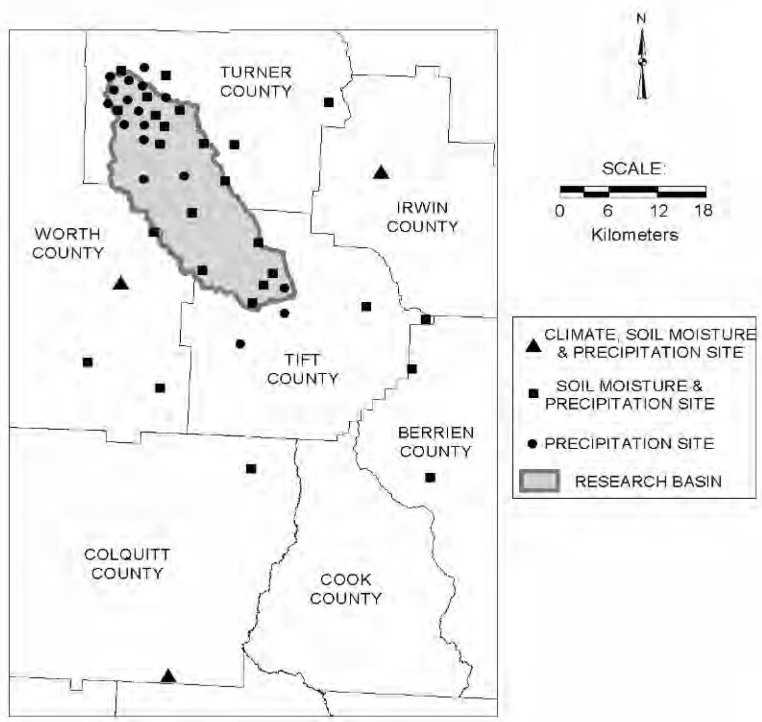


Figure 1: Little River Experimental Watershed and surrounding hydrologic measurement network

Recent component research projects at SEWRL have focused on agricultural management and conservation practices (Sullivan and Batten, 2007) and their effects at field, landscape, and watershed-scale levels on soil carbon and nitrogen content, water infiltration capacity, moisture holding capacity, and erosion potential as well as the associated effects on crop stress and net production. Although the southeastern U.S. is generally considered to have sufficient rainfall for crop production, the growing season is quite hot and humid and the timing and intensity of rainfall can be critical. For example, while the long term average rainfall for the Tifton, GA area is 1203 mm, the region has experienced drought in 5 of the past 9 years. Even during average years, precipitation ends up as evapotranspiration (73%), surface runoff (7%), stream base flow (20%), and only 0.1% to groundwater recharge. Streams generally stop flowing sometime in early summer and supplemental irrigation is increasingly used by farmers to insure crop production. Our research program is designed to develop data sets that can be used to integrate information across spatial and temporal scales via modeling and to provide estimates of uncertainty associated with model output. Such information will better inform policy makers regarding agricultural impacts of regulations as well as the relative cost likely to result from programs designed to minimize negative environmental impacts from agriculture. Here we will summarize results from several previously published studies and report preliminary findings from several recently-initiated projects.

Figure 2: Plot scale experiments examine the effects of conventional versus conservation tillage on surface runoff and rainfall infiltration using whole plot flume and tile drain systems as well as rainfall simulation.

METHODS

The SEWRL in partnership with the University of Georgia at Tifton has established experiments at the small plot (100 m2), large plot (2000 m2), field (15,000 – 28,000 m2), and watershed (7 x 106 m2) scales (Figures 1-3). All experiments include comparisons between conventional tillage (chisel plow to 20 cm followed by disk harrowing to 8 cm to form planting beds), strip tillage (subsoiler cuts a strip 15 cm wide x 20 cm deep for planting) or no-till (seed drilled directly into residue with no soil preparation). All experiments include quantification of total soil (0-15 cm) carbon and nitrogen (via combustion in an Elementar Vario C&N Analyzer), microbial biomass carbon and nitrogen (Brooks et al., 1985), plant-available nitrogen (Myrold, 1987), and quantification of above ground biomass production by winter cover crops.

The large plot experiment (Figure 2) also captures surface runoff (flume) and lateral subsurface flow (tile drains equipped with flumes) from 3 conventionally-tilled and 3 strip tilled plots. In addition to quantifying whole plot runoff, we simulate the effect of a range of storm intensities using a portable rainfall simulation device. For both the whole plot and simulation plot runoff studies, we quantify sediment loss and associated sediment carbon and nitrogen loss via combustion as indicated above.

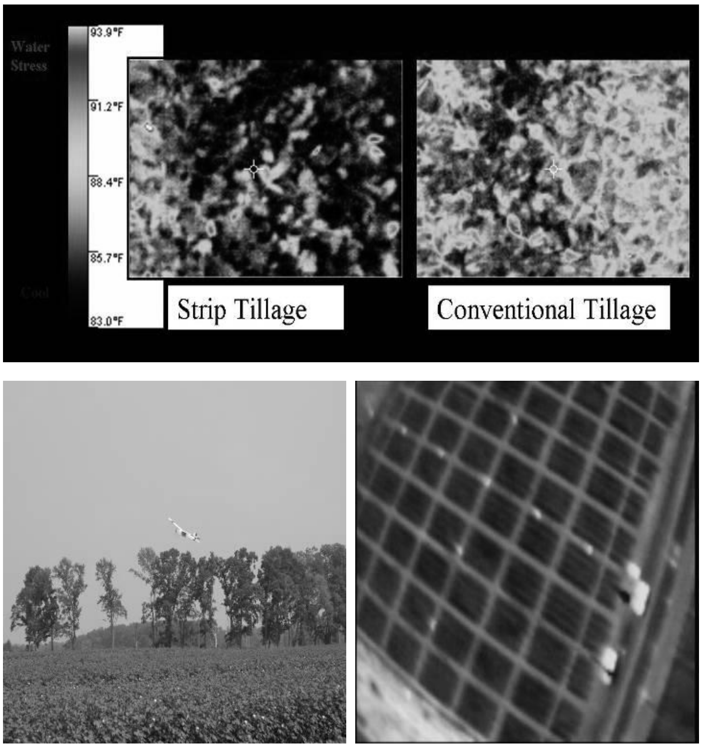


Figure 3: Plant water stress is estimated throughout the growing season at the plot and field level using both hand-held and unmanned aircraft thermal imaging systems.

Small plot and field scale experiments include measurement of soil moisture twice weekly at 10, 20, 30, 40, 60, and 100 cm using a Dynamax PR2 soil moisture probe. Crop water stress is estimated concurrent with soil moisture measurement using hand-held thermal imagers (Raytek ThermoView Ti30) on the small plots and an unmanned aerial vehicle equipped with a thermal camera for the field scale experiments (Figure 3). Plant rooting depths and soil carbon and nitrogen accretion are estimated by taking one meter soil cores (Figure 4) and determining total C and N as indicated above.

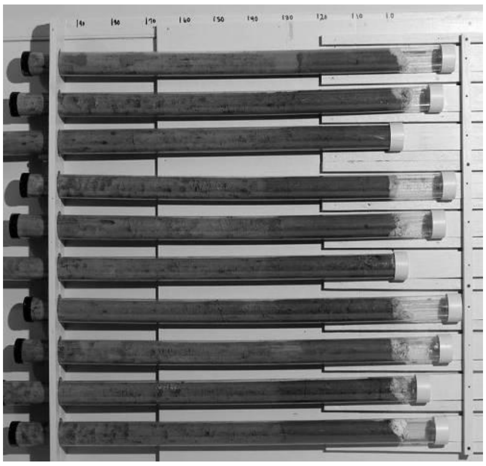
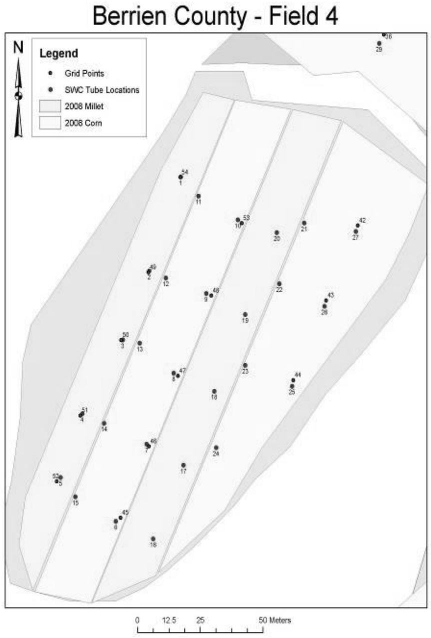


Figure 4: One meter soil cores used to characterize landscape variations in horizon depths and rooting depths.

Field scale experiments are also designed to evaluate the effects of landscape position on soil carbon, nitrogen, moisture and associated plant response and yield (peanut, corn, pearl millet) when grown without irrigation and under strip tillage (Figure 5). The results of correlations between soil characteristics, plant thermal stress, and crop yield will also be examined by comparison to crop management zones (e.g., Figure 6) which are generated based on satellite imagery (Landsat 5 TM and the Linear Imaging Self Scanner 3, LISS3, sensor on-board the Indian Remote Sensing P6 RESOURCESAT-1 satellite).



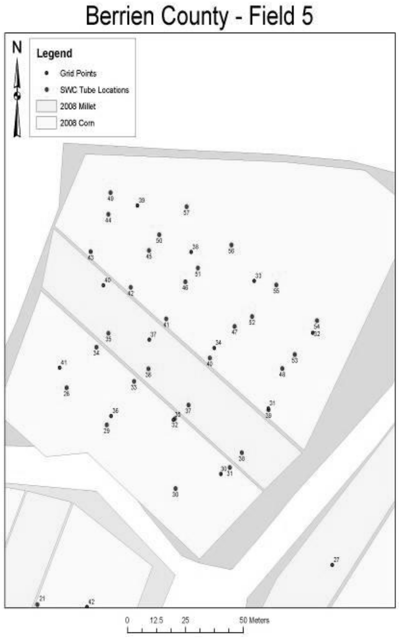


Figure 5: Whole field experiments capture landscape variability in crop response.

Our intent is to integrate all of these results at a watershed scale by characterizing the linkages between soil and plant responses at the plot scales and then extrapolating through patterns in plant stress responses (e.g., thermal and NDVI) at the landscape scale. Results will be used to determine whether relationships observed at the smaller scales do indeed manifest at the landscape and watershed scales. We will accomplish this step by conducting annual surveys of selected farms in the watershed that are managed in either conventional or conservation tillage regimes (Figure 7).

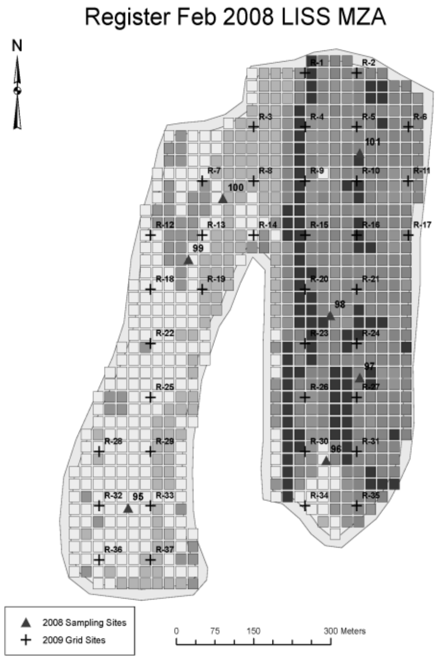


Figure 6: Management zones developed based on patterns in Normalized Difference Vegetation Index (NDVI).

Surveys are conducted on 25 farms in a seven county area surrounding the LREW. On each farm, soil and plant samples are collected from each of the major management zones established as described above (n = 122). Data collected include above ground biomass (AGB) and AGB %C and %N, soil (0-15cm) particle size distributions, %C, %N, and microbial biomass and plant available C&N. Five of the larger farms are sampled more intensively using a 100m x 100m grid as in Figure 6 to compare small versus large scale variability in the relationships between soil characteristics and plant responses. We will also conduct rainfall simulations at unique landscape positions and management zones within a few of the five intensively sampled fields to estimate the potential effects of winter cover cropping on soil erosion potential and to identify patterns in soil dry-down and crop heat stress response as related to landscape position.

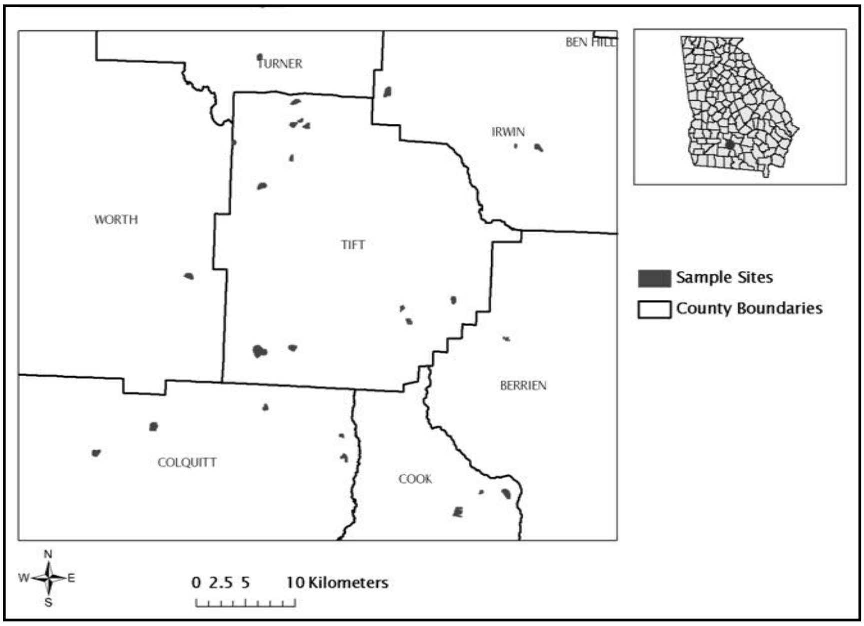


Figure 7: Watershed survey of selected fields serves as ground truth for remote sensing estimates of winter cover crop biomass production.

RESULTS

Small and Large Plots

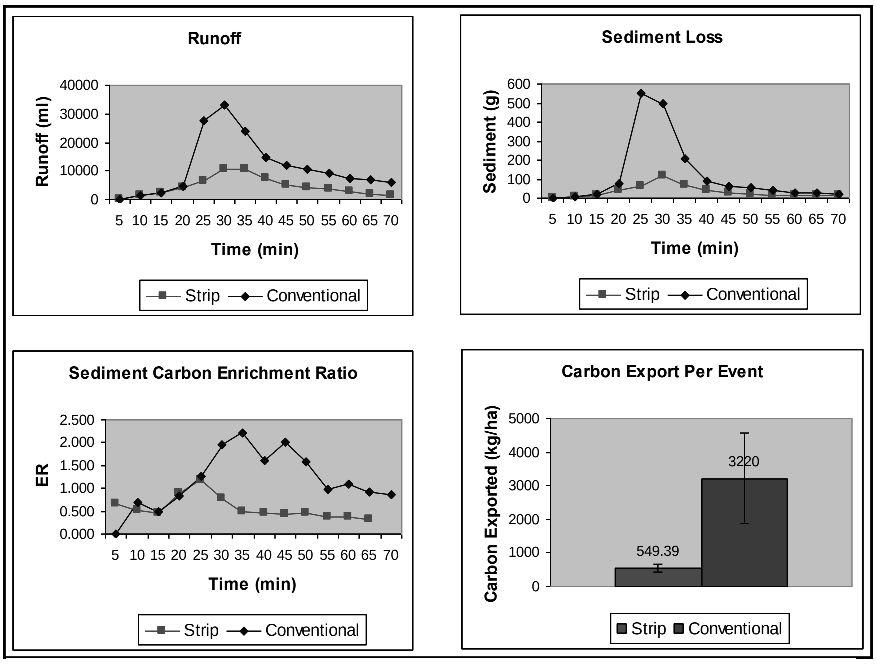


Figure 8. Strip tillage in a cotton-peanut rotation system reduced runoff, sediment erosion and carbon export.

Previously published results from rainfall simulations in the large plot experiment have demonstrated that conservation tillage in the form of strip tillage may reduce runoff and associated sediment and carbon export during the intense convective storms common to the southeastern U.S. (Figure 8, from Truman et al, 2007). Sullivan et al. (2007b) then used such rainfall simulation data from the Georgia coastal plain and piedmont in combination with estimates of row crop acreages and tillage practices at the county level (Conservation Technology Information Center, 2004) to provide estimates of water savings that may be possible as a result of conservation tillage adoption in Georgia. Their results (Figure 9) suggests that compared to water use under 100% conventional tillage, the current conservation tillage adoption rate (~ 30%) reduces irrigation water demands by 4-14%. Given the 2004 estimates of Georgia acreage under conservation tillage (~30%), they estimated that an increase to 100% adoption of conservation tillage would result in a 18-46% reduction in water being used to irrigate crops in the state of Georgia. Based on public water consumption rates in 2000, a 40% adoption rate for conservation tillage in the state of Georgia could result in water savings that translate to up to 234 days worth of water for the metropolitan Atlanta area which is the largest urban area in the state (Figure 9).

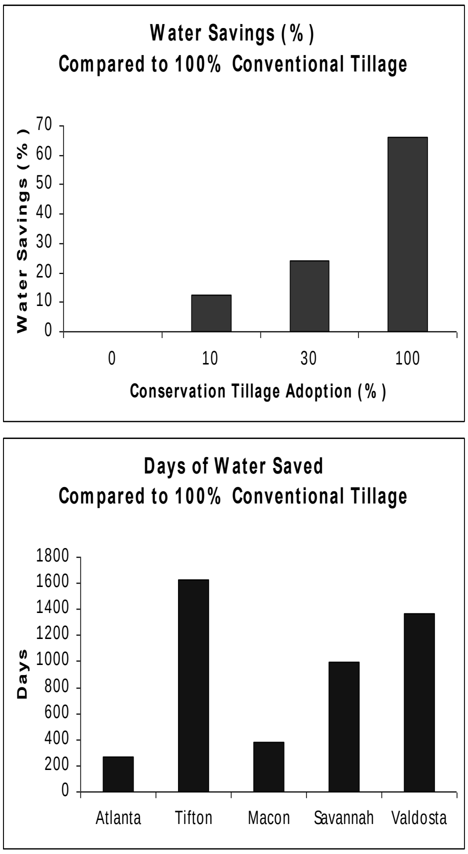


Figure 9: Potential water savings from conservation tillage in the state of Georgia.

Although some producers in our region have voiced concerns that conservation tillage may reduce yields, unpublished results from our small and large plot studies suggest that this is not the case (Figure 10). In fact, our data so far suggest that conservation tillage reduces fuel costs by $13/acre. Conservation plots were more tolerant of drought, delaying symptoms of stress by as much as 4 days. Thus, considering the cost to plant a winter cover crop, fuel savings and increased yield, long-term conservation tillage saved $41/acre in 2007.

Preliminary results suggest that changes in rooting patterns may be part of the mechanism controlling improved drought tolerance when crops are grown under conservation tillage (Figure 11). Soils under conventional tillage show a flatter slope of N increase as compared to C at depths of 5-55cm while plots that have been under strip tillage for six years show flatter slopes only at the 25-45cm depths.

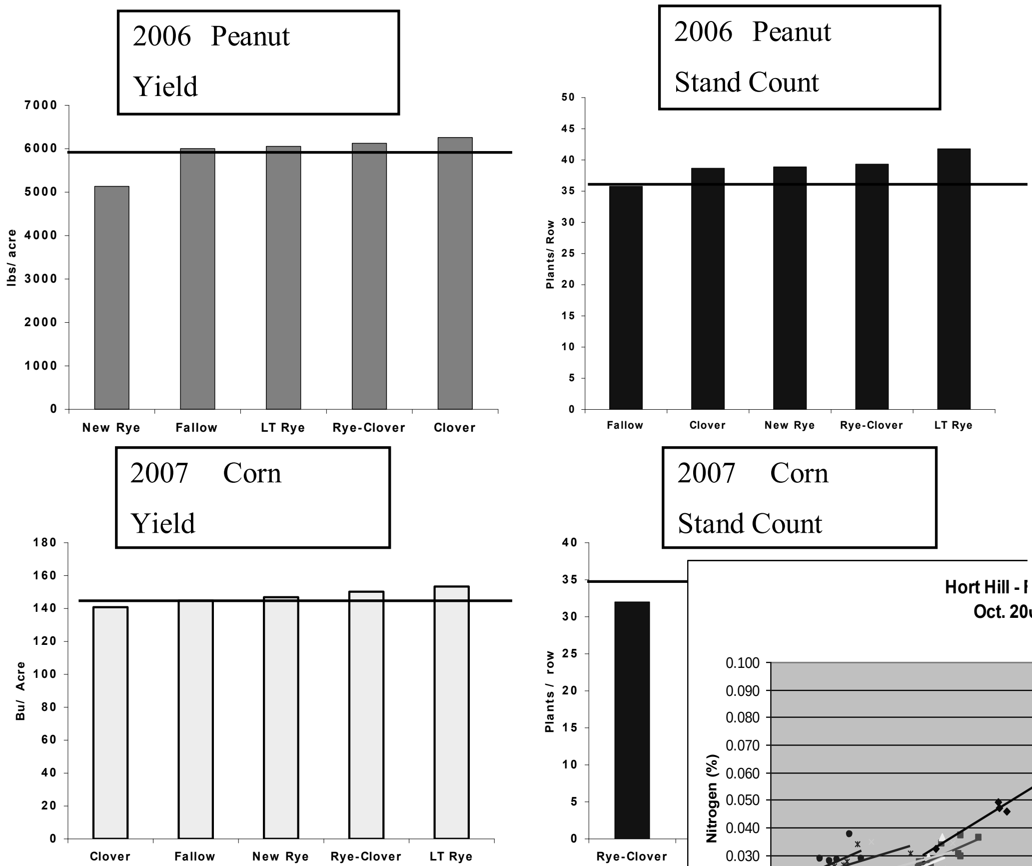


Figure 10: Conservation tillage with winter cover cropping had no negative effect on stand count or yield in corn and peanuts.

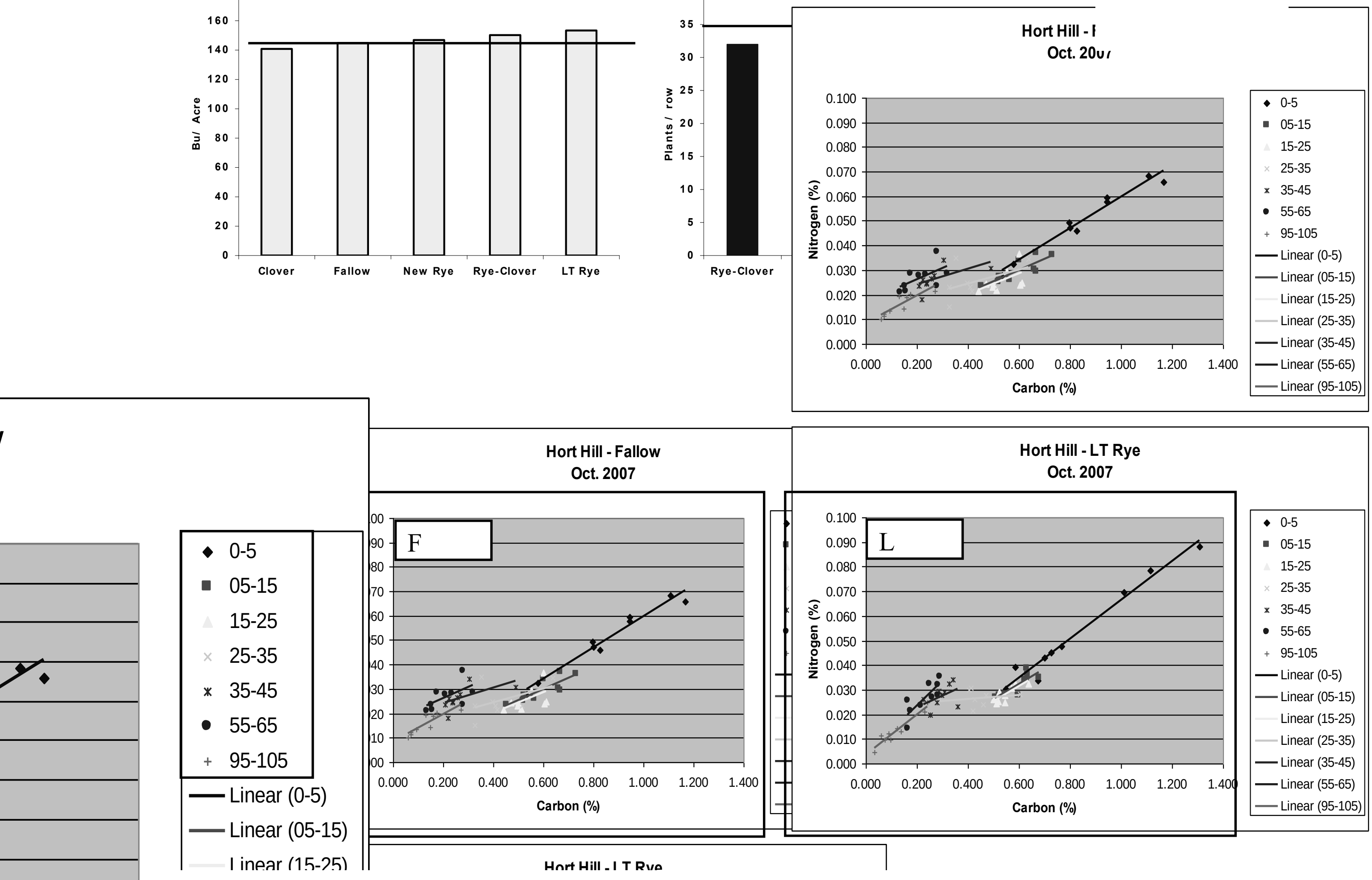
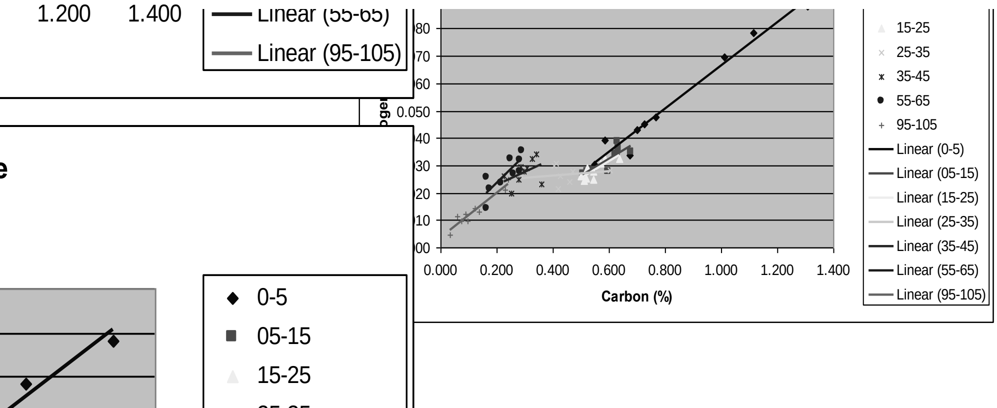


Figure 11: Plant rooting depths are estimated to be in regions where the slopes of N versus C increases flatten



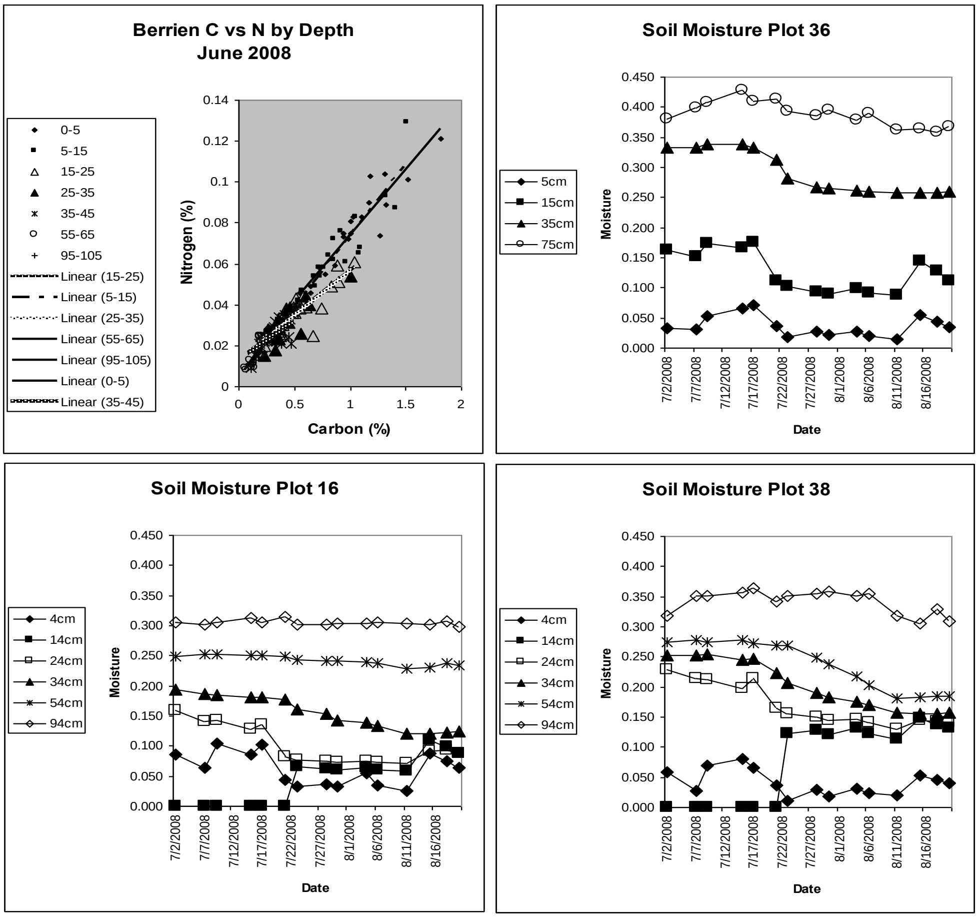


Figure 12: Estimated pearl millet rooting depths and associated growing season soil moisture variation at three different landscape positions in Berrien County, GA.

Landscape Scale

At the whole field or landscape scale, we are beginning to see similar patterns of rooting behavior under strip tillage along with some interesting relationships between rooting depth, soil moisture, and plant response (Figures 12, 13 and Table 1).

The data presented here are from the farm fields shown in Figure 5. As with the small plots, a flattening of the slope between soil N and C content at the 15-45 cm depths suggests root exploration of this zone. The pattern of soil moisture depletion over the growing season at these depths appears to match the general rooting pattern, although there are differences specific to each sampling location (Figure 12). When these patterns of rooting and water availability are then compared to plant canopy temperature as an indicator of stress (Figure 13), preliminary data suggest that plants growing in landscape positions that provide more available water through the rooting zone (plots 36&38) experience less heat stress and return higher grain yields (Table 1).

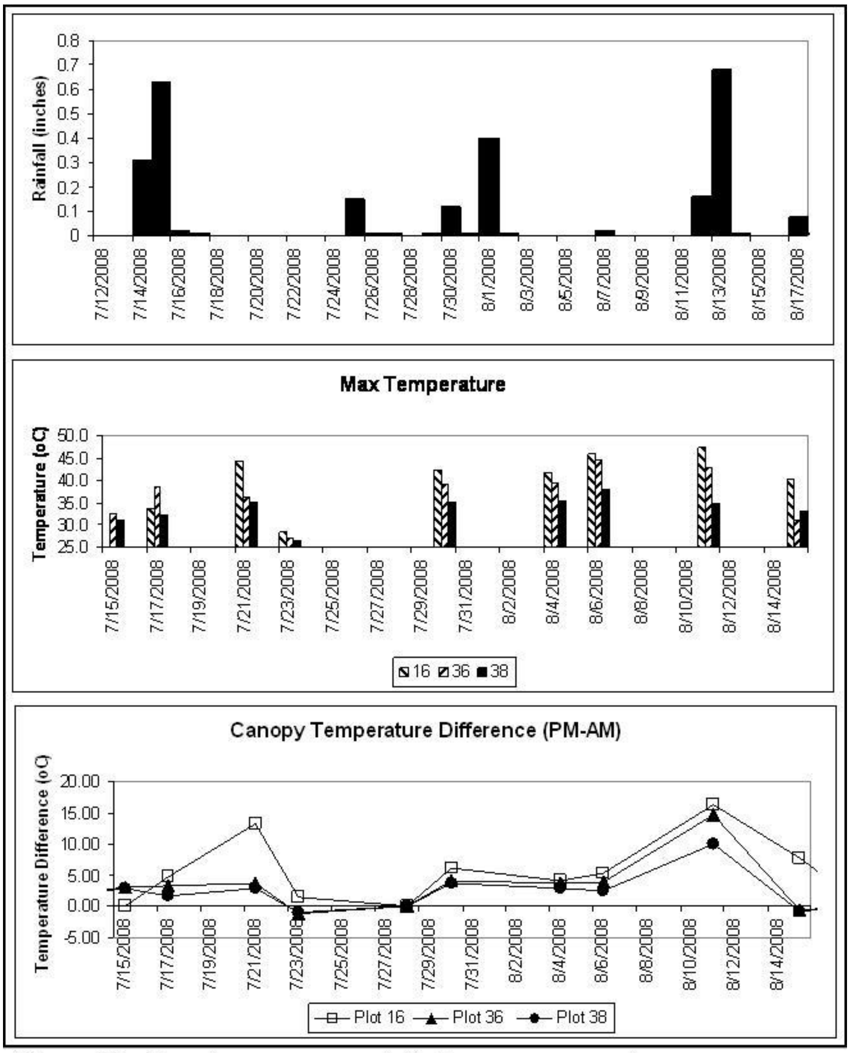


Figure 13: Growing season precipitation, canopy maximum temperature, and daily canopy temperature range at three landscape positions.

Table 1. Pearl millet grain yield from plots represented in Figure 12

Plot	Yield (lbs)
36	5.38
38	4.27
16	2.96

Watershed Scale

The 25 farm survey we began in 2008 has yielded some interesting data with respect to adoption of winter cover and conservation tillage practices, variation in quantities of winter cover biomass produced, spatial patterns of soil C and N relationships, and type of winter cover and tillage practice most likely to result in accretions of soil C & N across a seven county area surrounding the watershed. We have been able to develop remote sensing methodology that accurately estimates the amount of winter cover biomass produced in the watershed and develop maps of biomass levels across the seven-county sampling area (Figure 15). Soil samples (0-15 cm) collected concurrent with winter cover biomass collection exhibit a very close relationship between total carbon and nitrogen as well as between total carbon and plant available nitrogen (Figure 16). Such a relationship is not surprising given the high (>90%) sand content of soils in the LREW. In these soils where there is very low cation exchange capacity, soil organic matter may become the primary form of nitrogen storage. This first year data also suggests that some winter covers are more likely to be associated with increased soil carbon and nitrogen accretion potentials (Figure 17). Specifically, winter cover cropping to rye as opposed to either wheat or winter fallow (weeds) results in significantly more carbon and nitrogen in the surface soil.

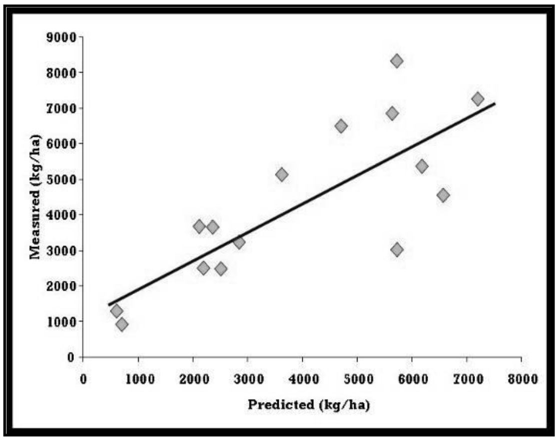


Figure 14: Measured versus predicted winter cover biomass using NDVI.

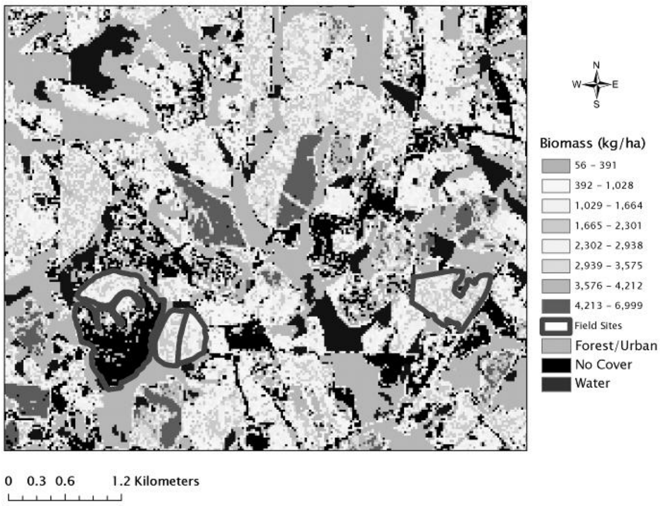


Figure 15: Mapping of winter cover biomass production within field boundaries.

DISCUSSION AND CONCLUSIONS

The combination of winter cover cropping and conservation tillage substantially affect soil carbon and nitrogen accretion, plant available water, and overall soil quality in the sandy soils of the U.S. southeastern coastal plain. In cropping systems where soil carbon consistently ranges between 4 and 6 grams per kilogram under conventional tillage, even small increases in total soil carbon can result in substantial improvements to soil quality as measured by water and nitrogen retention, as well as susceptibility to erosion.

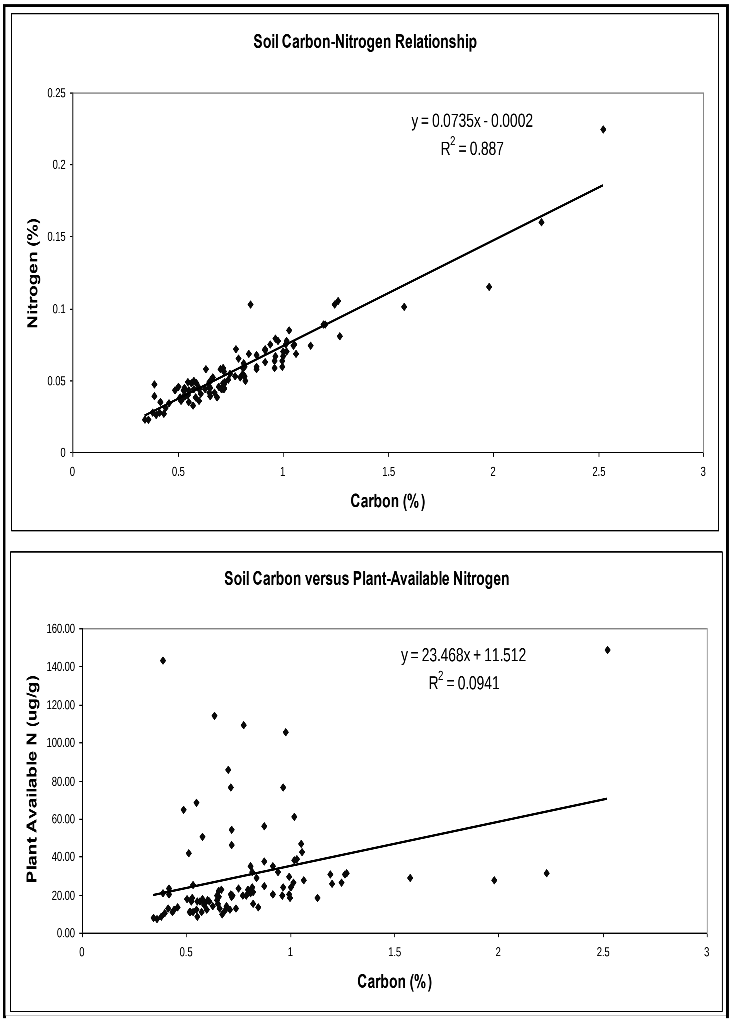
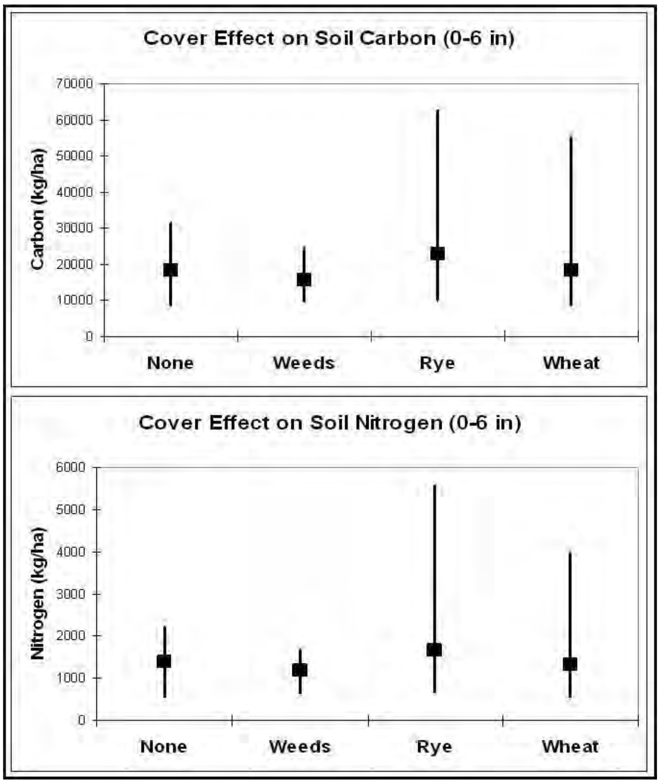


Figure 16: Tight relationship between soil total carbon and nitrogen in sandy LREW soils (0-15 cm).



Soil Carbon T-test, P (T<=t)			
	Weeds	**Rye**	**Wheat**
NC	.268	.035	.956
Weeds		.009	.296
Rye			.065

Soil Nitrogen T-test, P (T<=t)			
	Weeds	**Rye**	**Wheat**
NC	.139	.108	.601
Weeds		.013	.456
Rye			.077

Figure 17: Relationship between winter cover crop and soil C&N.

Our research has demonstrated the many benefits of conservation tillage and cover cropping at the small plot, farm, and watershed scales. Plot scale research has provided evidence of significant reductions in runoff and erosion as well as increased plant available water. At the current adoption rate of conservation tillage in Georgia, these results translate into a 4- 14 % reduction in irrigated water requirements for the state.

Preliminary assessments at the farm and watershed scales indicate higher yields and a reduction in crop canopy temperatures in areas that have maximize winter cover crop returns and minimize tillage. Data suggest that many of the conservation tillage benefits observed at the small plot scale are manifest at the landscape level as well. As a direct result, ongoing research efforts have been dedicated to the development of remote sensing tools to map levels of winter cover biomass, associated patterns in soil moisture and plant heat stress. Such maps offer promise as tools to streamline spatial irrigation, nutrient and pesticide application strategies.

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CARBON SEQUESTRATION AND WATER LOSS IN SEMI-ARID FOREST ECOSYSTEM

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ABSTRACT

We present a quantitative examination of pine forest functioning in semi-arid conditions based on measurements of carbon, water and energy fluxes in a 40 years old Aleppo Pine forest in southern Israel. The ecosystem activities showed a strong seasonal cycle with net ecosystem CO_2 exchange (NEE) during the winter reaching values <-0.12 mg C $m^{-2}s^{-1}$ (uptake) and continued activity throughout ~6 rainless months (including uptake spikes after sunrise), with soil moisture down to 3% (v/v, top 10 cm), under vapor pressure deficit, and with sensible heat fluxes reaching 800 Wm^{-2}. Maintaining continuous activity during the summer stress period enabled rapid ecosystem recovery both after the first rain event in the fall, and following short-term relaxations of stress conditions during the dry period. Eight years annual average NEE was 2.13 t C ha^{-1} (213 g C m^{-2}) and the gross primary production (carbon uptake, GPP) was 8.18 t C ha^{-1}. Although this forest grows at the dry and hot timberline, NEE is only about 0.3 t C ha^{-1} lower than the average reported for the global FluxNet system. This reflects moderate NEE during the short wet season (monthly average NEE of -100 g C m^{-2} s^{-1} during peak activity period) combined with low rates of ecosystem respiration (<18 g C m^{-2} s^{-1}) during the extended dry season. Tight water budget was reflected in leaf-dominated evapotranspiration (ET) and high annual scale water use efficiency (***W*** = GPP/ET) of 3.4 mg C g H_2O^{-1}, with winter ***W*** higher by ~2.5 than the summer values.

Results from the studied site indicate that afforestation activities in the semi-arid region have the potential to capture a relatively large amount of carbon and play a significant role in mitigating the CO_2 effect on climate, because semi-arid regions cover almost 20% of the land surface. The results may become increasingly relevant also to currently wetter regions, due to observed and predicted drying trends.

INTRODUCTION

A global effort has been underway over the past decade to study different aspects of carbon, water and energy exchange between the land biosphere and atmosphere (Baldocchi et al., 2001). It is currently based on over 400 FluxNet stations in diverse climatic and ecological conditions (http://www.fluxnet.ornl.gov/fluxnet/index.cfm). Ideally, flux measurement sites should be distributed over the entire range of climate on land, but the majority of measurement sites are currently located in temperate to cold climate conditions in North America, Europe, and Japan.

This is particularly significant when the measurement network is regarded not only as a monitoring system for carbon inventory, but also as an experimental setup used for improving our understanding of processes underlying ecosystem functioning and its response to change (e.g. Melillo et al., 1995; Osmond et al., 2004; Pielke et al., 1998).

To extend the climatic range of flux measurements and add to the very limited information on forest performance under dry conditions, a flux-measurement site was established in the 2800 hectare *Pinus halepensis*, afforestation system (Yatir) at the transition between the Mediterranean region and the northern edge of the Negev desert in Israel. This is, most likely, the hottest and driest forest flux measurement site in the global network, with the midday summer average temperature above 30^0C; an annual rainfall of about 284 mm (40 years mean) over only five to six winter months; a ratio of precipitation to potential evapotranspiration of ~0.18; and the annual mean Bowen ratio above 5.

Research sites at both the cold and hot extremes of forest survival are important for comprehensive understanding of ecosystem response to change. While cold forests are active (e.g. high CO_2 assimilation) when temperatures warm up, semi-arid forest activity is triggered when the temperature drops and water availability increases. Such forests are particularly sensitive indicators to environmental and climatic changes. Forest functioning under dry conditions may become increasingly relevant to currently wetter sites according to some future climate change scenarios (e.g. Geider et al., 2001), as well as according to current trends in precipitation observed in regions such as the Mediterranean region (Alpert et al., 2002).

Afforestation has been suggested as an important approach to increase carbon sequestration in the terrestrial biosphere (e.g., Canadell and Raupach, 2008). The results from this semi-arid site offers quantitative information on the little explored potential of afforestation in the vast climatic transition zone between the sub-humid and arid climates (Grünzweig et al., 2003; Paul et al., 2002; Warren et al., 1996), with implications both for carbon cycle and for wood productions, with the latter often a critical component for human habitation in these areas (e.g. Clarke and Noin, 1998; Mainguet, 1994). Afforestation in dry regions is also associated with changes in surface albedo (from 0.13 – 0.35 for bare soil to 0.05 - 0.20 in forests; (Campbell and Norman, 1998), and surface Bowen Ratios, both of which can influence regional climate (Charney, 1975) and environmental conditions (Baldocchi and Meyers, 1998) if applied on a large scale.

METHODS

The Yatir afforestation system is located at the transition between the Mediterranean region and the northern Negev desert, on a hilly (undulated) area at an elevation of 600 to 800 m a.s.l. An instrumented tower is located at the center of the forest ($31^0\ 20'\ 49.2''$ N; $35^0\ 3'\ 7.2''$ E). Trees within the tower footprint are mainly *P. halepensis* (above 90%) planted during the years 1965-

68. The forest density is currently ~ 300 trees/ha, with leaf area index (LAI) of about 1.5. During the measurement period, the average tree height was 10-12 m, with mean Diameter at Breast Height (DBH) of 17 cm. Understory vegetation consists of dwarf shrubs and herbaceous species, which constitutes only a minor portion of the total biomass. The forest was planted on about 0.20-1 m deep soil. The climate at Yatir is semiarid, with yearly average (1964 – 2009) rainfall (P) of 284 mm, ranging from ~ 140 to 490 mm. The rainy season starts in mid October and ends in mid April (6 months), but its duration can vary. The water table at the Yatir area is at 300 m deep. Annual mean air temperature during the period surveyed was 18.2 ^{0}C, and the long term annual mean relative humidity (RH) was 54 %. Potential evaporation (PET) rate at a nearby open space station using standard Penman-Montieth equation is on average around 1600 mm y^{-1} (Z. Zimal, IMS, pers. comm.), thus having a long-term mean aridity factor (P/PET) of ~ 0.18.

The method for measurements gathered at the instrumented tower erected in the geographic center of the Yatir forest follows the European methodology (Aubinet et al., 2000), and uses Unitus software (University of Tuscia, Italy). The system centers on a 3D sonic anemometer (Omnidirectional R3, Gill Instruments, Lymington UK) and a close path Li-Cor 7000 CO_2/H_2O gas analyzer (LI-COR Inc., Lincoln, Nebraska, USA). Together they measure the evapotranspiration (ET, mm m^{-2} s^{-1}) rate and the net ecosystem CO_2 exchange (NEE) between the forest ecosystem with the atmosphere, and also the energy fluxes of latent (LE) and sensible (H) heat (Wm^{-2} s^{-1}). Measurements of air temperature and relative humidity, wind speed, air pressure and precipitation (Campbell Scientific Inc, Logan, UT, USA) were carried out below the sonic at 15 m height. Radiation fluxes of solar, thermal, and net radiation (Rn) were measured by two CM21 sensors for solar radiation (Kipp and Zonen, Delft, The Netherlands) and by two PIR sensors for the thermal radiation (Epply Lab., Newport, USA). In seven locations around the tower, soil heat flux units (SHF) measured heat fluxes (Gs, HFT3 soil heat flux plates flux, Campbell Scientific). Rain fall data represented here were taken from the standard station located at the KKL forest house, 1.5 km to the southwest of the meteorological tower.

Gross primary production (GPP) is calculated as the sum fluxes of NEE and ecosystem respiration, Re. As stated, NEE is measured directly but Re is modeled from nighttime measured NEE (nighttime NEE = Re at night) and the correlation between sporadic daytime respiration measurements of the ecosystem components and the environmental conditions at the same times (Afik, 2009; Maseyk et al., 2008). ET is assumed to be correlated with T, the stem flow fluxes, with T measured at representative trees in this ecosystem, and T about 60-70% of ET (Schiller et al., in prep.).

RESULTS AND DISCUSSION

Carbon and Water fluxes

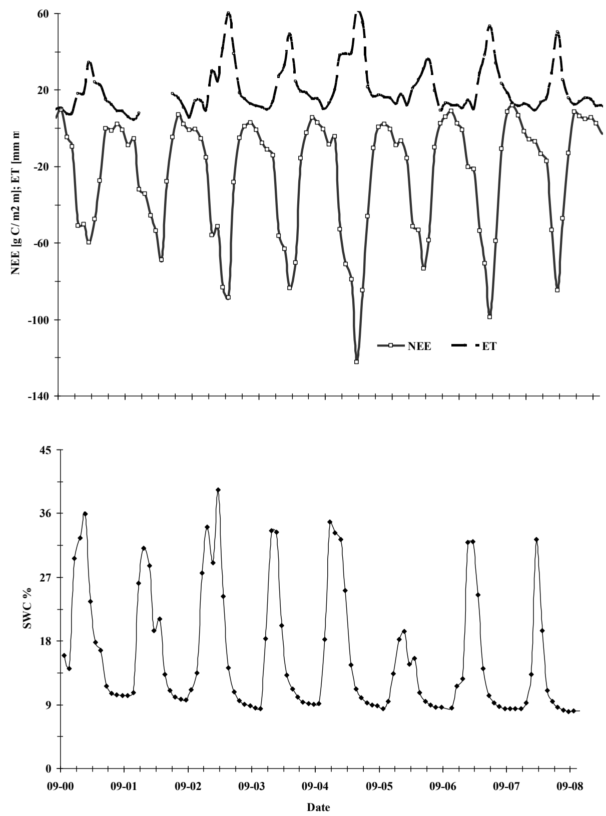

Figure 1: Eight years (2000-2008) monthly values of a) net ecosystem exchange (NEE, [gC m-2 month-1]; Negative values - carbon uptake by the ecosystem) and evapotranspiration (ET, mm M-1); and b) monthly mean of soil water content (SWC, v/v%) at the soil top 0–30 cm layer.

Annual average NEE of the Yatir forest for the eight year ecological study, after corrections for nighttime flux losses, was -213 gC m^{-2} y^{-1} (-2.13 t C ha^{-1} y^{-1}), ranging from -111 to -354 gC m^{-2} y^{-1}, depending on the climatic and the trees' conditions. These yearly corrected NEE values compare well with estimates of long-term ecosystem carbon stock reported previously (Bar Massada et al., 2006; Grunzweig et al., 2007; Grünzweig et al., 2003), assuming these values are near the annual mean value of the forest lifetime. Generally, high uptake occurred during the third in a 3-in-a- row sequence of above average rainy years. This high uptake enabled the trees' leaf area to expand considerably (leaf turn around period at Yatir is ~2.5 years). The seasonal pattern, Figure 1a, shows that most carbon uptake occurred during winter to early spring, months January to April; Leaf-scale measurements of assimilation showed maximal rates at temperatures between about 16 and 19ºC. Hence, temperatures favorable for photosynthetic activity occurred from November through May, and in other times only in the early morning hours or late afternoons. During the intermediate months, when water supply for transpiration was scarce due to low soil water content (Figure 1b), the trees' photosynthetic activities were limited and the ecosystem became mostly carbon neutral (NEE around zero). The forest becomes a small carbon emitter in the summer months, from July through September. In spite of the low precipitation and the dry environment (see below), the Yatir annual average NEE value is only about 30 gC m^{-2} y^{-1}, lower than the annual means found for the all of the flux stations in the Fluxnet (~250 gC m^{-2} y^{-1}, Luyssaert et al., 2007).

Both relative humidity (RH) and leaf to air vapor pressure deficit (D) reflected the dry conditions at the study site. Events of extreme dry condition occurred in spring and in autumn. The lowest RH measured since the station's establishment was 5% and 1/2-hour recordings of RH of ~10% occurred during most of the forest's high photosynthetic activity months. A typical day-to-night temperature range of around 10°C resulted in high RH values on many nights, thus moderating annual mean values (of 54%). During the day, low RH values combined with high air temperatures led to high D values throughout the year, with values above 3000 Pa during 12.3% of the time. These values are considerably higher than values reported for other Fluxnet forest sites, including semiarid *Pinus ponderosa* forest sites (Law et al., 2000b). Notably, preliminary measurements of the long-wave radiation budget at the forest (not shown) indicated that canopy temperatures can be about 5 °C above air temperature over extended time periods. Such results significantly raise the leaf-to-air D well beyond the already high atmospheric values reported above.

The data reported above clearly demonstrate the extreme conditions in which the Yatir forest is growing. The low precipitation, and its distribution, results in low soil water content and severe water stress over much of the annual cycle. Furthermore, the rainfall distribution pattern enhances this effect (Rambal and Debussche, 1995). Clearly, plants under limited water availability and exposed to extreme D must tightly control their water budget to survive. Indeed, these conditions seem to result in special adaptations and patterns of activity that allow the forest to maintain surprisingly high carbon sink levels on an annual scale.

Evaporative water from the ecosystem, the combination of water transpired from the vegetation tissues and evaporation water mainly from the soil surface (ET) mirrored the NEE fluxes (Figure 1a). It peaked toward the end of the rainy season, during the months of March or April, at about 60 mm M^{-1} (month) when there was enough soil water available for the trees to assimilate. At that period, the soil surface was also wet and the energy reaching the ground was enough for extensive evaporation. During the rest of the year, the soil's upper surface became extremely dry (down to ~3%; v/v) halting direct soil evaporation. Water in deeper layers decreased markedly as well (Raz-Yaseef, 2008), reducing T; consequently, CO_2 exchange (NEE) stopped. Thus, because of the high atmospheric water demand toward the end of the summer and until the first seasonal rain, ET decreased to below ~10 mm $month^{-1}$.

Annual evapotranspiration at a given year matches the annual precipitation (Figure 2). The ecosystem's water balance is calculated for the hydrological year, starting on October 1st before the start of the rainy season. Except for the first two measurement years (2000-01 and 2001-02), the ratio of ET to precipitation (P) (ET/P) was 0.8 and 1.1, with low values in wet years (300 mm or more), and high values in drought years (<230). The pattern may be understood to suggest trees' higher water harvesting efficiency in drought years, which decreases in wet years, enabling some water storage for subsequent dry years. (Note that low ET values in the first two years may reflect also technical problems in the early stage of the project, as well as the cumulative effect of the previous five dry years, before 2001). Ignoring the ET values for those two years, for a first approximation, the forest utilizes most of the incoming rain (ET/P>0.9 over the years), leaving only small amounts of water for any others uses.

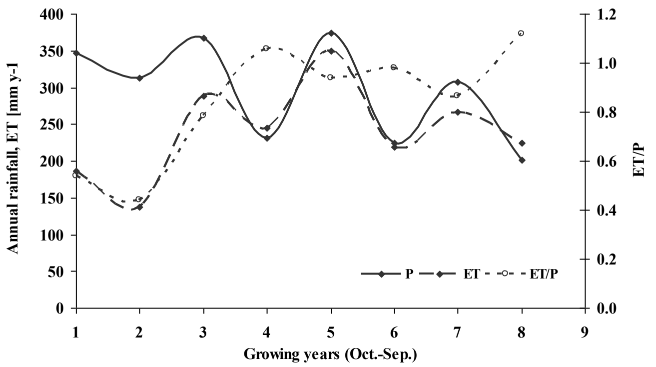

Figure 2: Annual precipitation (P), evapotranspiration (ET) and the ratio (ET/P) for eight years, where year 1 is October 2000 to September 2001. Note ET/P higher than 1, it is below 1 in drought years and above 1 in wet years.

Water use quotient *(W)*

Adjustments in the ratio of plant or ecosystem carbon uptake to water loss, defined here as the water use quotient, ***W***, is one of the mechanisms used by plants to adapt to drought conditions (see Jones, 1992). It is often used as an indicator for plant performance and its response to environmental conditions (Pataki and Oren, 2003; Stanhill, 1986), including increasing concentrations of atmospheric CO_2 (e.g. Drake et al., 1997; Wullschleger et al., 2002). Here we estimate ***W*** from the relationships between GPP and ET.

The results show a clear seasonal trend in ***W***, changing during midday times (09:00-15:00) from ~3.5 mg C g H_2O^{-1} in February (years 2004 and 2005) to ~1.3 mg C g H_2O^{-1} in the following summer and some recovery in November (~1.8 C g H_2O^{-1} in 2005). Notably, the decrease in ***W*** in summer was observed when GPP decreased and approached zero, while residual evaporation driven by high D reduced ***W*** and weakened the overall GPP vs. ET correlation. It is also interesting to note that summer water fluxes were less than half the winter values, even though the ecosystem to air water vapor gradients (D) during the summer might have been be three times higher than in winter. Thus, despite the D effects and consequent decrease in ***W***, plants clearly controlled water loss, and on the whole, decoupled ET from environmental conditions.

Values of ***W*** are calculated and reported differently by different authors; consequently, conducting a comparison is difficult. Plants growing in dry conditions may adapt to maximize ***W***, but the high environmental water demand can compromise this effort. A reduction in ecosystem ***W*** with increasing D was recently reported by Scanlon and Albertson, 2004. Lacher, 2003 reports ***W*** values between 1.3 and 2.1 mg C g H_2O^{-1} (converted from dry matter production values) for coniferous trees. Reichstein et al. (2002) reported GPP-based ***W*** values in Mediterranean forests and macchia between a maximum of 6 and 2 mg C g H_2O^{-1} in winter and summer, respectively. Across evergreen conifers forests, Law et al., 2002 reported an annual ***W*** (as NEE/ET) of 0.8 mg C g H_2O^{-1}, and higher values but minor seasonal changes from 3.1 to 3.0 mg C g H_2O^{-1} in winter and summer, respectively, in a pine forest in Metolius, Oregon (Law et al., 2000a). During the measurement period at Yatir, the estimates of annual ***W*** (***W*** =GPP/ET) ranged between 3 and 4.9 mg C g H_2O^{-1}. Across sites, the comparison of ecosystem scale ***W*** is sensitive to differences in accuracy of NEE and ET measurements, the assumptions behind GPP calculations, and variability in ecosystem parameters such as canopy density (influencing the ratios of soil evaporation to ecosystem transpiration). It is nevertheless significant that despite the dry conditions in Yatir, its ***W*** values are close to the upper values for C3 plants. In the dry summers, ***W*** is low and reflects the water stress that characterizes the forest under such conditions, with GPP near zero and only residual evaporation resulting from the extreme D values. We speculate that the Yatir results, which demonstrate a conservative system maintaining high ***W*** even during mild environmental conditions, reflect interactions with the low hydraulic conductivity in the soil-plant-atmosphere system. This may be part of the overall adaptation to water scarcity at the site.

CONCLUSIONS

1. Eight years mean annual NEE of the semi-arid Yatir forest was -213 gC m^{-2} y^{-1}, and it is only about 30 gC m^{-2} y^{-1} lower then the annual mean found for the global flux stations network (Fluxnet).

2. Mean ratio of ecosystem evapotranspiration to local precipitation, ET/P, is over 0.9, thus leaving only a small amount of water for others uses.

3. Estimates of the eight years' annual ecosystem water use efficiency; ***W*** (***W*** =GPP/ET), ranged between 3 and 4.9 mg C g H_2O^{-1}, with the highest values in the main activity season (January-April). High ***W*** values despite the dry conditions in Yatir are close to the maximum values for C3 plants. Low ET even during the wet season, combined with moderate mean NEE values, resulted in high wet season gross ***W*** values reflecting predominantly the canopy response. The decrease in ***W*** in going into the dry season reflected proportionally greater decline in C uptake than in water loss to evapotranspiration, which was due to the coupled effects of seasonal decrease in soil water content and very high D values.

4. Aleppo pine afforestation shows suitability to the semi-arid conditions, and resilience, resulting in relatively high annual carbon sink. This is potentially significant for C sequestration in the land biosphere if applied on a large scale in the semi-arid regions, as well as for currently wetter regions that are subject to drying climatic trends.

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BIOCHAR FOR 21ST CENTURY CHALLENGES: CARBON SINK, ENERGY SOURCE AND SOIL CONDITIONER

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ABSTRACT

Biochar, a charcoal produced from biomass, can sequester carbon in soil for hundreds to thousands of years. Pre-Columbian Amazonian Indians used it to enhance soil productivity, and it is still found in large concentrations in Amazon soils abandoned thousands of years ago. Its modern equivalent is produced by pyrolysis, the direct thermal decomposition of biomass in the absence of oxygen to an array of solid (biochar), liquid (bio-oil) and gas (syngas) products. The specific yield from pyrolysis depends on process conditions, and can be optimized to produce either energy or biochar. Being an exothermic process, biochar production produces 3-9 times more energy than is invested, and is carbon-negative (withdraws CO_2 from the atmosphere). In addition, modest additions of biochar to soil have been found to reduce NO_x emissions by up to 80% and to completely suppress methane emissions, thus directly reducing agricultural greenhouse gas emissions. While some fresh organic matter is needed by agricultural soil to maintain its productivity, much agricultural waste (and other kinds of waste streams) can be turned directly into biochar, bio-oil, and syngas.

In addition to its potential for carbon sequestration and decreased greenhouse gas emissions from agriculture, biochar is reported to have numerous benefits as a soil amendment: increased plant growth yield, improved water quality, reduced leaching of nutrients, reduced soil acidity, increased water retention, and reduced irrigation and fertilizer requirements. The quality of biochar as a soil ameliorant depends on the character of the biochar and on regional conditions including soil type and condition (depleted or healthy), temperature, and humidity.

Estimates for biochar residence time in soil range from 100 to 10,000 years, with 5,000 years being a common estimate. Whilst the means by which biochar mineralizes are not completely known, it is apparent that mineralization rates depend on the feedstock material, the extent of charring, the surface:volume ratio of the particles, and the soil environment. Lab experiments confirm a decrease in carbon mineralization with increasing pyrolysis temperature, so careful control over the charring process can increase the soil residence time of the biochar C.

Bio-oil created in the pyrolysis process can be used as a replacement for numerous applications where fuel oil is used, as well as a feedstock for chemical production. Syngas and bio-oil can also be "upgraded" to transportation fuels like biodiesel and gasoline substitutes. If biochar is used for the production of energy rather than as a soil amendment, it can be directly substituted for any

application that uses coal. Syngas can be burned directly, used as a fuel for gas engines and gas turbines, or used in the production of methanol and hydrogen.

INTRODUCTION

According to the Intergovernmental Panel on Climate Change (IPCC), the earth's temperature rose 0.6°C during the 20th century, and is projected to continue to rise between 1.5 to 4.5°C by the year 2100 (*1*). Man-made, anthropogenic greenhouse gas emissions are considered the dominant causal factor for these increasing temperatures which lead to other related changes in climate. Consequently, there is a world-wide drive to develop different strategies for reducing net greenhouse gas emissions, and part of that drive has brought us to the cusp of a paradigm shift from a "petroeconomy", fueled by fossil carbon, to a "bioeconomy", fueled by biomass created through photosynthesis (*2*). The petroeconomy is overwhelmingly carbon positive - contributing carbon to the already existing load. In contrast, the bioeconomy is conventionally considered to be carbon neutral, whereby the carbon emitted through biomass burning replaces the carbon absorbed during the growing of the crop (*2*). The reality of the bioeconomy as carbon neutral is currently the subject of intense debate, with detractors arguing that much of the biofuel production in temperate climates is almost entirely carbon positive due to the heavy inputs of fossil fuels for agricultural production and the use of fertilizers (*3-5*). However, this controversy could be entirely eliminated by producing carbon negative biofuels, in other words, fuels which remove more carbon from the atmosphere than they put back in through burning (*2*). This can be accomplished by treating biomass by pyrolysis, the direct thermal exothermic decomposition of biomass in the absence of oxygen to an array of solid (biochar), liquid (bio-oil) and gas (syngas) bioenergy products. Instead of burning the produced charcoal (biochar), it can be returned to the soil as a soil conditioner (*6*), where it remains in an essentially permanent form.

Soil amendment with biochar, a charcoal produced from biomass, can sequester carbon in soil for hundreds to thousands of years (*7*). Pre-Columbian Amazonian Indians used char to enhance soil productivity, and it is still found in large concentrations in fertile Amazon soils abandoned thousands of years ago. Modern biochar is produced by pyrolysis, the specific yield of which depends on both the process conditions and the feedstock. Pyrolysis can be optimized to produce syngas, bio-oil or biochar. Being an exothermic process, pyrolysis of biomass and biochar production produces 3-9 times more energy than is invested (*7*), and when the biochar is applied to soil, the whole process becomes carbon-negative (*8*). In addition, modest additions of biochar to soil have been found to reduce emissions of greenhouse gases from cultivated soils, for example, reducing N_2O emissions by up to 80% and completely suppressing methane emissions (*8-10*). While some fresh organic matter is needed by agricultural soil to maintain its productivity, much agricultural waste (and other kinds of organic waste streams) can be turned directly into biochar for reapplication to the soil and for creation of biofuels. For example, biochar production can utilize much urban, agricultural or forestry biomass residues, including and not limited to wood chips, corn stover, rice or peanut hulls, tree bark, paper mill sludge, animal manure, olive mill waste, municipal waste, municipal sludge, and recycled organics (*11*).

Consequently, biochar and bioenergy co-production from urban, agricultural and forestry biomass has been proposed to help combat global climate change in a number of ways: (i) by displacing fossil fuel use via production of energy from waste materials, (ii) by sequestering carbon in stable soil carbon pools, and (iii) by reducing soil emissions of nitrous oxides and methane, more potent greenhouse gases than carbon dioxide. Moreover, there is evidence that biochar applied to soil can increase crop yields and productivity, reduce soil acidity, and reduce water, chemical and fertilizer requirements (*12*). In the soil, biochar provides a habitat for soil organisms, but is not itself consumed by them to a great extent, such that most of the applied biochar can remain in the soil for several hundreds to thousands of years (*13, 14*). When used as a soil conditioner along with organic and inorganic fertilizers, biochar appears to significantly improve soil tilth, productivity, and nutrient retention and availability to plants via both direct slow-release fertilizing properties and indirect effects on improved water holding capacity, nutrient holding ability, and soil aggregate stability (*12*). Because biochar aids in soil retention of nutrients and agrochemicals for plant and crop utilization (*15, 16*), and is a good sorbent for organic and inorganic pollutants, it can be anticipated that chemical leaching to groundwater and run-off to surface waters will be reduced. As such, biochar systems may help in the fight against soil degradation, and can be a tool in the creation of sustainable food and fuel production in areas with severely depleted soils, scarce organic resources, and inadequate water and chemical fertilizer supplies.

AGRONOMIC VALUE OF BIOCHAR

Currently, very little biochar is utilized in agriculture, and its agronomic value in terms of crop response and soil health benefits still needs to be quantified. The few reports available show a general increase in crop yield and soil quality (*12, 17-19*), but a review of the scant literature showed a wide range of biochar application rates (0.5 – 135 ton/ha), as well as a wide range of plant responses (-29 to 324% increase in dry matter) (*12*). More importantly, for the most part, properties of the biochar used in the investigations were not reported. Biochars can be produced from a vast array of organic materials and under different conditions (*11*), resulting in products with varying physical and chemical properties. For example, although biochar produced from greenwaste (mixture of grass clippings, cotton trash, plant prunings) and poultry litter had similar total N contents (1.8% and 2%, respectively), the greenwaste biochar had virtually no KCl-extractable N (<0.3 mg/kg), while the poultry litter biochar had 2.4 mg/kg extractable N (*17, 18*). Little research has been published elucidating the mechanisms responsible for the reported benefits of the biochars on crop growth, production and soil quality. Such understanding is essential for the development of agricultural markets for biochars and for the future development of technology for the production of biochar products with improved quality and value (*18*). What is clear from the limited research that has been performed is that the quality of biochar as a soil conditioner depends on the character of the biochar and on regional conditions including soil type and condition (depleted or healthy), temperature, and humidity (*12, 17, 18*).

In an early study, Iswaran et al. (*19*) reported that charcoal added to soil at 500 kg/ha increased the yield of moong, soybean and pea in a pot culture experiment by 22, 51 and 60%, respectively. The increases in yield upon charcoal amendment were only slightly less (9 to 25%) than increases in yield obtained upon soil inoculation with rhizobacterium. Later, Kishimoto and Sugiura (*20*) reported that five years after the application of 0.5 Mg charcoal/ha, the heights of sugi trees (*Cryptomeria japonica*) increased by a factor of about 1.3, and biomass production by a factor of 2.5 to 3.2. Crop yields of soybeans were also reported to increase by a factor of 1.5 after an application of 0.5 Mg charcoal/ha (*20*). However, yield declines were observed at much higher amendment rates (5 Mg and 15 Mg charcoal/ha) (*20*). A study of the effect of charcoal on birch and pine growth reported that birch shoot and root biomass was five times greater in charcoal-amended soil from a site dominated by shrub-released phenolic root exudates, an effect which was attributed to sorption and detoxification of allelopathic phenolic compounds (*21*).

More recently, studies from the group of Lehmann examined the effect of both ancient and recent biochar on soil fertility and nutrient leaching from highly leached tropical Ferralsols. Lehmann et al. (*22*) compared soil fertility and leaching losses of nutrients between an Anthrosol (relict soil from pre-Columbian settlements in the Amazon with high organic C and large proportions of black carbon), and an adjacent un-amended Ferralsol. The Anthrosol showed significantly higher P, Ca, Mn, and Zn availability than the Ferralsol, and an increased biomass of both cowpea and rice by 38–45% without fertilization. Despite the generally high nutrient availability in the Anthrosol, leaching was minimal. When charcoal was added to the Ferralsol, uptake of P, K, Ca, Zn, and Cu by the plants increased. Leaching of applied fertilizer N was significantly reduced by the charcoal amendment, and Ca and Mg leaching was delayed. Rondon et al. (*10*) studied the potential for enhanced biological N_2 fixation by common beans through biochar additions at 0, 30, 60, and 90 g biochar/kg soil on a Ferralsol. The proportion of fixed N increased from 50% without biochar additions to 72% with 90 g/kg biochar amendment. The primary reason for the enhanced biological N_2 fixation with biochar additions was greater B and Mo availability. In addition, biomass production and bean yield were significantly improved with biochar additions, with biomass maximized at a biochar application rate of 60 g/kg (increase in biomass by 39%) and yield increasing monotonically with increasing biochar loading (increase in yield of 46% at 90 g/kg). Soil N uptake by N-fixing beans decreased by 14, 17, and 50% when 30, 60, and 90 g/kg biochar were added to soil, respectively, whereas the C/N ratios increased from 16 to 23.7, 28, and 35, respectively. Results of a field trial testing the influence of charcoal, compost and fertilizer on a tropical Ferralsol on retention of N were also recently reported (*15*). The total N recovery in soil, crop residues, and grains was significantly higher on compost (16.5%), charcoal (18.1%), and charcoal plus compost treatments (17.4%) in comparison to mineral-fertilized plots (10.9%). One process in the increased retention of applied fertilizer N was found to be recycling of N taken up by the crop. Overall, results from this group demonstrate the potential of biochar applications to improve N input into agroecosystems, while pointing out the need for long-term field studies to better understand the effects of bio-char on nitrogen dynamics.

A pot trial was carried out to investigate the effect of biochar produced from greenwaste on the yield of radish in a hard-setting Chromosol (Alfisol) (*18*). Three rates of biochar (10, 50 and 100 t/ha) with and without additional nitrogen application (100 kg N/ha) were investigated. In the absence of N fertilizer, application of biochar to the soil did not increase radish yield even at the highest rate of 100 t/ha. However, a significant biochar-nitrogen fertilizer interaction was observed, in that higher yields were observed with increasing rates of biochar application in the presence of the N fertilizer. For instance, additional increase in dry matter of radish in the presence of N fertilizer varied from 95% in the nil biochar control to 266% in the 100 t/ha biochar-amended soils. The results of this trial contrast interestingly with the results of a similar trial utilizing biochars produced from poultry litter (*17*). In the latter study, two biochars produced from poultry litter under different conditions were tested in a pot trial with radish. Both poultry litter biochars produced increases in dry matter yield of radish without N fertilizer. The yield increase compared with the un-amended control rose from 42% at 10 t/ha to 96% at 50 t/ha of biochar application. The yield increases were attributed largely to the ability of the poultry litter biochars to increase N availability. Significant additional yield increases, in excess of that due to N fertilizer alone, were observed when N fertilizer was applied together with the biochars, highlighting the other beneficial effects of these biochars. These works emphasize the importance of feedstock and process conditions during pyrolysis on the properties and, hence, soil amendment values of biochars.

Soil Quality Changes In Biochar-Amended Soils

Charcoal has been argued to enhance soil physical properties, including soil water retention and aggregation, both of which may improve water availability to crops, as well as decrease erosion (*12*). Glaser et al (*23*) reported that charcoal-rich Anthrosols from the Amazon region, whose surface area was 3 times greater than that of surrounding soils, had 18% greater field capacity. In a much earlier study, Tyron (*24*) examined the effect of charcoal on percentage of available water in soils of different textures. In a sandy soil, there was a monotonic increase in the percentage of available moisture as a function of charcoal volumetric proportion, with an increase of about 6% in a soil amended with 15 volume % charcoal. The loamy soil showed no improvement in available moisture percentage under any amendment amount, while the available moisture percentage in the clay soil decreased by nearly 7% under a 15 volume % load of charcoal. Recent studies by Chan and colleagues (*17, 18*) reported a noteworthy improvement in texture and behavior of a hard-setting soil, with a significant reduction in tensile strength at higher rates of biochar application. Charcoal has also been reported to form complexes with minerals as a result of interactions between oxidized carboxylic acid groups at the surface of the charcoal particles and mineral grains (*12*), suggesting that charcoal amendments may improve in this way soil aggregate stability.

Important effects of charcoal on soil chemical properties have also been reported, most notably increases in pH (in acid soils), cation exchange capacity (CEC), base saturation and exchangeable bases, and organic carbon content, as well as decreases in Al saturation in acid soils (*12*). The pH of biochar depends on the pyrolysis temperature, increasing from a low of about 4 pH units to a pH of around 9 in the optimal biochar production temperature range of 400-550^{o}C (*7*). Applied to soils, there is ample evidence that biochar additions can increase the pH of amended soils by 0.4 to 1.2 pH units, with greater increases observed in sandy and loamy soils than in clayey soils (*24-26*). There is also evidence that charcoal additions to soil increase the amounts of exchangeable bases, the total N content, the available P, and the available K, Ca and Mg, with cation availability exceeding the CEC by a factor of 3 (*24*). This is apparently because cations contained in the ash portion of the charcoal are present as dissolvable salts, and therefore are readily available for plant uptake. On the basis of these results, Glaser et al. (*12*) conclude that the charcoal may be more than just a soil conditioner, but may act as a fertilizer itself, as seen also in the results of Chan et al.(*17*). Regarding this, Day et al. (*27*) suggested using biochar to scrub CO_2, SO_x, and NO_x from fossil-fuel power plant flue gases, and in the process, creating a slow release fertilizer which sequesters additional CO_2. In addition to the effect of biochar amendment on soil nutrient content, charcoal amendments have been reported to have a positive effect on nutrient retention, particularly in highly weathered soils with low ion-retention capacities (*12*).

Some of the positive agronomic and soil physical effects described above have been attributed to biochar promotion of mycorrhizal fungi, according to a comprehensive recent review (*28*). For example, it was reported that biochar applied at a rate of 800 g/m^3 to abandoned orchard soil resulted in an increase in mycorrhizae response of more than 600% (*29*), and a rate of biochar applied to soil at 1500 g/m^2 resulted in a 300% increase in mycorrhizae response in soybean fields (*30*). A few studies which reported decreases in mycorrhizal fungi upon biochar additions were attributed to nutrient limitations, and in particular, limitations in P availability in biochar-amended media (*28*). According to Warnock et al. (*28*), there are at least 4 mechanisms by which biochar can influence mycorrhizae abundance or activity in soils and plant roots: (i) by altering levels of nutrients or nutrient availability, or other soil physico-chemical characteristics that lead to changes in mycorrhizal response; (ii) by having beneficial or detrimental effects on other soil microbes, which cascade to effects on mycorrhizal response; (iii) by altering plant- mycorrhizal fungal signaling processes or allelochemical toxicity; and (iv) by providing a physical refuge for mycorrhizal fungi from hyphal grazers. Understanding the relative importance of any one of these mechanisms, or alternative ones, is in its infancy.

BIOCHAR FOR WASTE MANAGEMENT

The production of biochar from various waste streams (including biosolids such as sludge and manure) can mitigate many nuisances associated with those wastes, such as nitrogen and phosphorous run-off and leaching, odors and pathogens (*31*). Conventionally, energy recovery and nutrient reuse from biosolids has been achieved via anaerobic digestion/power generation with land application of the biosolids. By contrast, thermal processes such as pyrolysis have typically been used only for energy recovery. Bridle and Pritchard (*32*) showed that by treating biosolids with pyrolysis, all the energy in biosolids could be beneficially recovered and reused. Their results demonstrated that the phosphorus in the biosolids char was plant available, although the nitrogen was insoluble. Based on these results it appears that there is potential to use pyrolysis as an effective means to recover and reuse both the energy and the valuable phosphorus present in biosolids, without the odors and other negative connotations associated with biosolids direct application on land. Additional benefits of conversion of organic residues to biochar include the elimination of pathogens and the speciation of some heavy metal contaminants into forms with reduced levels of toxicity (*31*). Thus, the creation of energy from waste via pyrolysis also converts a nuisance into a renewable energy resource.

ENERGY RECOVERY FROM PYROLYSIS OF BIOMASS IN ISRAEL

Based on figures for energy and biochar production from fast pyrolysis of biomass at a temperature of 500°C given by Laird (*6*), enough bio-oil to displace $1.185 \cdot 10^6$ tons of fossil fuel oil per year could be generated from the total 5 million tons of organic residues available in Israel (*33*), representing 14% of Israel's yearly consumption of fossil fuel oil for the year 2006 ($8.31 \cdot 10^6$ tons; http://www.cbs.gov.il/energy/). According to data from the United Nations Statistics Division (http://indexmundi.com/israel/carbon-dioxide-emissions.html), CO_2 emissions from Israel in the year 2004 reached 71 Tg. Following the assumptions in Laird (*6*), the generation of biofuels and sequestering of biochar in the soil could maximally offset 1.185 Tg of fossil fuel emissions per year and sequester 0.63 Tg of C per year in the soil. Together these represent 8.5% of the average C emissions for Israel in the year 2004. More reasonable estimates for possible biomass utilization would be about 1/3 of these values (*33*). None of the estimates take into account biochar's potential to reduce N_2O and methane emissions from agriculture (*9*) or the possibility of using biochar as a scrubber for flue gases containing NO_X, SO_X and CO_2, followed by its application to the soil as a slow-release fertilizer (*27*).

POTENTIAL PITFALLS AND KNOWLEDGE GAPS IN THE USE OF BIOCHAR IN AGRICULTURE

Lehmann (*7*) discussed impediments to the adoption of biochar use in agriculture, first and foremost among them being the great variability in biochar characteristics as a function of feedstock and production conditions (such as temperature). Biochar produced at temperatures below 400°C may have low CEC and low surface area, making it less suitable as a soil conditioner than biochar produced between 400-550°C. Likewise, production conditions can have a dramatic effect on the stability of the char in the environment, affecting its utility as a long term carbon sink. The aging of biochar in soil tends to increase its CEC, but the factors involved in the development of CEC during aging are not well-defined. Understanding and optimizing these features require an organized research effort.

Additional aspects of biochar use in soil that need to be considered include the possible occurrence of phytotoxic compounds or leachable metals in the biochar (*31*). Levels of metal contaminants present in some feedstocks may limit the safe level of biochar application. For the most part, there is little information on contaminants present in different biochars, and more importantly, on their availability to plants and their potential for leaching to the environment. On the other hand, it should be borne in mind that carbon-based materials make excellent sorbents for many organic and inorganic pollutants, and the presence of biochar in a soil may help reduce pollutant leaching out of the soil zone.

A further challenge to the use of biochar in soil is the means of application (*31*), which will depend largely on the biochar physical properties and intended function. Tilling biochar into the soil can disturb soil structure and increase carbon turnover rates, as well as lead to dust and erosion problems. On the other hand, broadcasting the char on the soil surface may lead to runoff and erosion of the char, obviating its carbon sequestration potential.

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Session 5: Advances in Plant Sciences

HYDRAULIC CONDUCTANCE TRAIT TO IMPROVE CROP YIELD IN WATER-DEFICIT ENVIRONMENTS

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ABSTRACT

Since humans have been sowing seeds, a goal has often been to maximize yield for the water available. This paper reviews the factors that influence the relationship between yield and water use, and then examines a solution that might contribute to a modest yield increase on a fixed amount of water. The physics of gas exchange by leaves imposes a limit on the relationship between plant growth and transpiration water loss. Both water uptake by the plant to support transpiration and the water loss as driven by atmospheric vapor pressure deficit (VPD) play major roles in determining maximum crop yield in a given environment. There are no biological solutions to break this physical relationship no matter the sophistication of genetic approaches. However, there is the possibility to achieve modest yield increases by developing plants to minimize leaf gas exchange, i.e. transpiration and CO_2 assimilation, during periods when VPD is high. In recent studies, soybean genotype PI 416937 was found to not have continued increases in transpiration rate as VPD increased about 2 kPa. Rather, the stomata of this genotype closed at high VPD and maintained a constant transpiration rate. While stomata closure limits CO_2 assimilation, an important advantage is that soil water is conserved so that it is available later in the growing season for crop use when water-deficit conditions develop. The basis for this trait

was traced to a low hydraulic conductance in the leaves of PI 416937. Field tests with advanced breeding material and an environmental analysis have shown that this trait results in increased yield over a wide range of environments. Seeds of high-yielding genotypes with the water-saving trait are now being incorporated into most commercial breeding programs in the U.S.

BACKGROUND

Sufficient water to grow plants was likely a major concern soon after humans sowed the first seeds. Certainly a major factor in the development of early human civilizations was a need to organize people to manage water resources for crop production. With the advent of modern science one of the first experiments with plants was a set of observations on the ratio of plant growth to water use (Woodward, 1699). About one hundred years ago, there was tremendous activity world-wide to quantify the ratio. (Actually, these studies reported the ratio as the 'water requirement' defined as the inverse growth to water used.) Major projects were undertaken in U.S. in Nebraska by T.A. Kiesselbach (1910), in Wisconsin by F.H. King (1914), and in Colorado by L.J. Briggs and H.L. Shantz (1913, 1917). The results of these studies showed that water use by plants was very much environmental dependent and that there were differences among species. Indeed, Briggs and Shantz (1913) concluded that "The millet, sorghum, and corn groups have been found the most efficient, while alfalfa and sweet clover are least efficient in producing dry matter with a given amount of water. The small-grain crops have a water requirement intermediate between the legumes and corn." These conclusions were confirmed in deWit's 1958 classical analysis of much of this early data on crop water use. He found that the ratio of plant growth (G) to transpired water loss (T), i.e. transpiration water use efficiency, was closely defined over a wide range of conditions by the following simple equation.

$$G / T = m / E_o \,, \qquad \textbf{(1)}$$

where m = an empirical coefficient and E_o is atmospheric water demand, usually measured using an open pot of water. The value of m varied among species exactly as concluded by Briggs and Shantz (1913).

Tanner and Sinclair (1983) moved Eqn [1] from an empirical relationship to a mechanistic one. Their theoretically derived relationship follows.

$$G / T = k / VPD \qquad \textbf{(2)}$$

where VPD is atmospheric vapor pressure deficit and k defined below.

$$k = b\, c\, (P\, Ca / 1.5\, \rho\, \varepsilon\, (L_d / L_T) \quad .$$

All variables defining k are essentially constant except for b and c. The variable b describes the conversion coefficient of photosynthate to plant components and is primarily dependent of the carbohydrate, protein, and lipid composition of the plant products. The variable c depends on whether a plant species has the precursor organic acid pathway (C4) in photosynthesis. Unless stomata regulation is by internal leaf CO_2, the values of c have maximum values of about 0.3 for C3 species and 0.7 for C4 species. Based both on theoretical and experimental analyses, the value of k is essentially constant for any given plant species. As examples, the value of k for the C4 grasses is 9 Pa, for C3 grasses is 6 Pa, and for legumes is 5 Pa. These values are exactly consistent with the conclusions of Briggs and Shantz (1913) and deWit (1958).

YIELD AND WATER

The limit to plant mass production based on water availability for plant use in transpiration is readily defined by rearranging Eqn [2].

$$G \leq T\, k / VPD \qquad \textbf{(3)}$$

Eqn [3] shows clearly that plant mass is linearly dependent on the amount of water a plant can uptake for transpiration. Also, this equation illustrated the critical role that atmospheric VPD plays in limiting yield. In dry climates with elevated VPD, the growth of the plants is necessarily limited to a lower level. For example, the graph below shows the change in rainfall and VPD in going from west to east in the Great Plains state of Nebraska (Fig. 1). Not only does the western side of the state suffer from low rainfall, but the high VPD further decreases potential plant growth.

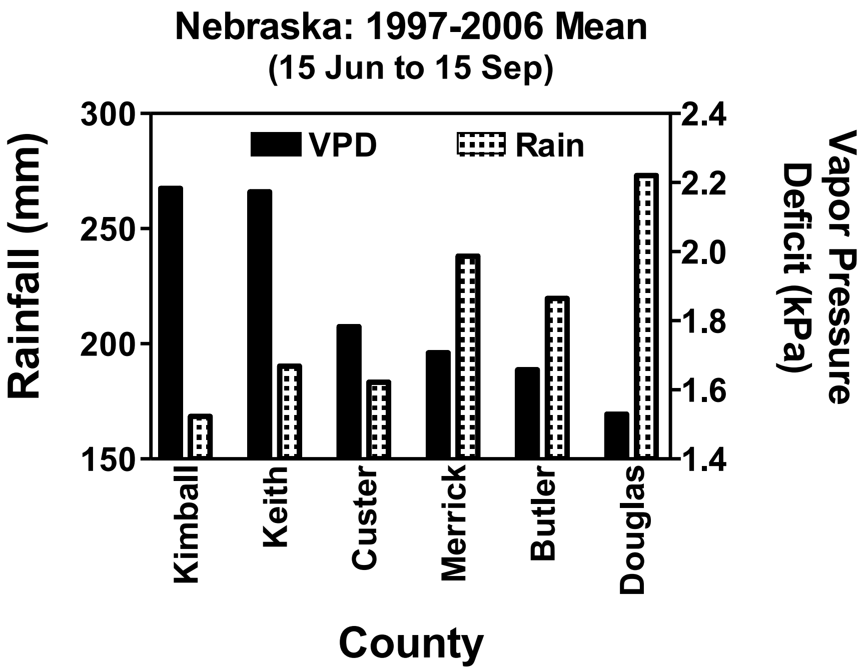

Figure 1: Rainfall and vapor pressure deficit during summer growing season in six counties in the state of Nebraska, going west (left side) to east (right side).

Eqn [3] can be expanded to define the limits on yield (Y) when only parts of the plant are harvested. For grain crops, harvest index (HI) is the ratio of grain yield to total plant yield that can be used to calculate limits on harvested yield.

$$Y = HI\ G < HI\ T\ k / VPD \quad \textbf{(4)}$$

For most drought situations that are relevant in agriculture, advanced cultivars have HI's that are nearly insensitive to water-deficit condition. In those species that have HI sensitive to water-deficit, such as rice, yield progress is possible by seeking genotypes that have stability in HI.

The dependence of yield on the environment can be readily envisioned from a graph based on Eqn [4]. Yield limitation is linearly related to water availability and inversely related to VPD. Since this is a physical relationship, altering this limitation is not amenable to genetic alteration of the plant. Under conditions of low water availability, there is a hard limit to maximum crop yield (Fig. 2).

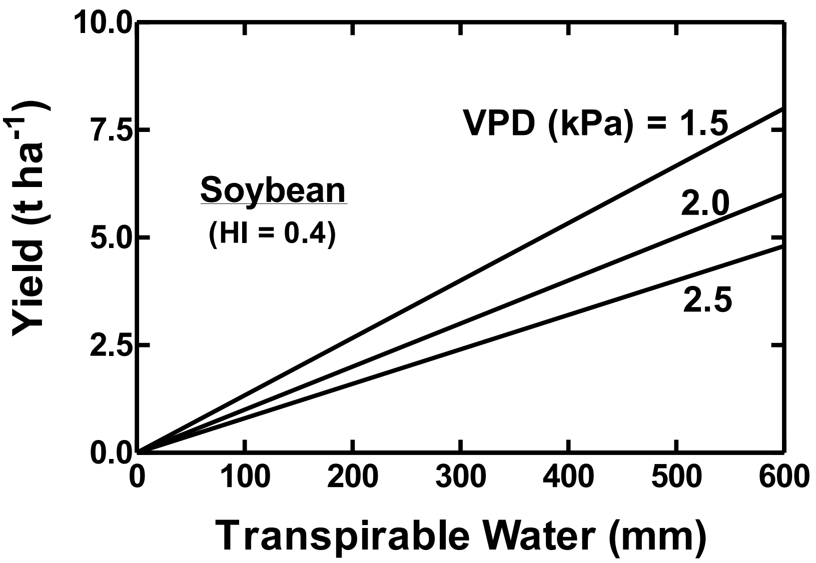

Figure 2: Maximum soybean yield under various vapor pressure deficit environments as a function of transpirable soil water .

As is clear in Fig. 2, any important management approaches that increase the amount of water available to plants for uptake to increase T will increase the limit on yield. Genetic improvements that allow roots to access more water in the soil, e.g., deep rooting, will raise the limit on yield. Nevertheless, under water-deficit conditions yield will be constrained and no genetic manipulations --no matter how sophisticated-- will break the limit defined in Equation [4].

One alternative that often does not enter the discussion of increasing crop yields in water-limited environment is the variable VPD. Of course, a key factor in the growth of many small grains is their ability to grow in cooler seasons of the year when by definition VPD is lower. Therefore selection of cool-tolerant genetic material is an option for increasing crop yields in some water-deficit environments.

While the value of VPD is an environmental factor beyond biological control, we have become interested in the possibility of plants reacting to VPD so the effective VPD for transpiration is decreased. This can be achieved by decreasing plant gas exchange when VPD is high so that the fraction of total plant gas exchange that occurs is shifted to a lower average VPD. The observable consequences of such a strategy would be midday stomata closure. Another benefit in addition to increase Y/T would be the resulting soil water conservation that could be used later in the season to sustain crop growth during late-season periods of water deficit. We have become active in the regulation of crop gas exchange as a result of sensitivity to VPD.

TRANSPIRATION REGULATION BY PLANT HYDRAULICS

Passioura (1980) proposed to limit wheat transpiration by selecting genotypes with small diameter xylem elements resulting in decreased hydraulic conductance. Success was achieved in identifying genotypes with small diameter elements that conserved soil water, this trait was never advanced for use in commercial germplasm. A possible limitation of this anatomical approach to decreased hydraulic conductance is that it might result in limited transpiration and CO_2 assimilation under a range of conditions.

We began our studies to identify possible hydraulic regulation of transpiration by investigating the soybean genotype PI 416937, which expresses delayed wilting under water-deficit conditions in the field. We hypothesized that the delayed wilting phenotype was a cause of soil water conservation resulting from lower stomata conductance. The first step in our investigation was to examine the response of T to increasing VPD around the shoot. A system was developed that allowed 12 plants to be exposed to a range of VPD during a single experiment. While T at low VPD of PI 416937 was the same as other cultivars, the results were quite different at high VPD (Fletcher et al., 2007). In contrast to other genotypes in which T increased linearly over the whole range of tested VPD, in PI 416937 there was a breakpoint at about 2 kPa above which there was little further increase in T (Fig. 3).

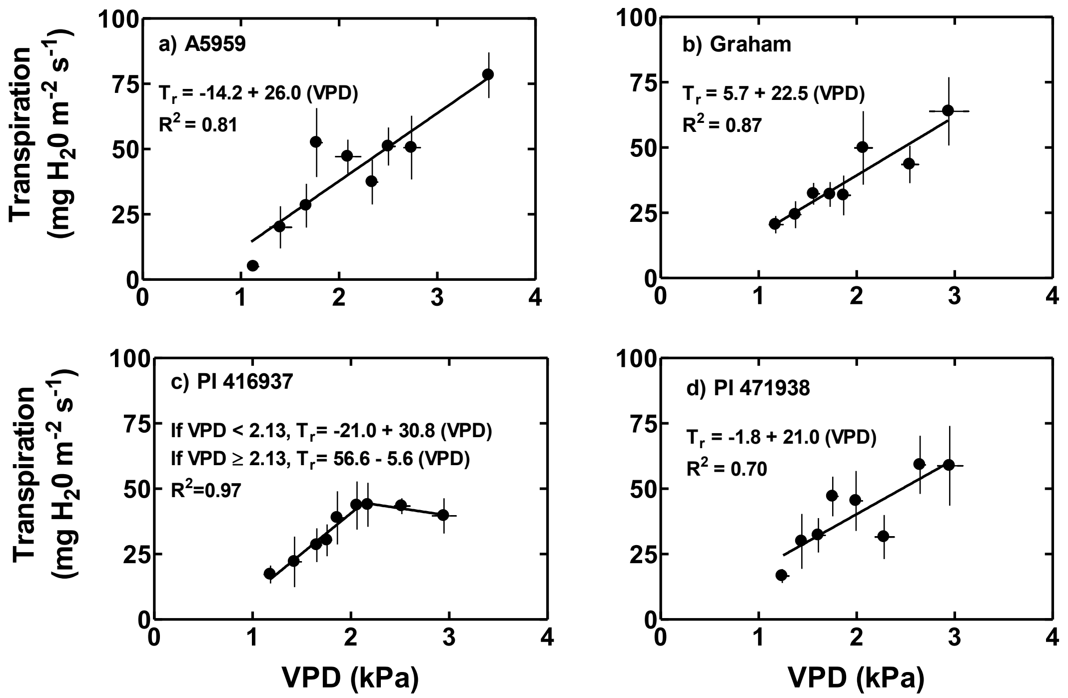

Figure 3: Transpiration rate of four soybean genotypes over a range of vapor pressure deficits (Fletcher et al., 2007).

Constant T at VPD greater than 2 kPa might result from a limiting hydraulic conductance in the plant that could not supply water to the stomata guard cells at a sufficient rate to sustain their water loss rate at high VPD. To examine the possibility of a hydraulic limitation in PI 416937, an experiment was done to examine the VPD response when possible hydraulic limitations in the roots and shoot were overcome. In this experiment, pots of soybean plants were sealed in a pressure chamber and pressure was applied so that the xylem potential in the leaf petiole was zero. A pressure transducer was attached to a petiole so that the pressure around the pots was continuously adjusted no matter the VPD treatment so that the leaf xylem potential was maintained at zero. Surprisingly, the response of the plant to VPD was unchanged even though any possible limitation by root and shoot hydraulic conductance was overridden (Fig. 3) (Sinclair et al., 2008). These results were interpreted to indicate if there was a hydraulic limitation it had to exist in the leaves between the petiole xylem and the guard cells.

To resolve the hypothesis that PI 416937 might have an unusually low hydraulic conductance in the leaf, two experiments were undertaken (Sinclair et al., 2008). The first experiment was simply to cut the petioles of leaves underwater of intact leaves and track their gas exchange over time. The concept is that the surge of water into the leaves on cutting would result in a rapid closure of stomata because of the mechanical advantage of the epidermal cells surrounding the guard cells. Indeed, the petiole-cutting experiment resulted in the initiation of rapid stomata closure in control soybean genotypes (Fig. 5). On the other hand, the initiation of stomatal closure in PI 416937 was delayed and the rate of closure was less than the other genotypes. These results incidated a lower hydraulic conductance in the leaves of PI 416937.

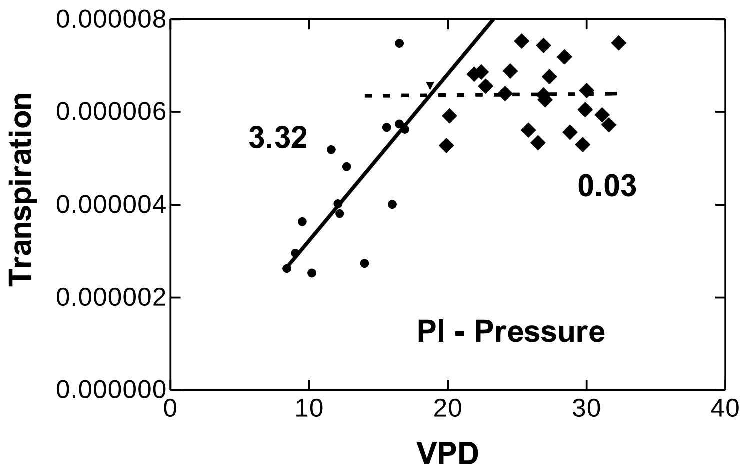

Figure 4: Transpiration rate vs. vapor pressure deficit for PI 416937 when leaf xylem was maintained at zero potential by encasing pots in a pressure chamber (Sinclair et al., 2008).

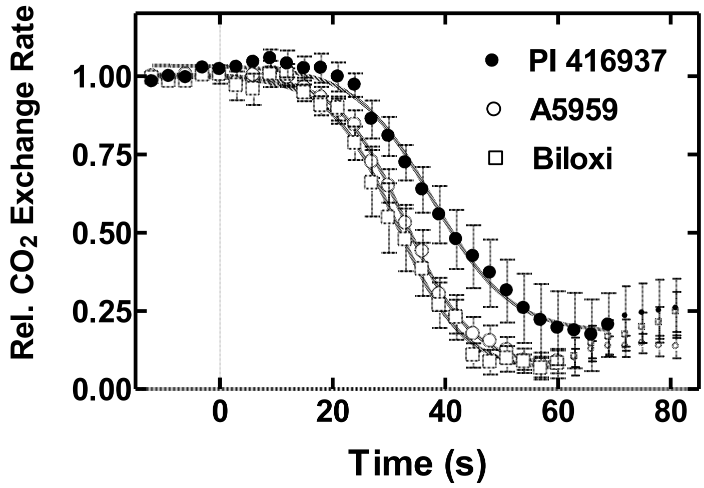

Figure 5: Carbon dioxide assimilation following cutting of petiole under water at time zero (Sinclair et al., 2008).

In the second experiment, petioles of slightly dehydrated leaves were cut and immediately connected to a water source. The rate of water flow into the leaves was measured. The time constant for flow into PI 416937 was much less than of the other cultivars again indicating a hydraulic limitation in the leaves (Fig. 6).

On-going experiments are attempting to examine the basis for the apparently lower leaf hydraulic conductance in PI 416937. Results to date do not show any obvious, consistent anatomical difference in the leaves of PI 416937 as compared to other soybean lines. Studies are now being undertaken to determine if the aquaporin population or activity in the hydraulic pathway in leaves account for the apparent unusually low leaf hydraulic conductance in PI 416937.

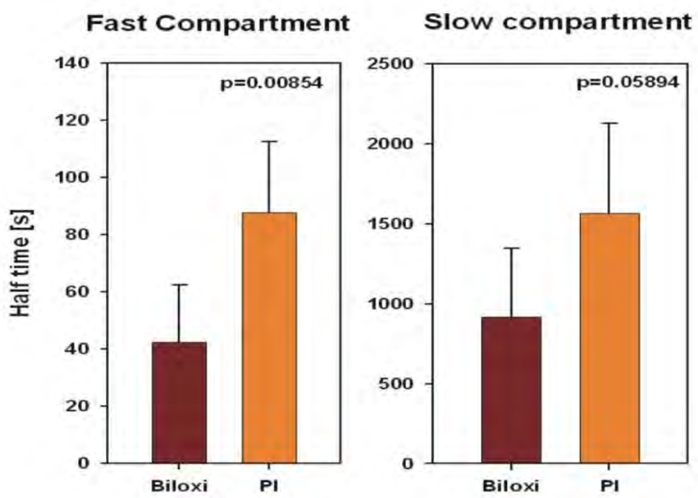

Figure 6:

Half life for water movement into slightly dehydrated leaves after petioles were cut under water (Sinclair et al., 2008).

YIELD AND TRANSPIRATION REGULATION

The association of low leaf hydraulic conductance in PI 416937 with the unusual response to VPD and to the delayed wilting phenotype is intriguing. However, it is unknown whether this trait that would increase Y/T and conserve soil water would actually contribute to yield increase in the field. The beneficial side of this trait is offset by the loss of CO_2 assimilation at all the times when VPD exceeds to 2 kPa. If no period of water deficit develops later in the season when the conserved soil water could be used to advantage, then a yield loss could be predicted from this trait. Fortunately, Dr. Tommy Carter (ARS-USDA, Raleigh, NC) initiated a breeding effort to transfer the delayed-wilting phenotype into high yield soybean lines. To date, Dr. Carter has tested two lines that have consistently greater yields than high yielding commercial cultivars in water-deficit conditions. At high yield levels, the yields of these two delayed-wilting phenotypes appears to have little or no decrease in yield compared to the high yielding commercial lines. These two lines are now freely available to private, commercial soybean breeders in the U.S. for use in their breeding programs.

There remain questions about where and how often could soybean producers expect a yield gain from commercial cultivars with the delayed-wilting trait. We are involved in a cooperative environment analysis with Pioneer Hi-bred Seed company (Charlie Messina, Johnson, IA) to resolve these questions. Pioneer has developed a GIS data base for the entire U.S. crop areas by dividing the country into 2800 grids of 30 km x 30 km dimension. At least a 50 year weather data base has been developed for each grid. The weather data set was used to simulate soybean yield in each year using a relatively simple, mechanistic model of soybean development, growth, and yield. The model simulated growth, crop water loss rate, and soil water balance on one-hour time steps. First, yield of a 'normal' soybean crop was simulated in each of the 50 years for each grid (>140,00 simulation runs). The simulations were then repeated with adjustments in the model to maintain a constant maximum transpiration rate and CO_2 assimilation rate at any time step when VPD exceeded 2 kPa. Surprisingly, the trait proved to increase yields in nearly all regions of the U.S. in more than 75% of the years. While the trait for sensitivity to VPD as a result of the apparent low leaf hydraulic conductivity is especially useful in some regions, these results indicate that it might be acceptable in all regions of the U.S. Even in those years when the trait was simulated to result in yield loss, the yield decrease was usually quite small. Soybean producers will have the information to make risk decisions about the possibility of yield increase in most years at the price of small yield decreases in the wettest years. The enthusiasm of incorporation of the delayed-wilting trait in commercial breeding program makes it seem likely that soybean cultivars across the U.S. will be producing modest yield increases as a result of what appears to be decreased hydraulic conductance in their leaves

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THE TONOPLAST ROLE IN REGULATING PLANT STRESS TOLERANCE AND YIELD PRODUCTION

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ABSTRACT

Anisohydric plants are thought to be more drought tolerant than isohydric plants. However, the molecular mechanism determining whether the plant water potential during the day remains constant or not regardless of the evaporative demand (isohydric vs. anisohydric plant) is not known.

Here, it was hypothesized that aquaporins take part in this molecular mechanism determining the plant isohydric threshold. Using computational mining, tonoplast intrinsic protein 2;2 (SlTIP2;2), a key tonoplast aquaporin, was selected within the large multifunctional gene family of tomato (*Solanum lycopersicum*) aquaporins, based on its induction in response to abiotic stresses. SlTIP2;2-transformed plants (TOM-SlTIP2;2) were compared with controls in physiological assays at cellular and whole-plant levels.

Constitutive expression of SlTIP2*;2* increased the osmotic water permeability of the cell and whole-plant transpiration. Under drought, these plants transpired more and for longer periods than control plants, reaching a lower relative water content, a behavior characterizing anisohydric plants. In 3-year consecutive commercial glasshouse trials, TOM-SlTIP2;2 showed significant increases in fruit yield, harvest index and plant mass relative to the control, under both normal and water-stress conditions.

In conclusion, it is proposed that the regulation mechanism controlling tonoplast water permeability might have a role in determining the whole-plant ishohydric threshold, and thus its abiotic stress tolerance.

INTRODUCTION

The global shortage of fresh water is one of the most severe agricultural problems affecting plant growth and crop yield (Toenniessen *et al.*, 2003). Studies in recent years have identified a large number of genetic and molecular networks underlying plant adaptation to adverse environmental growth conditions (Sreenivasulu *et al.*, 2007). All of these studies emphasize the complexity of the different traits and their polygenic nature. The current notion is that plants' defense mechanisms against stress conditions are tightly associated with their growth habits, and hence, every claim of tolerance enhancement needs to be tested on a crop-yield basis, coupled with its economic significance from an agricultural point of view. However, despite the large number of attempts to improve abiotic-stress tolerance of commercial crop plants through genetic engineering, no major progress has been made (Flowers, 2004; Passioura, 2007).

A number of previous studies have reported the regulatory role of aquaporins (AQPs) in cellular water transport (Chrispeels & Maurel, 1994; Knepper, 1994; Heymann & Engel, 1999; Aharon *et al.*, 2003). AQPs are considered to be the main channels for the transport of water, as well as small neutral solutes and CO_2, through the plant cell membrane (Tyerman *et al.*, 2002; Uehlein *et al.*, 2003). The total number of AQP members in plants, as compared to animals, appears to be surprisingly high, with 35 AQP genes identified in the Arabidopsis genome (Johanson *et al.*, 2001; Quigley *et al.*, 2002; Boursiac *et al.*, 2005), 36 in maize (Chaumont *et al.*, 2001) and 33 in rice (Sakurai *et al.*, 2005). The expression of AQP genes in plants is differentially regulated not only in various tissues, but also under different physiological states and various environmental conditions (Alexandersson *et al.*, 2005; Boursiac *et al.*, 2005).

In spite of their role in controlling cellular water permeability, AQPs were never mentioned, to the best of our knowledge, in the context of partitioning plants between isohydric and anisohydric groups. Isohydric plants differ from anisohydric plants in that the first maintain a constant water potential during the day regardless of the environmental conditions, while the latter decrease their water potential with the evaporative demand during the day, permitting a lower water potential in drought relative to watered plants (Tardieu & Simonneau, 1998). Anisohydric plants are considered more tolerant to drought then isohydric plants (McDowell *et al.*, 2008).

Even though AQPs are considered to play a key regulatory role in water transport, attempts to utilize them to improve crop tolerance to abiotic stresses have yielded contradictory results (Lian et al., 2004; Aharon et al., 2003; Lin et al., 2007; Peng et al., 2007). Thus, the overexpression of different individual AQPs might have opposite outcomes with respect to the whole plant's response to abiotic stresses, emphasizing the importance of accurately selecting the right candidate AQP genes from this large and functionally variable family to improve plant response to various stresses. In this study, by using a biologically driven computational approach, we identified a candidate AQP gene member, out of the family of 37 AQPs found in tomato (Solanum lycopersicum), which improved plant tolerance to water stress in terms of growth and other yield-related parameters. In contrast to previous studies that selected mostly plasma membrane- localized aquaporins as potential candidates to improve plant abiotic stress tolerance, apparently based on educated guesses, we selected a tonoplast-localized aquaporin gene isoform named SlTIP2;2 using a skilled computational program. We demonstrated that tomato plants overexpressing SlTIP2;2 adjusted their whole-plant transpiration regulation and relative water content under different conditions. These findings in addition to the fact that TOM-SlTIP2;2 plants showed significant increases in fruit yield supports the hypothesis that the constitutive expression of SlTIP2;2 might convert tomato from isohydric growth behavior to the drought tolerant anisohydric growth manner.

MATERIALS AND METHODS

Data Base Assembly and Mining

For gene discovery and data-mining, we used bioinformatics filtering approach as widely described by Sade et al. (2009).

Phylogenetic Analysis and AQP Naming

The ORFs of all 37 tomato AQP clusters were translated to amino-acid sequences (using the EXPASy translation tool; http://www.expasy.ch) which were aligned together with *A. thaliana*'s 35 AQPs (TIPs, PIPs, NIPs and SIPs from SwissProt; using ClustalX 1.8). The tomato AQP names were given based on similarity to known Arabidopsis AQPs. Drawing and analysis of the phylogenetic tree was accomplished using TreeIllustrator software (http://nexus.ugent.be/geert/).

Generation of Transgenic Tomato Plants

SlTIP2;2 cDNA was isolated from tomato (*Solanum lycopersicum*) seedlings and subcloned into the pPI binary vector. Miniature tomato lines (MicroTom) were genetically transformed using disarmed *Agrobacterium tumefaciens* transformation methods. Transgenic MicroTom tomato plants over expressing the *SlTIP2;2* gene were cross-pollinated with commercial variety M82 plants.

Salt- and Water-deficiency Stress Field Trial

All field trials were performed in a light soil, in an open field (net-house). In each trial different irrigation systems were established: a normal water regime, a continuous irrigation with saline water (addition of 180 to 200 mM NaCl) and different water levels and intervals (WLI-0, WLI-1, WLI-2,). WLI-0 treatment (control) received the recommended total weekly irrigation volume divided into three irrigations. In the WLI-1 treatment, irrigation was performed three times a week, but the amount of water supplied was half that supplied to WLI-0. At the end of every week, WLI-1 plants received the amount of water required to reach maximum soil water capacity.

WLI-2 plants were irrigated only once a week until soil saturation levels were achieved. At the stage of about 80% red fruits *in planta*, fruit yield, plant fresh weight, and harvest index were calculated. Harvest index was calculated as yield/plant biomass.

Transient Expression and Sub-cellular Localization of SlTIP2;2 in Arabidopsis Protoplasts

Protoplasts were isolated from Arabidopsis leaf mesophyll and the chimer GFP::SlTIP2;2 was transiently expressed using PEG transformation method (Locatelli *et al.*, 2003). Protoplasts transiently expressing cytosolic GFP were used as control. Imaging of GFP was taken using fully motorized Epi-fluorescence inverted microscope (Olypmus- IX8 Cell-R, Japan). All images were processed using Olympus imaging software Cell-R for Windows.

Osmotic Water Permeability Coefficient (P_f) Measurements

P_f was measured from the initial (videotaped) rate of volume increase in a single protoplast in response to hypotonic solution. The P_f was determined by a numerical approach (off-line curve-fitting procedure using several algorithms), which has been proven to yield accurate

P_f values over a large span of water-permeability values. The analyses were performed with a "***P_fFit*** program" incorporating these equations, as described in detail previously(Moshelion et al., 2002; Moshelion et al., 2004; Volkov et al., 2007).

Whole Plant Transpiration Measurements

Tom-SlTIP2;2 and control plants were grown in 3.9-liter pots and the whole plant transpiration and transpiration rate were measured as described by Sade et al. (2009). All plants were treated in 3 different irrigation conditions (normal, saline and drought) as described by Sade et al. (2009).

Relative Water Content

Leaf relative water content was measured in control and Tom- SlTIP2;2 plants as described by Peng et al. (2007).

Statistical Analysis

Student's t-test was used for comparison of means, which were deemed significantly different at $P < 0.05$.

RESULTS

Transcriptome identification of tomato AQPs

The contradictory reports regarding the contribution of different plant AQP isoforms to the resistance of plants to abiotic stresses, together with the large size and diverse functions of this family in regulating plant water homeostasis, renders the AQP family as a good model for selection of suitable candidate genes to improve stress-associated traits in crop plants. We have chosen to focus on AQP from tomato plants due to: (i) the relatively high tolerance of this crop species to salt stress; (ii) the availability of well defined yield parameters for this species; and (iii) the availability of relevant genomic databases. In this study, we analyzed the transcript expression level of different tomato AQP genes by digital gene-expression analysis (also known as electronic Northern blot). Upon mining the database of tomato AQP gene sequences, we identified 37 different AQP genes. To the best of our knowledge, this is the largest AQP gene family detected in any single species tested to date. A comprehensive phylogenetic analysis was conducted to establish groups of homology within the tomato AQP gene family. The 37 AQPs were classified into 18 PIP, 9 TIP, 6 NIP, and 3 SIP isoforms. We also identified a new AQP member with high similarity to the novel plant AQP subfamily XPIP recently reported in poplar (Danielson & Johanson, 2008), and named it Solanum lycopersicum XIP.

Next, we used our computational approach to select AQP genes that are overrepresented in various abiotic stresses, such as nutrient deficiency, heat, salinity and heavy metal stresses, as well as biotic stresses, such as application of elicitors and pathogens, considering the possible strong overlap in the expression pattern of AQP genes under many abiotic and biotic stresses. Among all the AQP genes analyzed, SlTIP2;2 was the only one that is highly expressed in roots as well as under both biotic and abiotic stresses. Thus, we selected to test in field trials the effect of overexpression of this tonoplast AQP gene isoform on stress tolerance and yield parameters under favorable growth conditions and under salt and drought stresses.

Transgenic Tomato Plants Expressing SlTIP2;2 Show Improved Tolerance to Salt and Water Stresses under Field Conditions

Transgenic tomato genotypes over expressing SlTIP2;2 (Tom-SlTIP2;2 plants) were evaluated for their tolerance to water deficiency (a single field trial including two different water-limiting regimes) and salt stress (two different field trials) in respect to plant vigor and yield parameters. Tom-SlTIP2;2 plants appeared on average to be more vigorous than the control plants in both field trials, as determined by their big size and less severe symptoms of leaf and shoot necrosis and also accumulated higher fruit yield than the controls.Under water deficiency stresses, Tom-SlTIP2;2 plants developed significantly higher (26%) plant biomass than the control plants and this was also associated with a significant, up to 21%, increment of fruit yield under both a relatively mild (WLI-1) and a more severe (WLI-2) regimen of water deficiency stresses (see details in M&M). In addition, the harvest index of the Tom-SlTIP2;2 plants was significantly higher (20%) than that of controls under mild water stress (WLI-1) and remained similar to that of control plants under more severe drought stress (WLI-2).

All in all, the results from the three field trials imply that over-expression of SlTIP2;2 improves yield parameters when compared to controls, under both favorable growth conditions and exposure to salt and drought stresses.

Subcellular Localization of SlTIP2;2

Based on its amino acid sequence, SlTIP2;2 is predicted to be a tonoplast aquaporin. We thus wished to confirm this prediction by transient expression of a chimeric GFP::SlTIP2;2 fusion protein in Arabidopsis mesophyll protoplasts. Pinpointing the location of any tonoplast protein is a tricky task, as the vacuole takes up more than 90% of the cell volume, surrounded by many organelles and often touching the plasma membrane (PM). Our approach here was to use the chloroplasts as a cytoplasmic 'data-point' separating the PM from the tonoplast. The relatively large-sized chloroplasts which were very densely packed in the cytoplasm and emitted red autofluorescence were surrounded by cytosolic GFP, as expected, and located above the green fluorescent signal coming from the GFP::SlTIP2;2, thus, strongly indicating its vacuolar localization. In addition, we extracted vacuoles of cells expressing GFP::SlTIP2;2 and detected the GFP-labeled aquaporin only in the tonoplast while no traces of GFP were detectable in the cell debris.

SlTIP2;2 Increases Cell Water Permeability

Taking into account the major effect of over expression of SlTIP2;2 in respect to tomato yield parameters under normal growth conditions as well as drought and salt stresses, we were further interested to unravel the mechanism through which SlTIP2;2 AQP exerts its cellular physiological effects. To address this issue, we measured the impact of SlTIP2;2 on the osmotic water-permeability coefficient (P_f) of isolated plant cells, using Arabidopsis as a model system. By a cell-swelling assay, we measured the P_f value of Arabidopsis mesophyll cells transiently expressing *GFP::*SlTIP2;2. Notably, the SlTIP2;2 expressing cells revealed significantly higher P_f values than control cells, indicating that *Sl*TIP2;2 indeed functions as a water channel.These results suggested a regulatory role of SlTIP2;2 in cellular water homeostasis regulation.

Tom-SlTIP2;2 Plants Revealed an Anisohydric Behavior of Increasing Their Transpiration Performance up until Turgor Loss

To further understand the impact of this regulatory function on a whole plant's water balance, we measured the whole-plant transpiration rate under favorable growth conditions as well as under salt and water stresses. Transpiration rates, as well as relative transpiration levels of Tom-SlTIP2;2-transgenic plants were significantly higher than those of control plants under normal growth conditions, on the 1^{st} and 3^{rd} days after the application of 100 mM NaCl, and upon subsequent first day recovery from this salt stress. Despite the fact that transpiration levels of all plants were dramatically decreased by the water stress treatment, the relative transpiration level of Tom-SlTIP2;2 plants remained significantly higher than that of the control plants up to the point of leaf turgor loss, where it became similar to the control plants and recovered to a comparable level like control plants. Moreover, the significantly larger stomatal aperture in Tom-SlTIP2;2 vs. control plants (see Sade et al.,2009) most probably accounted for the higher transpiration levels of Tom-SlTIP2;2 plants. This higher and prolonged water loss behavior, resulted in lower relative water content of TOM-SlTIP2;2, compared to control plants subjected to drought stress.

DISCUSSION

The growing world-wide limitations in fresh water and high-quality soils are becoming two major humanitarian and economical factors that limit crop yield (Toenniessen et al., 2003), motivating both conventional breeders and seed companies to maximize plant yield potentials under a wide range of sub-optimal environmental conditions. Many abiotic stresses, such as soil salinity and drought, cause rapid decreases in plant hydraulic conductance (Steudle, 2000; Boursiac *et al.*, 2005), resulting in stomatal closure, thereby reducing transpiration. Unfortunately, this process also causes a reduction in photosynthesis, plant growth and yield. It has also been strongly suggested that salt and drought stresses predominantly affect CO_2 diffusion in the leaves, via a decrease in stomatal and mesophyll conductance, rather than the biochemical CO_2-assimilation capacity (Flexas et al., 2004). Anisohydric plants, which regulate this mechanism differently than isohydric plants, are considered more tolerant to drought than isohydric plants (McDowell et al., 2008). In this study, we hypothesized that specific aquaporins, which take part in the plant water balance regulation, might also have a regulatory role in determining the plant isohydric behavior, and hence could be used to convert an isohydric plant to a more tolerant- anisohydric plant. As the selection of suitable AQP candidates to improve stress tolerance was not easy due to the large size of this gene family, we used a computational mining process focusing on expression patterns of different isoforms of the AQP gene family. As opposed to many previous trials to select suitable AQP candidates to improve plant drought and salt tolerance that were unsuccessful, our success in selecting an AQP isoform that did improve the tolerance of tomato plants to drought and salt stress under field conditions illustrates the strength of the computational system applied. In addition, our results show that manipulation of AQP function on the vacuolar tonoplast membrane is of central importance to improve water homeostasis as well as salt and drought tolerance under field conditions.

Our results suggest that SlTIP2;2 regulates cell water permeability, and most probably does not participate in other putative stress resistance mechanisms, such as absorption of Na^+ ions to the vacuole or regulating the plant osmoticum (Yamaguchi & Blumwald, 2005; Sade et al., 2009).

Our results also show that SlTIP2;2 expression exerts multiple functions, increasing transpiration under normal growth conditions, limiting the reduction in transpiration under drought and salt stresses, and also speeding up the revival of transpiration upon recovery from these stresses. Nevertheless, under prolonged dehydration stress, Tom-SlTIP2;2 plants did not lose their ability to significantly reduce transpiration. The characteristics exerted by over expression of the TIP isoform SlTIP2;2 do not appear to exist in many of PIP-overexpressing plants. In fact, PIP over expression seems to induce deleterious effects in response to water-deficiency stress (Aharon et al., 2003). The mechanism underlying the differential effects of TIP and PIP overexpression on salt and drought tolerance is still unknown. However, it is likely related to the fact that the vacuole is by far the largest organelle in the adult plant cell, comprising up to 95% if its volume. The water permeability of the tonoplast is known to be much higher than that of the plasma membrane and is considered a means of improving the vacuole osmotic buffering capacity of the cytoplasm (Tyerman et al., 1997; Morillon & Lassalles, 1999). Under stress conditions, tonoplast water permeability appears to be reduced (Vera-Estrella et al., 2004).

In conclusion, we propose that overexpressing the tonoplast AQP SlTIP2;2 can bypass the stress-induced down-regulation of the tonoplast's endogenous aquaporins, and thus prevent the slowdown of osmotic water permeability into the vacuole. The high water permeability of the tonoplast extends the vacuole's capacity for osmotic buffering of the cytoplasm under stress conditions, allowing the leaf to attain lower water potential (Sade et al., 2009; Peng et al., 2007) and preserving the water potential of the cytoplasm at the same level. This constitutes, in fact, a conversion of the tomato plants from isohydric behavior to an anisohydric one. In other words, overexpressing the tonoplast aquaporin extends the ability of the plant to maintain relatively normal physiological functions and also growth and yield production - even under relatively severe stress conditions. Thus, our results support the hypothesis stating that "isohydric and anisohydric water potential regulation may partition species between survival and mortality" (McDowell et al., 2008). The benefit of maintaining a certain level of transpiration during stress, as opposed to a complete shutdown of transpiration, ensures not only continuous CO_2 uptake, but also a continued supply of nutrients and a reduction in leaf temperature, promoting plant growth (Idso *et al.*, 1987). This offers a new approach for biotechnological application in various agricultural crops exposed to different environmental stresses.

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THE PATTERNS OF SYNCHRONIZED PHYSIOLOGICALLY-INDUCED OSCILLATIONS IN WHOLE-PLANT TRANSPIRATION AND THEIR ROLE UNDER DROUGHT CONDITIONS

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ABSTRACT

Oscillations in stomatal aperture have been measured for single and groups of stomata, and whole leaves. Here, we report on synchronized oscillations in whole-plant transpiration (WPT) rate and speculate upon their role in maintaining xylem water homeostasis and tension control. Synchronized oscillations in WPT rate were derived from frequent undisturbed measurement of potted plants' weight decrease with time by time-series analysis methods. These oscillations were quantitatively compared to simultaneous fluctuations in ambient conditions by cross-correlation function. Under high water availability, oscillations of WPT rate for tomato were partially self-regulated. As the soil progressively dried, the gradual decrease in transpiration rate of tomato plants was accompanied by an increase in self-regulated oscillations and changes in pattern. The switch from ambient condition-regulated to self-regulated oscillations in WPT rate as water stress increases indicates that the oscillations prevent xylem water tension from reaching levels at which cavitation can form or maintain xylem tension below a threshold value to impede runaway cavitation.

INTRODUCTION

Stomata play a critical role in regulating water loss from plants. Though the mechanism of stomatal regulation has been widely investigated, it is not yet fully understood. Stomata appear to respond to perturbations by many soil-plant-atmosphere signals but there is little agreement regarding the mechanism(s) by which stomata sense and react to such perturbations (Buckley, 2005). Stomata regulate diffusive conductance in leaves, and thereby influence water loss and carbon gain.

Oscillatory patterns in transpiration —rhythmic fluctuations in transpiration rate— have been attributed to cyclic opening and closure of stomata (Barrs, 1971). Oscillations have been observed by different methods and in different plant species and have been found to occur on different scales: at the cellular level, in "patches" of stomata, and in whole leaves (Barrs, 1971; Siebke & Weis, 1995; Mott & Buckley, 2000; West *et al.*, 2005). Previous measurements have shown that when the periodic variations in transpiration are plotted against time, a sine wave with a period of 10 to 90 min is obtained (Barrs & Klepper, 1968; Cox, 1968; Barrs, 1971; Teoh & Palmer, 1971).

Traditionally, two approaches have been used to study the effect of environmental conditions on oscillatory transpiration. The first involves looking at variations in transpiration rate of a small part of, or the whole leaf. The second focuses on the behavior of individual stomata. Adopting the first approach, Ehrler *et al.* (1965), Barrs & Klepper (1968), Lang *et al.* (1969), Cardon *et al.* (1994), Naidoo & von Willert (1994), Herppich & von Willert (1995), Jarvis *et al.* (1999), and Prytz *et al.* (2003) studied oscillations in whole leaves from a large variety of species, most often using gas-exchange techniques. Measurements of chlorophyll *a* fluorescence (Siebke & Weis, 1995), leaf temperature or leaf water potential in terms of water relations (Ehrler *et al.*, 1965; Barrs & Klepper, 1968; Lang *et al.*, 1969; McBurney & Costigan, 1984; Naidoo & von Willert, 1994; Herppich & von Willert, 1995; Prytz *et al.*, 2003) have also been used to record stomatal oscillations. A common conclusion in all of these works was that in-phase oscillations are induced by abrupt stomatal opening or closure by various agents. Reports on the synchronous rhythmic pattern of different leaves on the same plant have been reviewed (Hopmans, 1969; Lang *et al.*, 1969). These authors found oscillations in leaf-xylem water potential and proposed that they are a necessary condition for the stomata of all leaves to oscillate in phase. Oscillations in root xylem pressure were measured by Wegner & Zimmermann (1998) and Prytz *et al.* (2003), who noted that the synchronous behavior observed during oscillatory transpiration indicates strong coupling among stomata; however, they did not suggest a coupling agent. Herppich & von Willert (1995) measured pronounced oscillations in stomatal apertures under certain climatic conditions and noted that changes in transpirational water loss during these oscillations are closely accompanied by changes in leaf water potential (Ψ_l).

On the stomatal scale, the simultaneous occurrence of different stomatal apertures across a leaf and the possible implications of cross-CO_2 exchange were first discussed by Laisk and co-workers (Laisk *et al.*, 1980; Laisk, 1983). Terashima (1992) argued that under certain physiological conditions, the spatial distribution of different stomatal conductances is non-random (patchy), i.e. certain areas of a leaf can have a very different conductance from others. Patchy stomatal closure has been observed, particularly under water stress (Downton *et al.*, 1988; Beyschlag *et al.*, 1992), low humidity (Mott & Parkhurst, 1991; Mott *et al.*, 1993; Mott *et al.*, 1999) and abscisic acid application (Daley *et al.*, 1989; Terashima, 1992; Mott, 1995).

Several models of the mechanism responsible for the oscillations have been described (Lang *et al.*, 1969; Raschke, 1970; Cowan, 1972; Cardon *et al.*, 1994; Haefner *et al.*, 1997; McAinsh *et al.*, 1997; Shabala *et al.*, 1997; Meleshchenko, 2000; Bohn *et al.*, 2001), presenting a common basic assumption: that the oscillation behavior is part of a feedback loop in which evaporation rate influences the stomatal aperture which, in turn, affects the evaporation rate. Some have suggested that stomatal cycling is induced by internal fluctuations in water potential and flow resistance within the plant (Steudle, 2000).

Despite the fact that oscillations have been intensively studied in single stomata, patches and whole leaves, oscillations on the larger whole-plant scale have been rather neglected. The studies of Rose and co-authors (Rose & Rose, 1994; Rose *et al.*, 1994) and Steppe *et al.*, (2006) are, to the best of our knowledge, the only ones in which oscillations in whole-plant transpiration (WPT) have been measured. However, to date, the nature, extent, patterns and regulatory mechanisms of the oscillations in WPT and their putative role in plant-water relations have not been addressed directly. Thus, the current study focuses on these oscillations and their role in the homeostasis of whole-plant water potential.

As changes in xylem water status and tension are associated with temporary imbalance between water demand (controlled by the ambient conditions) and water supply (controlled by water availability in the root zone) before a new equilibrium state is reached, we hypothesized that the physiologically induced oscillations in WPT rate represent the plant's response to changes in xylem water tension, especially at its higher values, which may lead to cavitation and embolism. As has been suggested by Buckley (2005), stomatal control has two different specific roles: 1) to maximize the amount of carbon gained per unit of water lost, 2) to prevent "runaway" xylem cavitation, which would otherwise lead to embolism and decreased water flow to the shoot. This second goal is achieved by preventing leaf/xylem water potential from decreasing below a critical value. Furthermore, Buckley (2005) argued that cavitation avoidance is of primary importance for the optimization of water-use efficiency and that in every case in which the leaf/xylem potential reaches a critical value, the plant will reduce transpiration (by closing stomata) and prevent cavitation. Thus, the above hypothesis can be further extended to claim that oscillations in WPT rate are used by the plant as a means to control cavitation, by either preventing or repairing it.

MATERIALS AND METHODS

Experimental Setup

The experimental study was conducted in greenhouses at the Faculty of Agricultural, Food and Environmental Quality Sciences in Rehovot, Israel. The experimental setup included 3.9-l growing pots placed on temperature-compensated load cells (Tadea-Huntleigh, Natanya, Israel) connected to a CR10 data logger (Campbell Scientific Inc., Logan, UT, USA). The pots were filled with a commercial growing medium (a mixture of peat and tuff scoria) and each contained one plant. Each pot was immersed in a plastic container (13 x 21.5 x 31.5 cm H x W x L) through a hole in its top cover. The pot tops and containers were sealed with aluminum foil to prevent evaporation. The well-irrigated treatment included daily filling of the container. The water level fell to 2 cm above the pot base after the irrigation events due to a drainage hole in the container side wall. The excess irrigation was intended to leach salts accumulated daily in the growing media. The pot-container system ensured that water was available to the plant throughout the day following irrigation, without supplemental irrigations. A commercial fertilizer solution ("Super Grow" 6-6-6+3 Hortical, Kadima, Israel) was added at 0.2% (v/v) daily with the irrigation water (fertigation). This setup ensured that a) the plants would not be subjected to water stress throughout the following day, and b) the container weight on the following day would decrease monotonically solely due to plant transpiration.

The pot-weight readings, taken every 10 s, were averaged over 3-min periods. The averaging period was chosen arbitrarily, the only requirement being that it be lower than the oscillation frequency (20-40 min) and higher than the Nyquist frequency (the highest frequency at which meaningful information can be obtained from a set of data). Preliminary measurements revealed that lower averaged periods have only a negligible effect on the calculated oscillations. The load-cell reading stabilizes after 2 s, following excitation by dropping a 70-g steel ball from a height of 700 mm (manufacturer's data). Thus, a 10-s weight-sampling interval ensured that the maximum rate of weight decrease (0.5 g per 10 s) was appropriately followed.

To isolate intrinsic noise associated with the "measuring and data-acquisition systems" from the short-term fluctuations in plant transpiration, a constant weight of about 6 kg (typical of the container + pot + plant weight) was placed on the load-cells in the greenhouse for several days, during which the weight variation was monitored.

Tomato plants (*Solanum lycopersicum* cv. Ailsa Craig, previously known as *Lycopersicon esculentum* cv. Ailsa Craig) were grown in a controlled-environment greenhouse. The temperature in the controlled-environment greenhouse was 18°C during the night and 35°C during the midday hours with periods of gradual variation between them. The effect of water stress on the patterns of WPT-rate oscillations was studied by a dehydration experiment. Dehydration was achieved by continuous depletion of water from the growing medium by the plant during 5 successive days with no irrigation. This dehydration experiment was performed in the controlled-temperature greenhouse simply by stopping irrigation for 5 days.

Data Analysis

The rate of water loss from the system, being the negative value of the WPT rate, is calculated by the first derivative of the measured weight-time series

$$WPT \equiv -\frac{dW}{dt} \approx -\frac{W_{k+1} - W_k}{t_{k+1} - t_k} \quad \textbf{(1)}$$

where W_k and W_{k+1} are, respectively, the measured weights at time t_k and the consequent time step t_{k+1}. In general, differentiation acts as a high-pass filter, thus significantly amplifying the high-frequency noise. Noises are amplified as the measurement (sampling) interval (t_{k+1} - t_k, Eq. 1) diminishes. On the other hand, the resolution at which momentary variation in transpiration rate can be observed decreases as the sampling interval increases. Consequently, a signal treatment is essential when the noise associated with the transpiration-induced weight decrease is differentiated together with the high-frequency noises associated with the load-cell and data-acquisition system, as both are embedded in the measured time series, owing to amplification of the noise introduced by the latter. In fact, measurement errors, which can never be avoided, complicate the differentiation, because these amplify the noise to such an extent that additional signal treatment is essential. The noise associated with the differentiation of noisy signals has stimulated a large number of investigations which have led to several solutions, in both the time and frequency domains (Savitzky & Golay, 1964; Cullum, 1971; Anderssen & Bloomfield, 1974a; Anderssen & Bloomfield, 1974b; Wahba, 1975; Rice & Rosenblatt, 1983; Scott & Scott, 1989).

It is assumed herein that the container weight-time series follows an additive model

$$W_k = W(t_k) + \varepsilon_k \ , \qquad 1 \le k \le n \qquad t_1 < t_2 < \cdot\cdot t_k \cdot\cdot < t_n \quad \textbf{(2)}$$

where W is the value that the weight at time t_k would have if it varied smoothly with time, and $\{\varepsilon_k\}$ is the deviation from that value. The system's weight oscillations superimposing the smoothed time series also constitute a time series, and are designated "residual time series" (residuals are the differences between the measured data and the fitted curve). When the mean of the residual time series is zero, the trend of the measured time series has been properly removed. We assume that the residual time series ε_k (Eq. 2) is a superposition of two time series: one made up of residuals that originate from the noises related to data acquisition, ε_{k_1}, and the other of residuals originating from either the ambient conditions and/or the intrinsic oscillations in WPT, ε_{k_2}. The time series for the constant-weight, wet-wick and (whole-plant runs, which were independently measured, were used to study the properties of ε_{k_1} and ε_{k_2} and examine their randomness (white noise). Randomness was examined with the autocorrelation function.

The spectrum analysis of ε_k was used to explore the existence of cyclical patterns. The spectral analysis decomposes a complex time series with cyclical components into a few underlying sinusoidal (sine and cosine) functions of particular wavelengths. By identifying the important underlying cyclical components, the characteristics of the phenomenon of interest become apparent, namely, the wavelengths and importance of the underlying cyclical component in the WPT rate can be identified. This spectrum analysis enabled us to uncover a few cycles of different lengths in the time series of interest, which at first looked more or less like random noise.

RESULTS

The Oscillations in WPT Rate

Typical variations in weight during the night and subsequent daylight hours are shown in Fig. 1a for a control potted tomato plant grown in a temperature-controlled greenhouse. As water was supplied to the plants once a day (in the late evening), the weight decreased monotonically during the night and day hours between adjacent irrigation events. A moderate weight decrease was measured during the night (Fig. 1a), which indicates that these plants transpire at night. The rate of weight decrease (transpiration rate increase) intensified during the morning, stayed high during the noon and early afternoon hours, and weakened thereafter. The WPT rate-time series (the negative values of the weight decrease rate), calculated by the time derivative of the measured weight-time series (Eq. 1), is shown in Fig. 1b (dashed line). A noisy WPT rate was obtained despite what appeared to be a relatively smooth pattern of weight decrease (Fig. 1a). The amplitudes of the WPT rate were low during the night, early morning and evening hours and large at the other times. A detailed pattern of the daily transpiration rate, especially when the ambient conditions varied with time, could barely be identified from this noisy time series. The smoothed WPT rate, shown in Fig. 1b (solid line), was obtained by differentiating a smoothed weight-time series obtained by applying the S-G smoothing method with a window breadth of 30 data points (S-G 30). The fluctuations around the smoothed transpiration-rate pattern are usually considered random noise (white noise) associated with the measurement system, and as such are generally ignored without further analysis. Here however, these fluctuations were further analyzed in order to isolate the system-noise-induced fluctuations from those induced by the ambient- and/or physiologically driven oscillations.

The Effect of Water Stress on the Pattern of Oscillations in WPT Rate

The effect of water-stress buildup on the momentary WPT rate (smoothed and oscillatory) is shown in Fig. 2a for plant II. The difference between the smoothed and oscillatory WPT rates in Fig. 2a is shown in Fig. 2b, respectively, where the value of zero transpiration rate represents the smoothed transpiration rate in Fig. 2a, used as a reference. The last irrigation took place on the evening preceding the first day in Fig. 2. The containers in which the pots were immersed were removed after this irrigation. The smoothed and superimposed oscillatory evaporation rates from the wet wick for the 5-day dehydration period are shown in Fig. 2c and the isolated oscillations in evaporation rate (the difference between the smoothed and oscillatory patterns) for this period are shown in Fig. 2d. Note that Figs. 2c and 2d are similar and are shown for the readers' convenience. Fig. 2 indicates that: 1) Since the plant was grown in a temperature-controlled greenhouse with a repetitive pattern of daily ambient conditions (demonstrated by the repetitive daily pattern in wet-wick evaporation rate, Fig 2c), water can be considered fully available to the plant as long as the transpiration-rate patterns are similar for 2 consecutive days. Accordingly, water seems to be fully available to the plant only on the first day (Figs. 2a). The transpiration rate of the plant decreased substantially on day 2 and was markedly low during the last 3 days of dehydration. Note that the smoothed transpiration-rate pattern in Fig. 2a has two daily peaks: a lower peak at noon followed by a higher one in the afternoon. Note that the timing of the second daily peak coincides with that of the daily evaporation rate. The two peaks in transpiration rate occurred despite the single daily peak in evaporation rate (Fig. 2a,c). Furthermore, the two peaks in transpiration rate were accompanied by a change in the pattern of transpiration-rate oscillations; the oscillations were amplified while the transpiration rate increased toward the first and even the second peak, and were shifted from their concurrence with the oscillations in evaporation rate (Figs. 2a,b). The oscillation-amplitude increase during this period contrasted with the uniform distribution of oscillation amplitudes in evaporation rate (Fig. 2d). 3) The ratio between the values of the two daily transpiration-rate peaks diminished and was associated with a noticeable dip that formed between the two peaks. 4) The increase in oscillation amplitudes that was associated with transpiration-rate variation (increase in the morning hours or decrease in the afternoon hours) during the early stages of dehydration (Fig. 2a) were also seen in the dip between the two daily transpiration-rate peaks as the water stress progressed.

The substantial differences in oscillation patterns between the WPT and wet-wick evaporation rates that developed as the dehydration process progressed (Fig. 2) indicate that the formation of synchronized self-regulated oscillations in WPT rate when the plant is subjected to water stress are an intrinsic physiological process that enables the plant to cope with the ongoing increase in xylem tension and the cavitation that is associated with this increase.

Discussion

Frequent undisturbed measurements of weight loss in plants provide an accurate means of determining the momentary rate of WPT. A comparison between the patterns of smoothed and low-pass oscillations in WPT rate and wet-wick evaporation rate (after filtering out noise associated with the measuring and data-logging systems) can reveal whether the synchronized oscillations in WPT rate are self-regulated, i.e. independent of temporary fluctuations in ambient conditions, or whether the oscillations and ambient conditions are related. The patterns of oscillations in WPT rate relative to the temporary fluctuations in ambient conditions when water was highly available or under gradually developing drought stress indicated the role of these oscillations in maintaining water-potential homeostasis.

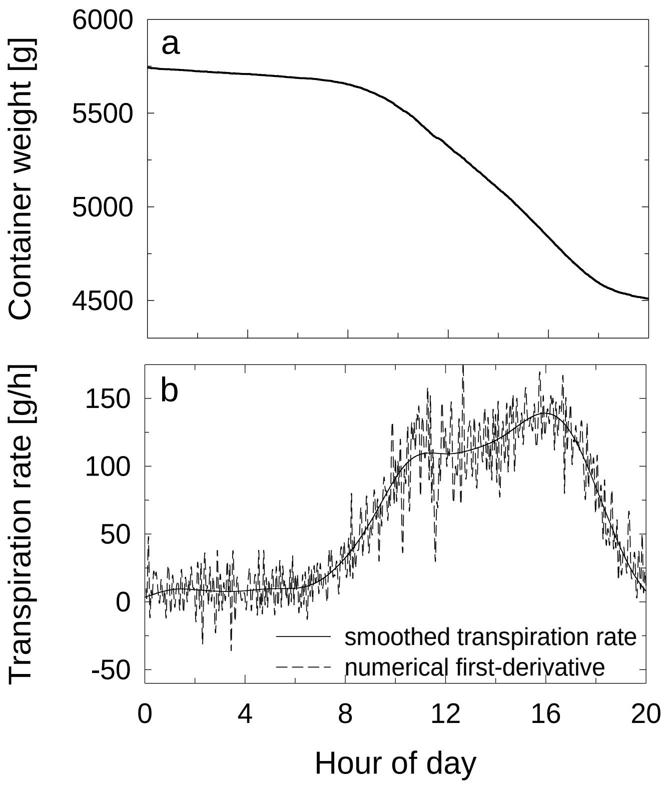

Figure 1: Time course of changing weight of a potted tomato plant (a). Time course of transpiration rate calculated by numerical derivative of the measured and smoothed time courses of the decrease in potted tomato weight (b).

When tomato plants were grown under conditions of high water availability and the plant-soil continuum could easily supply the water demand, the oscillation patterns in WPT rate were fairly in phase with the fluctuations in ambient conditions. However, deviations between these oscillations developed when the plants were subjected to a gradual increase in water stress as water in the growing medium was progressively depleted. At high water stress, the transpiration rate decreased significantly while the oscillations of the WPT rate became independent of the fluctuations in ambient conditions (Figs. 2b,d), their daily pattern being similar throughout the dehydration experiment (Fig. 2a,b). The ratio between the oscillation amplitudes and the smoothed transpiration rate increased with water stress. These findings suggest that the role of the self-regulated synchronized oscillations in WPT rate is to control the xylem water tension, which increases with the expanding margins between water demand (ambient conditions) and the soil/plant's ability to deliver this demand. As an increase in xylem tension may lead to xylem cavitation, which is generally seen as a potentially catastrophic dysfunction of the axial water-conducting system (Tyree & Sperry, 1989; Tardieu & Davies, 1993; Hacke & Sauter, 1995), the role of the self-regulated oscillations in WPT rate can therefore be attributed to the plant's effort to prevent either cavitation formation or runaway cavitation.

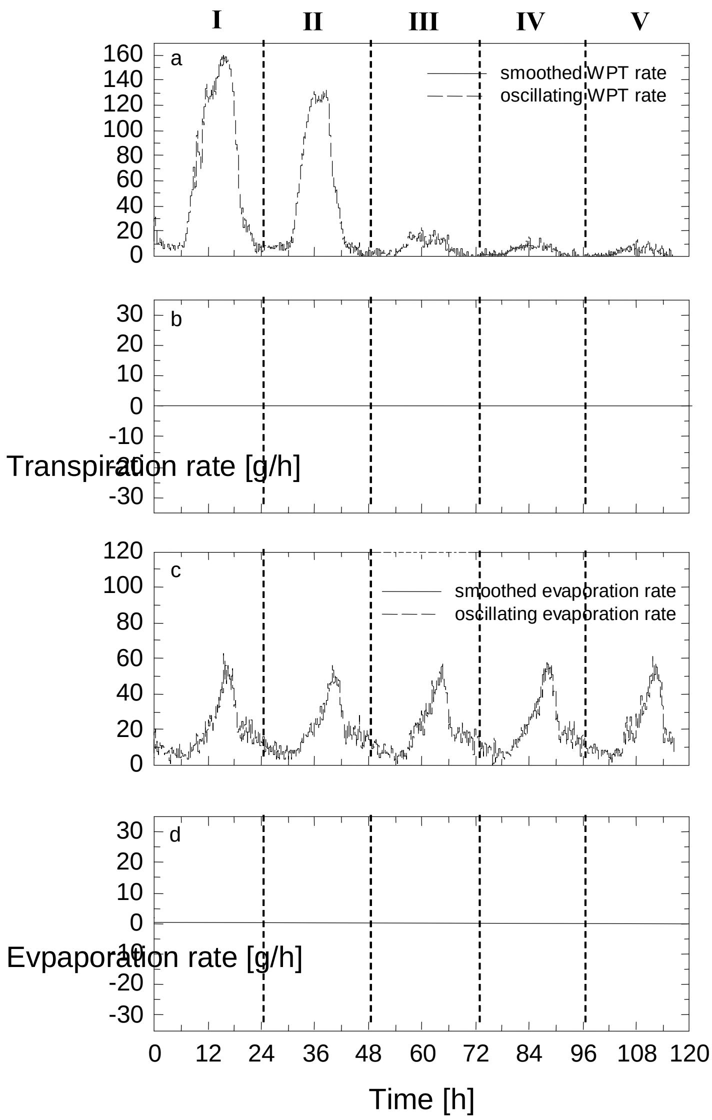

Figure 2: Results of 5-day dehydration of tomato plant II. Smoothed and superimposed oscillatory transpiration rates (a). Isolated oscillations in transpiration rate (b). Smoothed and superimposed oscillatory evaporation rates from the wet wick (c). Isolated oscillations in wet-wick evaporation rate (d).

The latter can be prevented by maintaining the xylem-tension thresholds within a range in which cavitation occurs but is repaired quickly enough to maintain the xylem water conductance at a value which does not induce further tension increases (leading to runaway cavitation) (Salleo *et al.*, 2000).

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THE ISOHYDRIC RESPONSE TO SHADING: PREDICTING ORCHARD WATER USE UNDER SCREENS

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ABSTRACT

Water use of crops shaded by screens and screenhouses has been a focus of our research for a number of years. All shade screens reduce radiation load and decrease wind speed at the crop. If leaf conductance does not respond to shading (i.e. anisohydric), these reductions reduce crop water use significantly.

Isohydric plants limit their leaf water potential (LWP), preventing it from dropping below a certain level. That level is apparently related to the hydraulic limits of the plant's water transport system. Isohydric behavior is usually defined as a response to reduced soil water potential. But well irrigated isohydric tree crops that we have studied in Israel typically close stomata during mid-day in hot, clear-sky conditions. For these crops, shading can lead to increased leaf and canopy conductance and productivity, as observed in citrus trees. But then the decrease in water use is minor or even insignificant, although water use efficiency increases.

Quantifying isohydric behavior is important for realistic predictions of crop water use and requirements and photosynthetic productivity under screens and in screenhouses. Here, we show that leaf specific hydraulic conductance, leaf area index, critical LWP and climate variables (via the Penman-Monteith equation) can be used to predict canopy conductance and water use in shaded isohydric crops.

INTRODUCTION

One of the primary approaches to dealing with water shortage is optimization of irrigation in order to conserve water. This involves a continuing effort to accurately determine and afterwards predict water use for new crops and agricultural configurations as they develop. Sometimes we introduce the changes, but at other times it seems like we are running after the farmers to optimize irrigation in the situations that they choose.

One of the interesting changes in recent years in Israel and other mild winter climate countries is the introduction of various structures that modify crop climate without controlling it. These structures involve screen coverings and screenhouses. In the former a screen is hung above the crop and the sides of the structure are left open. In the latter, the sides are closed and although the structure is technically closed, the screens allow higher rates of ventilation than those obtained in greenhouses and the climate in the structure is basically coupled to the outdoor climate.

The main climate variables changed by the structures are radiation and wind speed. Both solar radiation and wind speed at the crop are reduced (see Fig 1). Wind speed reductions can be described by a fixed linear factor, based on the logarithmic profile of wind speed observed below screens (Tanny and Cohen, 2009; Tanny et al., 2009). The reduction of radiation below screens depends on the solar zenith and azimuth angles, but for mid-day conditions can also be described by one factor (Cohen and Fuchs, 1999; Tanny and Cohen, 2009).

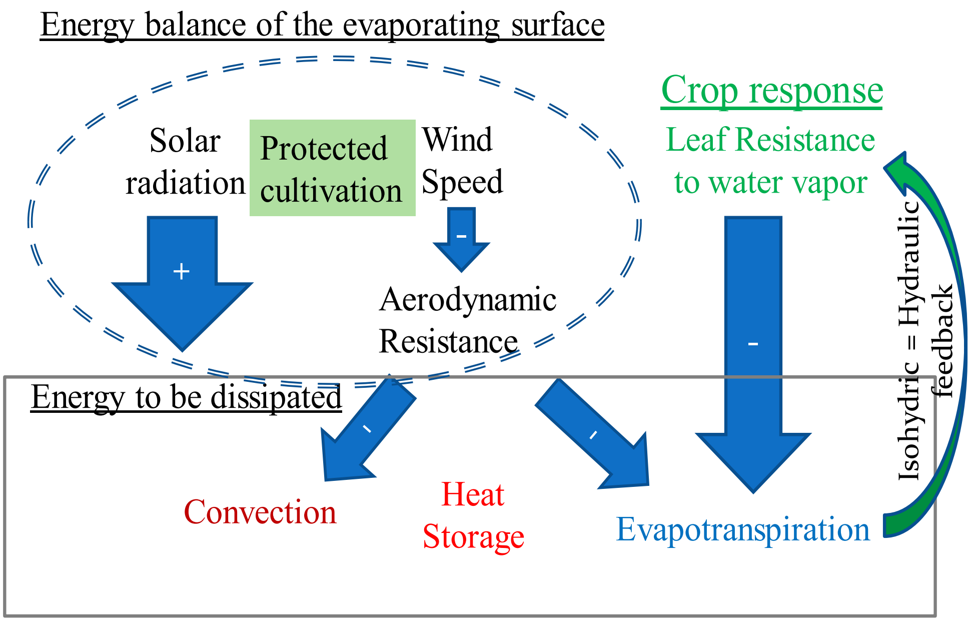


Fig. 1: Schematic diagram of the energy balance of the crop. Positive and negative influences are noted. The major climate variables influenced by shade screens are in the oval. Crops influence the energy balance through modifications of the leaf and crop resistance. The Isohydric response can be seen as a feedback from transpiration to crop resistance.

First estimates of the response of crop transpiration to the changed climate below screens can be made using the standard FAO-56 Penman-Monteith equation, which describes water use of standard well-irrigated cut grass (Allen et al., 1999). With this analysis (see below) reduced wind speed (above a threshold low windspeed) increases aerodynamic resistance (slightly), while reductions in radiation reduce transpiration more-or-less proportionately. Thus, if crop resistance to water vapor transport is unchanged, transpiration will always be expected to decline below screens.

This paper describes measurements of transpiration and related variables made in several projects in which sap flow was measured below screens and outside of the screen structures in citrus and apple trees. In these cases the screen structures were open to the sides. Analysis of the response of crop resistance shows that the latter was active in stabilizing transpiration in these situations. A recent conceptualization of crop resistance response to environment, termed ‘isohydric’, is invoked to explain the results.

THEORY

A simplified model which accounts for the climatic influences on potential transpiration but limits transpiration to the hydraulic limit of trees was applied to conditions outdoors and under a shading treatment. The model assumes the following:

Transpiration of a non hydraulically limited tree, E_{pm}, proceeds as that of a crop with maximum canopy conductance, and is similar to that for a standard grass crop described by the FAO56 implementation of the Penman-Monteith (PM, Allen et al., 1999 for details) equation, i.e.,

$$\lambda E_{pm} = \frac{\Delta R_n + \rho c_p D g_a}{\Delta + \gamma(1 + g_a / g_c)} \quad (1)$$

Transpiration is limited to a maximum value described by the hydraulic equation, where:
$E_{max} = k_l * \Delta\psi_{critical}$
Where k_l is leaf specific hydraulic conductance (kg m^{-2} s^{-1} Pa^{-1}), and $\Delta\psi_{critical}$ is a threshold water potential difference between soil and leaves (for well watered conditions) above which canopy conductance is adjusted in order to maintain this gradient.

Both values are calculated and E is taken as E_{pm} when it is less than E_{max}. Otherwise $E=E_{max}$.

Canopy conductance (g_c) and resistance (r_c) can be computed from inversion of the P-M equation as:

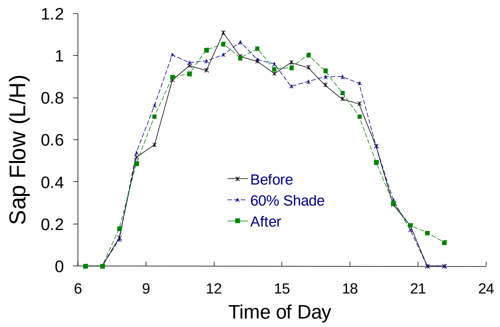
$$r_c = \frac{1}{g_c} = \frac{1}{\gamma g_a} * \left[\frac{\Delta R_n + \rho c_p D g_a}{\lambda E} - (\Delta + \gamma) \right] \quad (2)$$

METHODS

The citrus experiment was carried out in late July and August in 1994 and 1995 in an orchard at the Volcani Center, Bet Dagan, Israel (31°59'N, 34°49'E, 50 m above mean sea level). The trees were Citrus limon cv. Villafranca on Volcamarianna rootstock planted in Oct 1990. The orchard was drip irrigated and the soil is a sandy loam. Shade nets were hung horizontally above two trees in the hedgerow and two nets of different densities were used, both of highly reflective aluminized polypropylene (Polysack Ltd., Nir Yitzhak - Sufa, Israel). The shade nets were the width of one hedgerow giving shade mostly during mid-day, so that before 9 Am and after 4 PM much of the tree was not shaded. Stem sap flow was measured continuously with a heat pulse technique calibrated for citrus (Cohen, 1994) in six trees; two under each of the nets and two as control trees. Climate conditions were monitored, including net radiation with and without the net. Full details are given in Cohen et al (1997).

The apple experiment was carried out at Ein Zivan in the Golan Heights of Northern Israel in the summer of 2008. A clear white 20% shade net (Polysack Ltd.) was hung horizontally above approximately 4 dunams (0.4 ha) of an apple (Malus domestica) orchard. Four irrigation treatments were applied outside and below the screen, including 100% (regional recommendation) and 30% irrigation in a split plot design with 7 replicates. Details are given in Tanny et al. (2008). Stem sap flow was measured in trees of the Golden delicious cultivar with the thermal dissipation technique (Granier, 1983) using 20 mm long probes. Sap flow for the 20 mm annulus of xylem was computed based on Granier's general equation.

RESULTS



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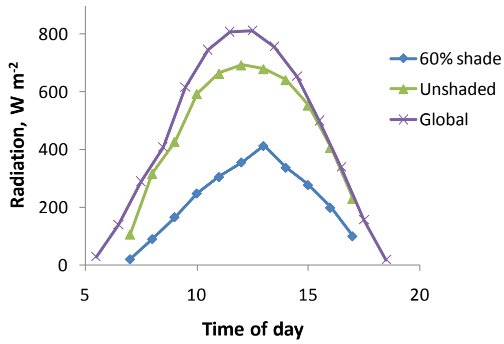

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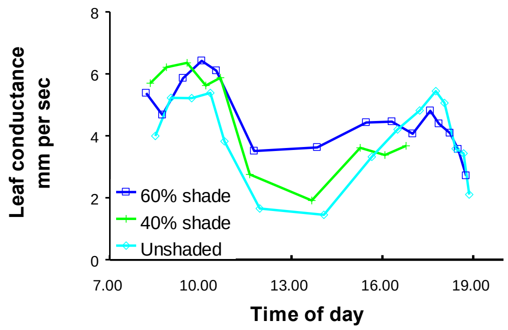

c.

Fig 2: (a) Sap flow in one citrus lemon tree on three days; before, during and after shading with a 60% shade screen (b) Global, and net radiation measured above unshaded and shaded trees, and (c) leaf conductance at two shade levels. After Cohen et al. (1997).

Daily course of sap flow for trees measured with and without screen shading are presented in Figs. 2a and 3. For citrus shaded with 60% screens, which reduce both net radiation (Fig. 2b) and wind speed by approximately 50% (Tanny and Cohen, 2003), no change in the daily course of sap flow was observed. Analysis of mid-day sap flow for the other trees shaded and for the whole period of shading showed that the shade reduced average mid-day sap flow by about 10% (Cohen et al., 1997). Results for apple trees (Fig. 3) show a similar phenomenon, i.e. during mid-day the shade screen had no influence on sap flow, even in the treatment with full irrigation. In the apple experiment the sap flow in the morning under shade lagged behind that outdoors. The lag can be explained by the shading of the screen in this experiment and that screen shading is more intense when solar elevation is low due to the geometry of the screen (see Tanny and Cohen 2008). In the

30% irrigation treatment shading did not change the daily course of sap flow significantly. Sap flow peaked in the morning and afterwards declined markedly during the day. This can be explained by depletion of water in the root zone during the day because of the deficient irrigation.

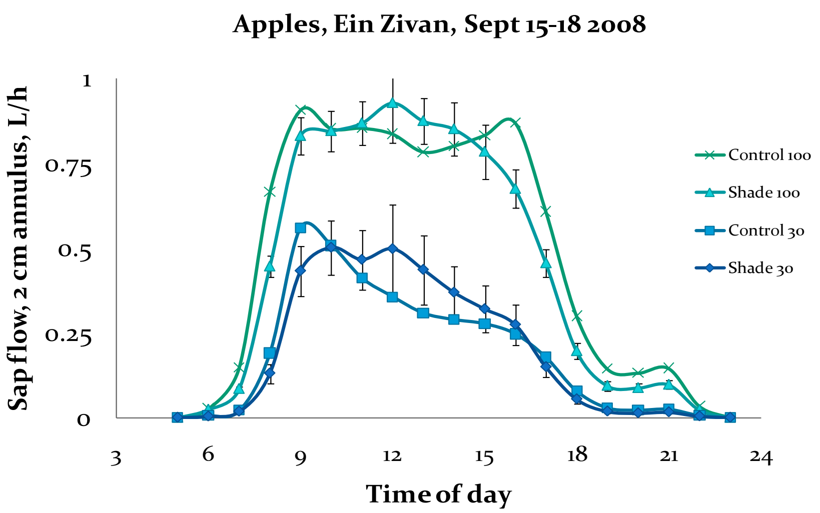

Fig 3: Hourly sap flow in apple trees averaged for 4 days. Vertical lines 2 standard errors of mean (n=9). Shading with 20% screen. 100% and 30% irrigation.

Leaf conductance during the course of the day was measured with a porometer in the citrus experiment and these results (Fig. 2 c) show that leaf conductance decreased at mid-day. This classic mid-day stomatal closure stabilizes sap flow so that in the full irrigation treatments it remains more-or-less constant (within 10% of maximum) for many hours (Fig. 2a and 3). Mid-day leaf conductance increased under shade, and this accounts for the fact that sap flow was the same as in the unshaded treatment.

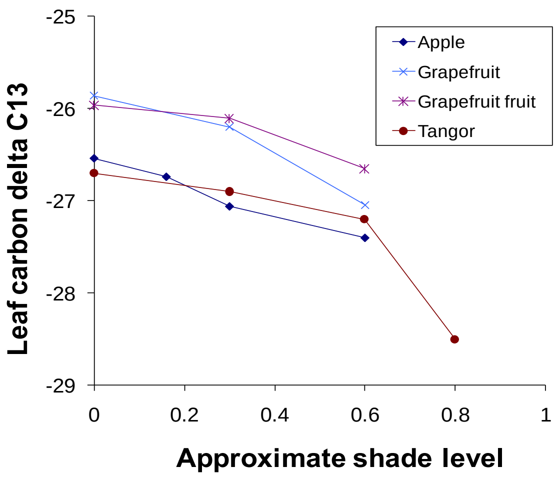

Fig. 4: Delta C13 of leaf and fruit samples from four shading experiments. Samples were taken from leaf and fruit tissue that developed in the upper portion of the trees during the hot summer months. Tangor is a citrus variety. Grapefruit data from Cohen et al. (2005).

Carbon isotope ratios (δC^{13}) were measured in several of our shading experiments. Results for grapefruit trees (from Cohen et al., 2005) and apple trees are given in Fig. 4. In general, δC^{13} is negatively correlated with the CO_2 concentration in the leaves when the photosynthesis that fixed carbohydrates in the plant material was done. In all the orchard shading experiments where we have analyzed δC^{13} we have found a significant decrease in δC^{13} with increased shading. In general, we take this response as an indication of increased leaf conductance at mid-day leading to higher internal CO_2 concentrations during photosynthesis.

The model calculations of transpiration for apple orchards were made using approximate values of hydraulic conductance, K_l (1.0e-4 kg m^{-2} s^{-1} MPa^{-1}) and $\Delta\psi_{critical}$ (1.2 MPa) that we measured in our previous work on apple trees at Ein Zivan (Cohen and Naor, 2002 and Cohen et al., 2007), and LAI=1. For climate conditions we took values measured at our weather station in summer 2008 and used the ratio of net radiation above the orchard to global radiation with (0.42) and without (0.63) shading observed in our experiments. Results (Fig. 5) show the same features for the daily course of transpiration that we observed in the shading experiments for well irrigated trees.

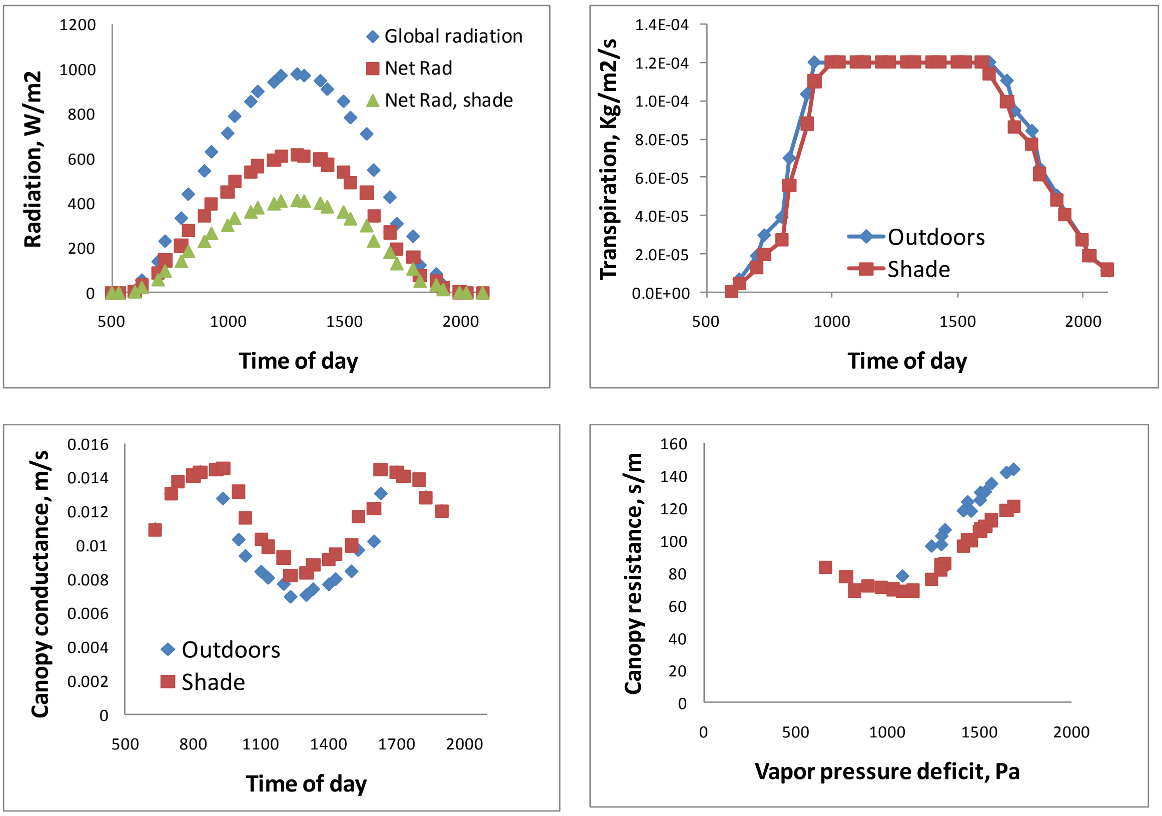

Fig. 5: Results of the simulation of transpiration based on the Penman-Monteith model and hydraulic limits. Radiation values based on the ratios of net to global radiation observed in the orchard shading experiments.

DISCUSSION

The results of the well irrigated shading treatments in orchards show that transpiration increases in the morning but levels off late in the morning and is relatively constant for many hours in the remainder of the day. No difference in transpiration, at least for the mid-day portion of the day, was observed between the shaded and non-shaded trees. Thus, since the large changes in wind speed and radiation below the screen should have led to a reduction in transpiration, it is clear that canopy conductance was modulating transpiration so that it proceeded at more-or-less the same rate in both cases.

During the past decade much attention has been given to the hydraulic limits of trees, and in particular we are now aware of the fact that water potential gradients exceeding certain values will lead to damage to the trees hydraulic system. Although it is not clear how mechanistically plants regulate transpiration in order to limit water potential gradients to safe levels, it is clear that this happens.

The terms 'isohydric' and 'anisohydric' have been introduced to describe responses of different plant species to drought conditions. Jones and Tardieu (1998) were among the first to make this distinction. They wrote that "the first group (of plants), so-called 'isohydric' plants, maintain daytime leaf water status relatively constant regardless of soil water status as a result of active stomatal control; examples include apple or maize (Tardieu and Davies, 1992). The second group, 'anisohydric' plants such as sunflower or sorghum, do not maintain leaf water potential constant and it tends to correlate with stomatal conductance (Tardieu et al., 1996)". Schultz (2003) wrote "isohydric, that is, when water is scarce, the stomata act to prevent leaf water potential from dropping below a critical threshold level" (H.R. Schultz, 2003). It is clear that the response to shading in the orchard trees that we observed can be termed "isohydric". In addition, the perhaps oversimplified initial model of transpiration presented here is based on the isohydric principle that daytime leaf water status (or water potential) is maintained relatively constant as long as the potential transpiration exceeds the hydraulic threshold.

Mid-day stomatal closure of stomata has been observed in citrus since the beginning of research on citrus water relations, and has often perplexed researchers. Today it is clear this is part of the isohydric response. In addition, cycling of leaf conductance at the leaf and canopy level have been observed. The cycling can be attributed to imperfection of the feedback control loop that involves canopy conductance modulation of transpiration through some currently unknown water potential sensor in the plant.

The parameters used to determine E_{max} are vital for predicting tree transpiration both with and without shade. As noted above, much attention has been given to the critical leaf water potential and its relationship to structural parameters of the xylem (e.g. Tyree and Sperry, 1988). Hydraulic conductance of plants has also been quantified for many species, and we have a good idea what values to expect (Tyree and Ewers, 1991). But leaf specific hydraulic conductance depends not only on the xylem, but also on the interaction between leaf area, root area and soil hydraulic conductance (Li et al., 2005). Thus, it is possible that if the trees under the screens were pruned k_l

would increase (Pataki et al., 1998) and the response to shading might be more coupled to the climate change in shade.

The current study shows that the 'isohydric' principle is applicable to shading studies and that if we are to properly anticipate water use of crops in the shade it is important to understand and quantify their hydraulic parameters and ascertain to what extent they are isohydric.

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ASSESSMENT OF THE EFFECT OF CLIMATE CHANGE ON THE INTERACTIONS OF PLANT, PATHOGEN AND MICROORGANISMS

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ABSTRACT

Disease development is the cumulative effect of various factors on the host and pathogen. Various a-biotic factors affect different aspects of the disease cycle. It was demonstrated that a slight change in microclimate conditions can affect the outcome of the interaction of plants with a pathogen, as well as the outcome of the interactions of the plant-pathogen relationship with microbial control agents. The effects of climate change may be different in different plant-pathogen systems. Nevertheless, it is clear that such effects will occur and that adaptive measures need to be developed in order to respond to these expected changes.

INTRODUCTION

Most of the studies regarding climate change focus on its impact on a global level, without considering the regional levels or single agricultural crops. Generally, it is expected that increases in temperature and decreases in precipitation due to climate change will add complexity and uncertainty to the agriculture system and threaten its sustainable management. Climate change is expected to have an effect on water availability, and will decrease biodiversity. Moreover, it will increase plant stress and will also influence crop quality, yield quality, and dynamics of pest and diseases. Furthermore, competition from a global agriculture may hamper the development of sustainable approaches to counteract global change.

The report published recently by the Intergovernmental Panel on Climate Change (IPCC, 2007) of the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP) (http://www.ipcc.ch) lists the current scientific understanding of impacts of climate change on natural, managed and human systems and on the capacity of these systems to adapt and their vulnerability. The assessment concludes that "*there is high confidence that recent regional changes in temperature have had discernible impacts on many physical and biological systems*." Natural systems, especially hydro-systems, have been affected, but the recent warming is also strongly influencing terrestrial biological systems and upward shifts of species. Although the impact of climate change has been well documented, it is still not clear whether this will lead to overall positive or negative effects on food production (Reilly& Schimmelpfenning, 1999). The effects indeed on agrosystems depend on their exposure and sensitivity to climate change, and their adaptive capacity (IPCC, 2007). Effects of temperature increases have been documented on agricultural and forestry management. Projections on the impact of climate change on crop productivity are available. But no information on plant-pest interaction is available.

Nearly all regions of Europe and the Mediterranean are expected to be affected by climate change and that will pose challenges to many of their economic sectors. Global-change associated costs are unexpectedly high. In the United States alone, for example, losses from exotic pests are estimated to be $137 billion annually (Pimentel et al., 2000). Failure to address the threat of climate change threatens to be the greatest and widest-ranging market failure ever seen (Stern, 2006).

Each species of plants and animals has different requirements for growth, survival and reproduction that determine its distribution, abundance, and interactions with other species (Andrewartha & Birch, 1954). This is why global warming will affect all species. Plants are directly affected by microclimate conditions and react to changes in their growth, flowering, fruit development and other life stages and therefore production and quality. Temperature changes can repress or enhance gene expression of plants and microorganisms, which in particular cases can lead to phenotypic changes such as production of particular substances or loss of functions. Plants are challenged by pathogens, among which fungi are important organisms. A plant pathogen that infects plants may either live in balance with the host plant or may gradually cause an infection that ultimately will kill the host plant. The development of a plant disease requires a susceptible host tissue, a compatible pathogen and involves also the natural microflora. Plant pathogens can roughly be divided into two groups, i.e., i. pathogens whose activity is promoted by high relative humidity (low vapor pressure deficit) and/or water presence on host surface and, ii. pathogens that are active over a wide range of RH conditions including low RH. The response of pathogens to ranges of temperatures is also distinctive. The prevalence of suitable environmental conditions can tilt the plant-pathogen relationship into a disease situation. Coakley et al. (1999) reviewed the impact of climate change on disease management, indicating that research has been limited, but climate change could alter stages and rates of pathogen development, modify host resistance and result in changes in the physiology of host-pathogen interaction.

Plant disease development depends on the interaction among host, pathogen, microbial antagonists and environment. If any of the four factors is altered, changes in the progression of a disease epidemic can occur. Climate (mainly temperature, moisture and rain frequency) change influences disease development. Increased temperatures will accelerate the development of some types of insects, possibly resulting in more generations/year. “Migratory” insects may faster migrate to the North or to higher altitudes, or the areas in which they are able to over-winter may be expanded. Lower winter mortality of insects or high disease inoculum survival due to warmer temperatures could increase insect/pest populations (Harrington et al., 2004) or favor early disease epidemics.

Natural enemies or biocontrol agents may respond differently to changes in temperature and natural antagonism could be changed. The various climatic factors affect also the microflora that exists on the plant surfaces which in turn influences also the outcome of the interaction plant pathogen. All in all, the change in a-biotic parameters will affect the multitrophic interactions between plant-pathogens-beneficial organisms, but the outcome is neither clear nor predictable. The general objective of our project is to model the effect of climate change on plants and their pathogens, illustrate expected scenarios and suggest adaptive measures.

METHODS

Oidium neolycopersici was isolated from young leaves of tomato plants grown in a commercial greenhouse at the Besor Research and Development Station, western Negev Desert, Israel, during January 2005. Conidia of the pathogen were collected by rinsing infected leaves with sterile water. For the artificial infection of tomato leaves, the concentrations of these conidial suspensions were determined under a light microscope using a haemocytometer. All suspensions were adjusted to 10^4/ml and then sprayed onto plants at a rate of 5 ml per plant. All suspensions were sprayed within 10 to 15 min of the initial conidia collection. Suspensions were applied with a hand-held spray bottle and plants were left to dry in an open greenhouse for up to 30 min.

Tomato plants were obtained from a commercial nursery (Hishtil, Ashkelon, Israel) at 40 to 50 days after seeding and transplanted into 1 l-pots, containing a peat: volcanic gravel (3:7 vol.: vol.) growth mixture. Plants were irrigated every 1 to 3 days, allowing for 30% drainage. Fertilization with 5 g/l 20:20:20 NPK fertilizer applied as 250 ml of fertilizer solution per pot was started one week after transplanting. Plants were maintained at 20 to 25ºC in a pest- and disease-free greenhouse for 2 to 3 weeks prior to the initiation of the experiments. Experiments were initiated after plants had reached the 5-node developmental stage.

The effects of microclimate on powdery mildew development were tested on tomato plants incubated in walk-in growth chambers at 16 to 28°C, 5150 lux and 70 ± 3% RH. The lights were turned on at 06:00 and turned off at 19:00. Temperature and RH were recorded hourly using data loggers (Hobo, Onset Computer Corp., Pocasset, MA, USA). Four groups of five plants each served as replicates in the growth chamber experiments. Disease severity as percent leaf coverage was evaluated using a pictorial key. Severity was evaluated at three different plant heights and averaged for the entire plant. The disease severity values for the mature and intermediate leaves and for the entire plant are described separately. Most of the disease symptoms were observed on the leaves and not on other plant parts, thus we chose to monitor leaf infection. The areas under the disease progress curves (AUDPC values) were calculated.

Tomato plants were planted in sandy soil at the Besor R&D Research Station located in the northwestern part of the Negev Desert (southern Israel). Cultivar 870 was planted on March 3,

2006. The plants were grown to one stem and then attached to ropes hanging from the ceiling of the greenhouses, drip irrigated, and fertilized. The plants were maintained according to local commercial standards. The following fungicides were applied once to control late blight: Acrobat WG (9% dimethomorph + 60% mancozeb; BASF, Ludwigshafen, Germany), Sandomyl WP (7.5% metalaxyl + 56% mancozeb; Dow Agrosciences, Indianapolis, IN, USA), and FolioGold SC (3.75% mefenoxam + 50% chlorothalonil; Syngenta, Basel, Switzerland). Walk-in tunnel greenhouses (30 m^2) were each planted with three 6-m-long double rows of tomato plants. Plants were planted 40 cm apart in rows spaced 60 cm apart. In order to achieve variability in climatic conditions, the greenhouses were different from each other in their roofing and the materials used for their front and back openings, as well as soil cover and their internal humidity sources. Roofing and front and back door materials included polyethylene, insect-proof netting, and shade netting.

In order to ensure the even availability of *O. neolycopersici* inoculum in the greenhouses, nine pots of two-month-old tomato plants with 40-60% powdery mildew severity were placed in each greenhouse, 21 days after the planting of each experiment. Three pots were placed in each of three rows (nine pots per greenhouse), evenly scattered in the greenhouse. Conidia spread naturally in the greenhouse. No fungicides against powdery mildew were applied during the entire growth cycles. Areas under disease progress curves (AUDPC values) were calculated. Ten centrally located plants were rated for disease severity every 2 to 4 weeks. Leaves from nodes 3 to 4, 7 to 9, and 12 to 14, corresponding to low, intermediate, and high heights, were evaluated for disease severity. Disease severity (percentage of the leaf surface covered with powdery mildew symptoms) was calculated for each plant height and for the entire plant by averaging the percent severity values for the three heights.

The effects of temperature, RH, and light intensity on germination, appressorial formation, and conidial viability were evaluated using regression analysis. Powdery mildew severity (leaf coverage) was averaged per leaf level (node), plant, and plot, and AUDPC values were calculated. Data in percentages were arcsin-transformed before further analysis. Disease severity and AUDPC data were analyzed using ANOVA and Fisher's protected LSD test. Standard errors (SE) of the means were calculated and disease levels were statistically separated following a one-way analysis of variance. The standard errors (SE) are marked in the figures (with error bars) and stated in the tables.

RESULTS

Biological phenomena are affected by temperature and relative humidity. The effect of microclimate conditions on plant pathogens and diseases they form is described schematically in Fig. 1 with respect to humidity promoted pathogens and to pathogens that are active also under conditions of low humidity. As an example, we studied parameters related to key components of the development of *Oidium neolycopersici* on tomato leaves and to the development of tomato powdery mildew that it causes. Changes in microclimatic conditions may affect the behavior of the pathogen on the plant surface (i.e., conidial germination, germ tube growth and appressoria formation) during infection, the growth of the fungus within plant tissue and/or the formation and survival of conidia. Ultimately, all of these factors affect disease severity. The range of microclimatic conditions tested was initially wide (5 to 35ºC, 23 to 99% RH and 0 to 5150 lux) and was later narrowed to temperatures of 18-28ºC, 70-99% RH and three levels of irradiation. The relationships between the different microclimate parameters and disease severity were studies.

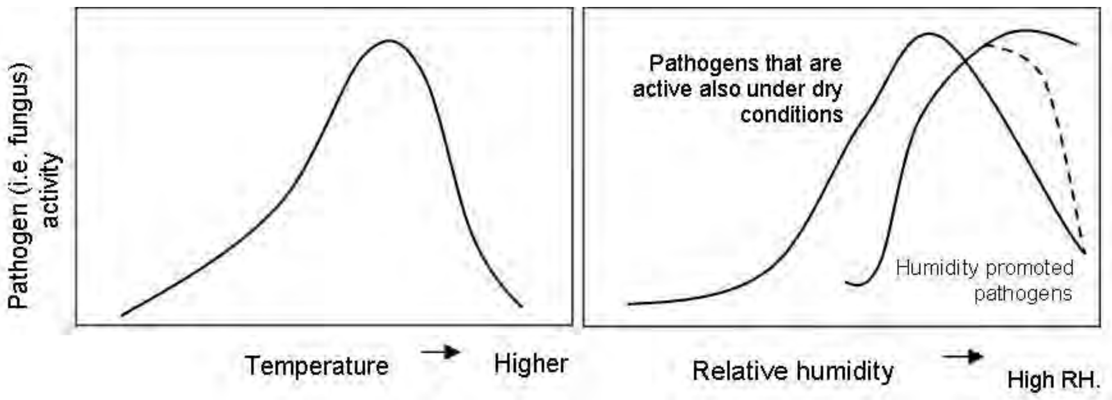


Fig. 1: Theoretical effect of relative humidity (right) on activity of humidity promoted pathogens and of pathogens that develop also at low RH, and of temperature (left) on both groups of pathogens.

In the growth chamber experiments, temperature changes (in 2ºC increments) resulted in significant changes in disease severity (Fig. 2). For instance a change from 22 to 24ºC resulted in a more than two-fold increase in disease severity and a change from 26 to 28ºC caused diminishing of the disease. Reductions in RH were associated with significant reductions in disease severity (results not shown). The ability of microorganisms and plant extracts to suppress disease was generally more significant at 26 than at 24ºC. In tunnel greenhouse experiments the disease did not develop well under conditions of higher temperatures (structure Y5, Fig. 2). After finding that these microclimate changes significantly affected disease severity, we tested two climate regimes in commercial greenhouses. In the warmer greenhouse (27-32ºC), which was closed during the day, the level of disease severity was significantly lower than in the standard commercial greenhouse (20-28ºC). In parallel we demonstrate the effect of microclimate on populations of beneficial/ pathogen-antagonistic microorganisms.

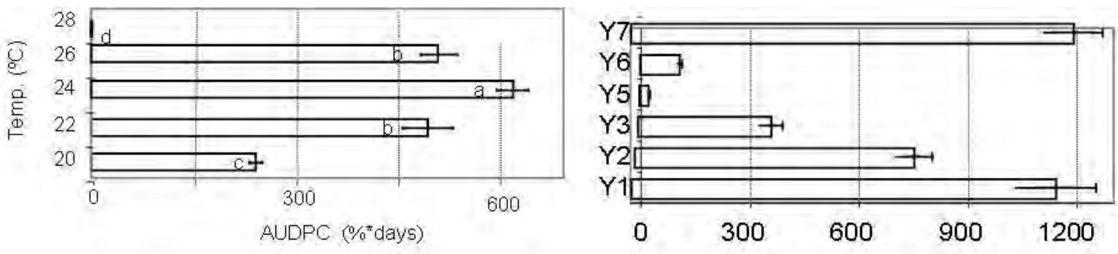
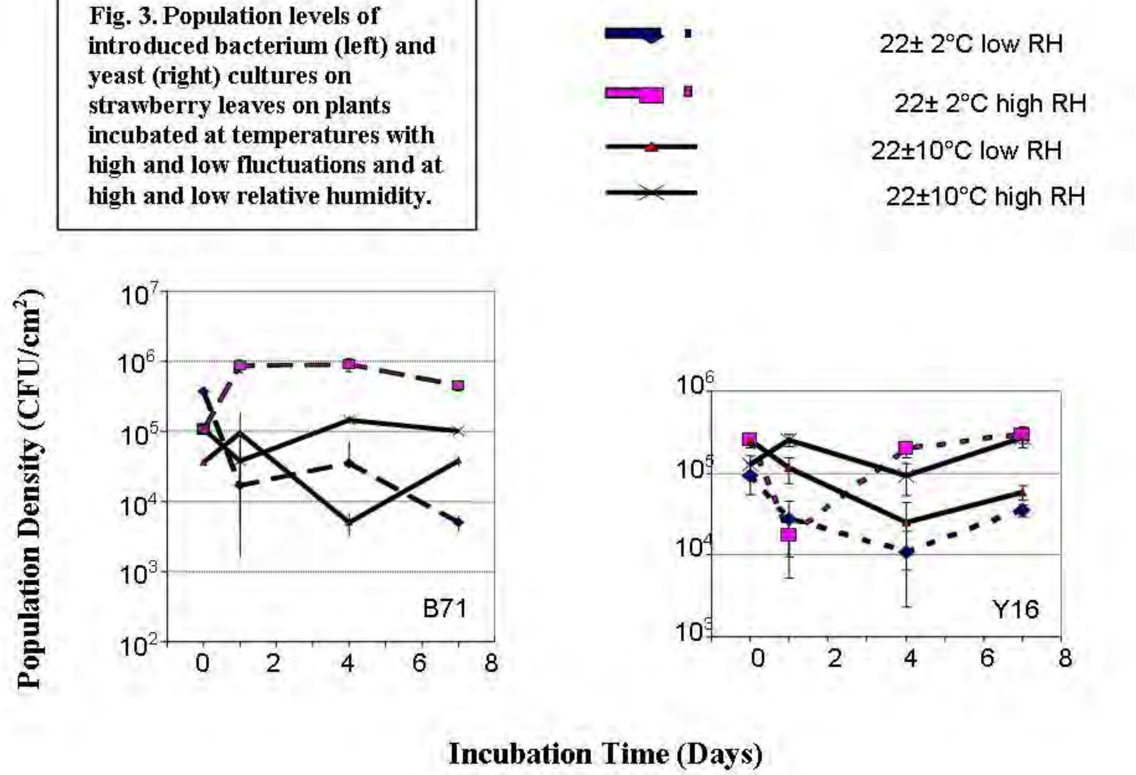


Fig. 2: Effect of temperature on powdery mildew (*Oidium neolycopersici*) severity in growth chamber experiments (left) and in walk-in tunnels in which the climate was modified by different covers and openings (right). Bars = SE

Fig. 3. Population levels of introduced bacterium (left) and yeast (right) cultures on strawberry leaves on plants incubated at temperatures with high and low fluctuations and at high and low relative humidity.



Microorganisms have a potential to affect pathogen activity. Microclimate affects also other members of the phyllosphere. A bacterium and a yeast isolate were introduced into leaf surfaces (Fig. 3). The temperature fluctuation affected the level of populations of both microorganisms. Higher temperature fluctuations were associated with lower populations of the bacterium but not of the yeast. Low RH was resulted in lower populations of both microorganisms (Fig. 3).

DISCUSSION

Negative impacts on plant associated pests and diseases (as pest outbreaks, invasion of exotic pests, etc.) are virtually certain to occur based on projections for 21st century in the Special Report on Emission Scenarios. A small number of impact assessments have now been completed for the scenarios mostly previewed for 2070 to 2100, none of them exhaustively including quality, production, pest and diseases. Nevertheless, the results of this report demonstrate that a slight change in temperature can result in a corresponding change in plant disease severity. This implies that the expected temperature change may result in changes in distribution of plant diseases either geographically or season wise. Furthermore, climate change is expected also to be associated with changes in precipitation and in extreme temporal changes in microclimate, that all may also affect pest severity and distribution. Thus, in the short term, severe changes in pest and diseases are likely to occur. This could increase the risk of crop losses and will need a modification of the control strategies with presently inestimable additional costs for agriculture.

Many early impacts of climate change can be effectively addressed through adaptation. The array of potential adaptive responses is very large, ranging from purely technological (e.g. pesticides application), through behavioural (e.g. crop change) to managerial (e.g. altered farm practices), to policy (e.g. planning regulations). While some technologies and strategies already exist, their application must be prompt and effective and therefore it must be planned in advance and customized to the specific situation whereas some, like beneficial microorganisms, need further development. Sustainable development is generally recognized as a key factor for the future of humankind. At present, however, few plans for promoting sustainability have explicitly included either adapting to climate change impacts, or promoting adaptive capacity.

Even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes fast adaptation essential. This suggests the value of a portfolio or mix of strategies that includes mitigation, adaptation, technological development and research. The ENVIROCHANGE project was established to: assess the short-term impact (up to 25 years) of climatic change on agriculture at the regional level focusing on quality and pest management that are more likely to be influenced by climate change in the short term; assess the biophysical and socio-economic impacts of climate change on the region with special attention devoted to evaluating the economic impact on farmer profitability and on community welfare; evaluate autonomous adjustments and adaptation strategies made by farmers to global change; and evaluate the economic, environmental and social sustainability of selected adaptation strategies.

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Session 6: Water Resources Management

ALLOCATING WATER WHEN AND WHERE THERE IS NOT ENOUGH

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ABSTRACT

Water is essential for life. It is also an essential part of the production of everything else we consume and use. Water is a part of the concrete, steel, glass, plastic and wood contained in the building you are in, and everything in it including the chair you are sitting in and the book you are reading. With few exceptions, water is needed for everything you see through the windows where you are. Humans use water not only to stay alive, but to provide the food, the clothes, the energy, and all the other materials we consume to maintain the standard of life we lead. In spite of the entire engineering infrastructure devoted to the treatment, regulation and beneficial uses of water, occasionally sufficient quantities and qualities of water become scarce. When this happens, just how do we decide how much less water to allocate to all of us who want it to sustain and enhance our quality of life? This paper addresses some of the complexities of answering such a question, especially as society increasingly recognizes the need to provide flow regimes that will maintain healthy aquatic and floodplain ecosystems that also impact the physical and even the spiritual quality of our lives.

We are indeed a part of our ecosystems. We depend on these ecosystems to sustain our wellbeing. We depend upon on aquatic ecosystems to moderate river flow qualities and quantities, reduce the extremes of floods and droughts, reduce erosion, detoxify and decompose waterborne wastes, generate and preserve flood plain soils and renew their fertility, regulate disease carrying organisms, and to enhance recreational benefits of river systems. This question

of deciding just how much water to allocate to each water user including the environment, especially when there is not enough, is a complex, and largely political, issue. This issue is likely to become even more complex and political and contentious in the future as populations grow and as water quantities and their qualities become even more variable and uncertain.

INTRODUCTION

We all know water is essential for life. We also know that many people – too many - are not getting enough of it, both quantity and quality, that allow them to live healthy lives. And for many of the world's poor, access to clean water too costly. For some countries, the percentage of people lacking adequate water supplies exceeds well over half of their total populations. As a result, many, especially the very young, die. Others are constantly sick, and hence cannot achieve their full productive potential (UNESCO, 2003 and 2009). So, the question is just how can we "optimize water for life" especially in situations where there is not enough to satisfy even the basic needs for life? How do we make decisions on how much water to allocate to each of the many beneficial uses of water in times of water stress?

In addition to drinking water, people need food and clothing, and the production of all of the world's food and fiber requires water. There is nothing we eat or wear that doesn't depend on water. The production of energy, either thermal (including nuclear) or hydropower, requires water. The materials in the buildings we live and work in, and their contents, require water for their manufacture. Water also serves as an inexpensive means of transporting cargo and water-borne wastes. And very importantly, we need water to maintain viable and diverse ecosystems. We depend upon our environment and ecosystems to sustain the quality of our lives, and indeed life itself (Postel et al. 1996; Fischlin, 2007).

In the past decade, progress has been made in providing more people with access to clean drinking water and basic sanitation. But a major effort is still required to extend these essential conditions to those still without them, the vast majority of who are poor and cannot pay the costs of these basic services. In addition, we are increasingly recognizing that we humans will not easily survive in the long run unless we pay attention to maintaining a quality environment and life-supporting ecosystems. Again, water is needed to do this, and in times of drought determining the 'optimal' allocations of water to sustain our lives, our economic activities, and our ecosystems is indeed a challenging economic and social endeavor (see for example, Doyle and Drew, 2008).

Balancing water demand allocations, especially when the demands exceed supplies, is a complex, and largely political, problem. It is not just an economic benefit-cost issue where all one has to do is allocate water in ways that will equate the present values of all marginal net benefits, unless otherwise constrained, to all water users. Some water use benefits, especially environmental and ecosystem benefits, and most non-use benefits, cannot be expressed adequately in terms of money. This is in spite of many such attempts by many highly respected individuals (Costanza, 1997; Doyle and Drew, 2008; Ecological Society of America, 1997; Daily, 1997) and in spite of the desire for such simplified analyses by politicians. The water allocation problem is likely to become even more complex and political and contentious in the future, as populations grow and as water quantities and qualities become even more variable and uncertain. But at least the political process of making allocations should be informed by the sciences of the likely impacts of alternative allocation decisions (Postel, 2000: King and Brown, 2006).

How can one allocate scarce water supplies optimally among all demands that impact on the quality of, or even the existence of, life – both human and ecosystem life – in times of critical scarcity? A general yet precise answer that fits all circumstances is never clear, but what is certain is that both humans and ecosystems should be kept alive and healthy! If the latter is not sustained, it is not(Postel and Richter. 2003).

HOW MUCH WATER DO WE NEED?

Just how much water does society need, now and into the future, to be sustainable? By 2025, an estimated 3.4 billion people will be living in countries defined as water-scarce. Many in those countries seem to be able to survive on as little as 3 liters per day. It takes about 3,000 liters of water to produce a daily ration of food, about 1,000 times what we minimally need for drinking purposes. Much of our food comes from irrigated lands. On average over 70% of total freshwater use in the world is devoted to irrigation. Over the next 30 years, about 70 % of gains used in cereal production are expected to come from irrigated land (UNESCO, 2009).

Water is needed for energy as well. Hydropower provides a substantial portion of the energy consumed by many countries, and this percent is increasing. Iran is a good example. Thermal energy production converts heat into steam to drive turbines, and water is often used for cooling as well. But the biggest consumer of water for energy production today is that used for the production and processing of crops used for biofuels. The demand for water in the production of biofuels is a growing concern. For example, in the U.S., about 40% of all water withdrawals in the Midwest are for biofuel production. This demand is expected to increase by 80% in the next 30 years. In Europe, where the issue is only beginning to be recognized, water consumption for energy production is expected to be equivalent to the daily water needs of 90 million people by 2030. (DOE, 2006; EPRI, 2002)

Water also transports cargo and assimilates much of our domestic and industrial wastes. In developing countries, more than 90 per cent of sewage and 70 per cent of industrial wastewater is dumped untreated into surface water. (UN, 2006).

Freshwater is vital to human life and societal well-being. Water use for energy production, domestic and industrial consumption, crop irrigation, and ship transport has long been considered a key factor in economic development and consequently human welfare. These direct human and economic uses or purposes have traditionally taken precedence over other commodities and services provided by freshwater.

Historically humans have withdrawn freshwater from rivers, lakes, groundwater, and wetlands for many different urban, agricultural, and industrial activities, but in doing so have often overlooked its value in supporting ecosystems. In more recent years there has been a growing recognition that aquatic and floodplain ecosystems provide many economically valuable services and long-term use and non-use benefits to society. Long-term benefits include the sustained provision of those goods and services, as well as a more resilient and adaptive capacity of ecosystems to respond to future environmental alterations, such as global warming and its impact on the hydrologic cycle. Clearly, the maintenance of the processes and properties that support freshwater ecosystem integrity should be included in debates over sustainable water resource allocations, especially in times of water shortages (Kates, 2001; Gleick, 1998).

The physical evidence of increasing periods of water scarcity (Figure 1) can be found almost everywhere in the world. Water scarcity affects rich and poor countries alike. Nearly three billion people live in water scarce conditions (over 40 percent of the world's population), and this situation could worsen if current population growth trends continue, and if the melting of some of the major sources of water – the glaciers – continues. The manifestations of pervasive water poverty include millions of deaths every year due to malnourishment and water-related disease, political conflict over scarce water resources, extinction of freshwater species, and degradation of aquatic ecosystems. Roughly half of all wetlands have already been lost and dams have seriously altered the flow of roughly 60 percent of the world's major river basins (earthtrends.wri.org/updates/node/264).

The situation only worsens with time. Figure 2 projects available water supplies per person per year by 2025 (earthtrends.wri.org/updates/node/179). The UN estimates that about a sixth of today's world population has inadequate access to safe drinking water, and twice as many do not have adequate sanitation facilities (UNESCO, 2003; 2009). Over a third of the world's population is water stressed. If we assume "business-as-usual" forecasts, by 2050 about 40% of the projected global populations of 9.4 billion are expected to be facing water stress or scarcity, as shown in Figure 3 (Hinrichsen and Upadhyay, 1997). With increasing variability being predicted by global climate models, we may have more people without adequate water more of the time, even in water richer regions.

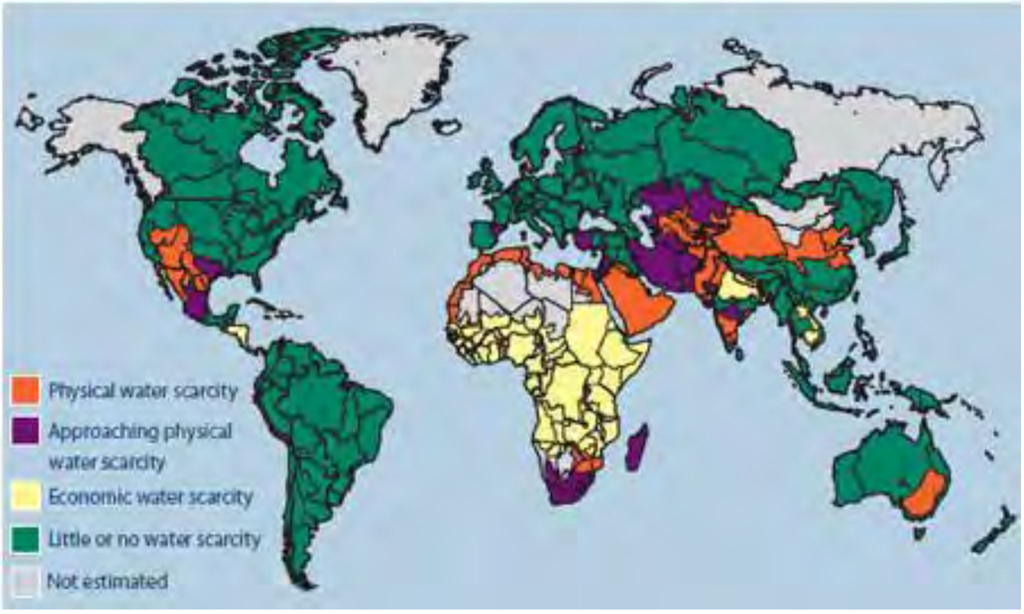

Figure 1: Water scarce regions of the world. Physically water scarce regions are not sustainable. The withdrawal and consumptive use of water exceeds 75% of the supply. Economically water scarce regions have sufficient supplies to meet demands, but potential users lack the means to access that water (earthtrends.wri.org).

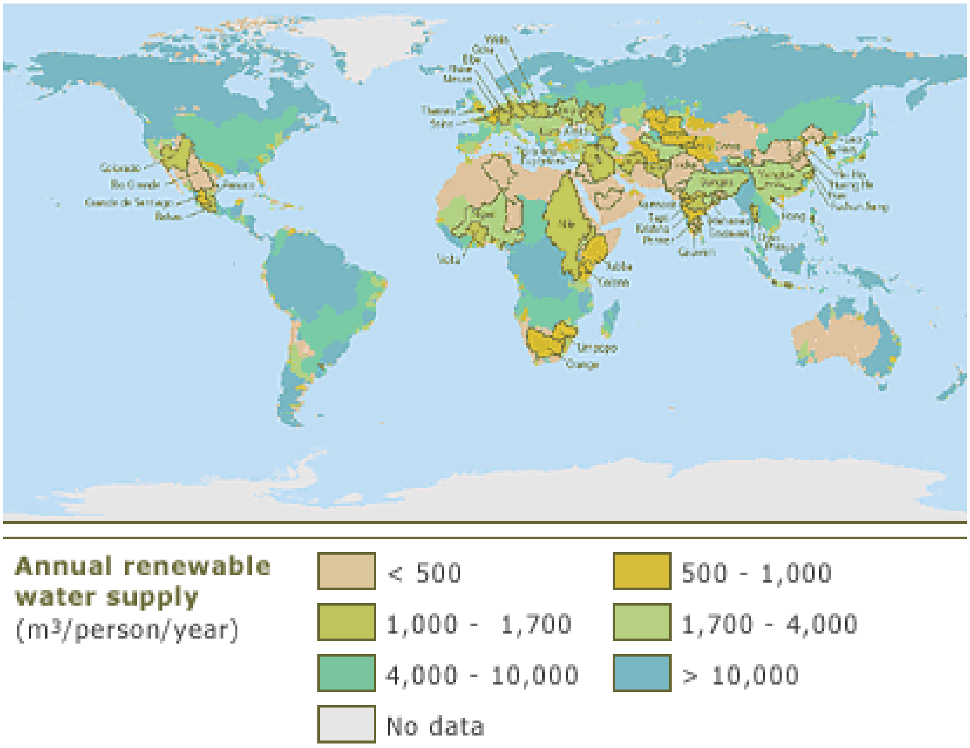

FIGURE 2: A Water Stress Map showing regions under stress whose available supplies in 2025 will be less than 1700 cubic meters per year per person (earthtrends.wri.org/ updates/node/179) .

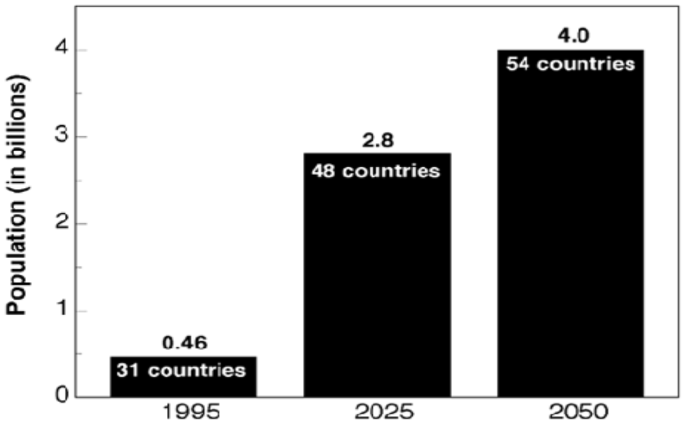

FIGURE 3: Populations in water stressed countries from 1995 to 2050. [**www.infoforhealth.org/pr/m14/m14print.shtml**](www.infoforhealth.org/pr/m14/m14print.shtml)

WHERE IS THE WATER WE WILL NEED?

Most of that freshwater we now use comes from various river basins and aquifers, as shown in Figures 4 and 5. Figure 4 locates 26 of the world's major river basins, and Figure 5 shows the location of the world's major aquifers. Rivers and aquifers will continue to be the major sources of our freshwater in the foreseeable future, in spite of a continual increase in the use of desalinated saltwater.

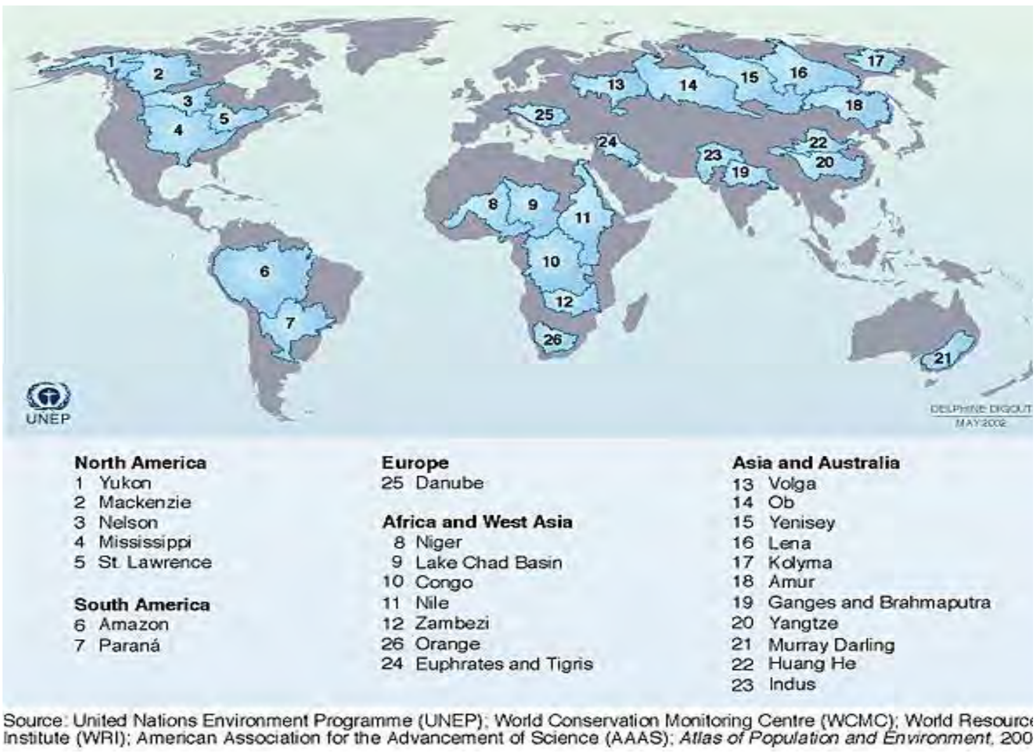

FIGURE 4: Major river basins in the world.

(**http://maps.grida.no/go/graphic/major_river_basins_of_the_world**)

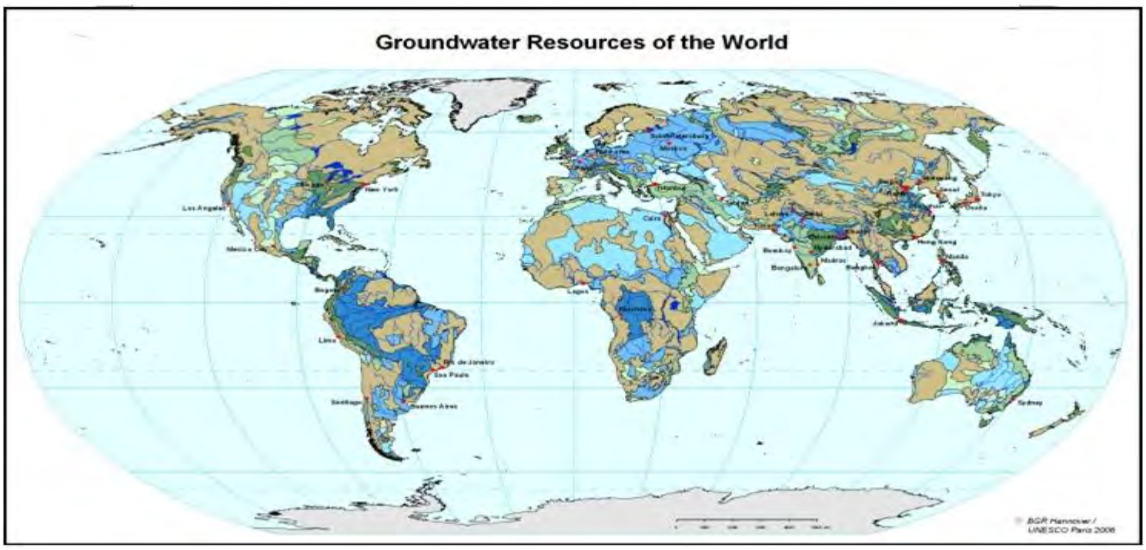

FIGURE 5: Major groundwater aquifers in the world (www.bgr.bund.de/nn_335088/EN/Themen/Wasser).

As illustrated in Figure 5, about 30% of the area of the continents (excluding the Antarctic) is underlain by relatively homogeneous aquifers (blue) and 19% is endowed with groundwater in geologically complex regions (green). Most of the remaining continental area contains generally minor occurrences of groundwater that are restricted to the near-surface unconsolidated rocks (brown).

WHERE IS THERE NOT ENOUGH WATER?

As Figures 1 through 3 suggest, over time an increasing number of places will not have adequate water supplies to meet all water demands, all of the time. Such regions are under water stress.

The countries of the Near East and North Africa face the greatest stress (see Figure 1). The Near East is the most water-short region in the world. The entire Near East uses more water from rivers and aquifers every year than is being replenished. Over the next two decades population increase alone—not to mention growing demands per capita—is projected to push all of the Near East into water scarcity. Many Near East countries are mining fossil groundwater to meet their water needs. Water is one of the major political issues confronting the region's leaders. Since virtually all rivers and most aquifers in the Near East are shared by several nations, current tensions over water rights could escalate into outright conflicts, driven by population growth and rising demand for an increasingly scarce resource (UNESCO, 2006).

Four Gulf states—Bahrain, Kuwait, Saudi Arabia, and the United Arab Emirates—have so little freshwater available that they resort to desalinization of sea water. Without desalinization, the Gulf States would be unable to support their current populations. Desalinization is too expensive and impractical for most water-short countries, not to mention land-locked countries, either today or in the foreseeable future.

Much of sub-Saharan Africa is facing serious water constraints and rapid population growth will make this problem worse. By 2025 some 230 million people will be living in African countries where water is scarce (UNESCO, 2009).

Parts of many large countries, such as India, China, and the United States, face water stress or water scarcity as well. India as a whole is expected to enter the water-stress category by 2025. Both India and China are considering substantial, and expensive, water transfers from water richer to water poorer regions to reduce some of that water stress. And if the glaciers of the Himalayan mountains and Tibetan plateau continue to retreat this will have a substantial impact on hundreds of millions of the world's population that depend on that water flowing in rivers such as the Indus, Sutlej, Ganges, Brahmaputra and the Yangtze, Salween, Mekong and Huang He (Yellow River) (UNEP, 2007).

China has over 20% of the world's population but only about 7% of the world's freshwater runoff. Water pollution, over-exploitation of underground water and low efficiency of water usage along with water shortages have continuously deepened the imbalance between water supply and demand in China (Cheng, et al., 2009). China's freshwater supplies have been estimated to be capable of adequately supplying only half of the country's current population. Despite periodic flooding in the south, along the Yangtze River, China faces chronic freshwater shortages in the northern part of the country. Two thirds of China's major cities, including Beijing, face critical water shortages each year. The water table under Beijing has been dropping by roughly two meters per year (Liu, 2006: http://www.worldwatch.org/node/4407; (http://china.org.cn/english/2003/Sep/76069.htm).

In the US groundwater reserves are being depleted in many areas. Overall, groundwater is being used at a rate 25% greater than its replenishment rate. In some areas of the western part of the country, groundwater aquifers are being depleted at even faster rates. In particular, the Ogallala aquifer, which underlies parts of eight states (shown in light blue in Figure 5 and totaling 173,000 square miles) and provides irrigation and drinking water for one of the major agricultural regions in the world. Withdrawals from the aquifer amount to about 30 percent of the nation's ground water used for irrigation. Additionally, the aquifer provides drinking water to 82 percent of the people who live within the aquifer boundaries. In some regions of Texas and K half of its available water has been withdrawn (http://www.usgs.gov/newsroom/article.asp?ID=121).

COMPETITION FOR SCARCE WATER SUPPLIES

Where and when water is scarce, competition among water users increases, and hence so does the potential for conflict. A number of developed water-short countries currently face tensions over water, including Belgium, the United Kingdom, Poland, Singapore, and the US. In southern Britain, for instance, urban demand for water is outpacing the capacity of rivers and aquifers to meet that demand during the drier summer months. In the western US, farmers who want more irrigation water for their crops are in conflict with growing urban areas that demand more water for households and other municipal uses.

India's states have disputes over water rights and over dams that might provide more water for one state but at the expense of another. Water disputes, if not attended to, could become a major cause of instability in India.

China already is practicing what some call the "zero sum game of water management". The zero sum game—when authorities increase water supply to one user by taking it away from another—is played both between competing areas of the country and between competing types of use, as when cities compete with farmers. China's Yellow River is so oversubscribed that, for an average of 70 days a year for the past decade, its waters have dried up before reaching the coast. In 1995 the dry period lasted for 122 days. To meet urban needs, the government of China is planning an aqueduct that will carry water from the Danjiangkou Reservoir in Henan Province to Beijing, across 1,300 kilometers of heavily farmed land—land that also needs the water for food production (Windfield-Hayes, 2004; Toirkens, 2005)

In nearly all water-short areas the threat of regional conflicts over limited water supplies is emerging as a serious issue. In Africa, for example, about 50 rivers are each shared by two or more countries. In particular, access to water from the Nile, Zambezi, Niger, and Volta river basins has the potential to ignite conflicts.

In Central Asia the Aral Sea Basin is beset by international conflicts over water. Turkmenistan, Uzbekistan, Kazakhstan, Kyrgyzstan, and Tajikistan all depend for their survival on the waters of the Amu Darya and Syr Darya rivers. The flows of both rivers have been almost wholly diverted to feed water-intensive crops such as cotton and rice. Very little if any water reaches the Aral Sea. As demand for this water grows, the countries are increasingly at odds over its division, with all five Central Asian republics demanding a greater share. Disputes are growing between Kyrgyz and Uzbeks over water and land in the fertile Fergana Valley; between Kyrgyz and Tajiks over the allocation of irrigation water from the Syr Darya; and between Turkmens and Uzbeks over the distribution of irrigation water from the Amu Darya.

The Southeastern Anatolia Project in Turkey, known as GAP after its Turkish title (Guneydogu Anadolu Projesi) comprising a network of 22 dams and 19 power plants has significantly reduced the downstream flow of the river Euphrates (and to a lesser extent the Tigris), causing increased salinity and seriously affecting agriculture. The GAP project poses a real threat to future water supplies in Syria and Iraq and hence is a potential source of conflict in a region already embroiled in conflict. Reduced releases of Tigris and Euphrates River waters due to GAP can only inhibit the restoration of some former marsh areas in southern Iraq. But this will not be the only reason for less than complete restoration success. Rapid reestablishment, high productivity, and reproduction of native flora and fauna in reflooded former marsh areas indicate a high probability for successful restoration, provided the restored wetlands are hydraulically designed to allow sufficient flow of noncontaminated water and flushing of salts through the ecosystem. To avoid conflict over water, cooperation among all riparian countries will be necessary (Inan, 2004)

In the US, the Colorado River, which flows through the southwestern part of the country, has fed irrigated agriculture and enabled the rapid growth of desert cities. Now, however, demands on the river's water supply for irrigation and urban use have become so great that the river flow no longer reaches its mouth in Mexico's Gulf of California. Instead, it trickles out somewhere in the desert south of the US- Mexican border. The premature disappearance of the river's flow has been a source of irritation between the US and Mexico (Postel, 1998; Gleick, 1998; Hinrichsen et al.,1997).

In light of all these potential serious conflicts, and need for water to drink, to produce energy, to serve industry and to irrigate crops, just how easy is it going to be to allocate some of what is needed for these other uses to environmental flows?

ESTIMATING ECOSYSTEM REQUIREMENTS

Economics teaches us that to achieve maximum net benefits, the allocation of any scarce resource to multiple uses over space and time should be such that the present value of the marginal net benefits derived from each use, unless otherwise constrained, are all equal. That advice is useful, perhaps, if net benefit functions can be defined for all uses and if everyone agrees that maximizing the present value of total net benefits is a reasonable criterion for optimality. Even if everyone agrees that this objective is worth pursuing, defining net benefit functions is very difficult when it comes to water needs to sustain life. So, the question is what criteria should be used to determine just how much should be allocated to maintain healthy humans and their ecosystems (Postel et al., 1996).

Different ecosystems in different regions have adapted to different flow regimes. But in any region, the fundamental requirement for maintaining aquatic ecosystem health is to maintain critical components of the natural flow regime. Natural freshwater ecosystems have adapted to and depend on natural hydrologic variability. The structure and function of freshwater ecosystems are also linked to the watershed, or catchment, of which they are a part. Aquatic ecosystems are the recipients of materials generated from the land, and hence they are greatly influenced by terrestrial processes, including human modifications of land use and cover. The environmental drivers that influence freshwater ecosystem structure and function include not only the flow regimes, but also the accompanying sediment, organic matter, nutrients and various pollutants, the thermal and light characteristics, and the interactions among the mix of species making up the ecosystem and in turn, their combined interactions with the water and land (Hughes et al., 2005).

The water stress indicator (WSI) map shown below as Figure 6 applies to environmental water needs – the amount of water needed to keep freshwater ecosystems in a fair condition. It was developed using global models of hydrology and water use. Red areas show where environmental water needs are not being satisfied because too much water is already being withdrawn for other uses.

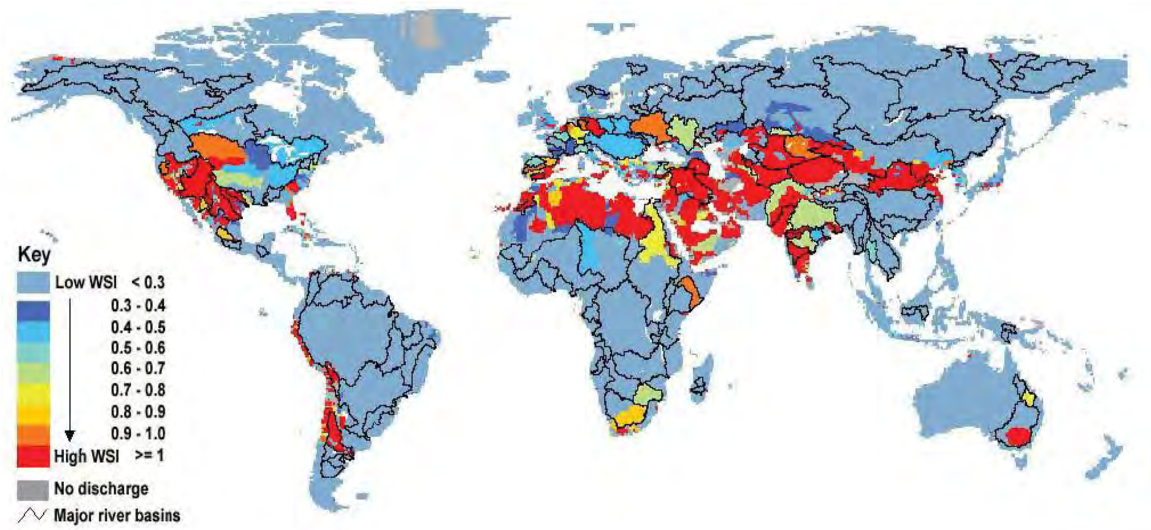

FIGURE 6: A current Water Stress Indicator Map that shows regions where environmental flow needs are not being met (http://www.cgiar.org/enews/june2007/story_12.html).

Estimating just how much water should be allocated to instream environmental flows, particularly in data-poor arid areas, can be challenging. Those deciding on what water allocations to recommend or make can benefit from having models that can predict ecosystem and geomorphologic responses to flow changes, and the impacts of such changes on other users of the rivers. Generally these predictions depend on several characteristics associated with the flow regime. These include base flow, annual or frequent floods, rare and extreme flood events, and annual variability. Flow regimes and hydroperiods also influence the circulation patterns, renewal rates, and types and amounts of aquatic plants in lakes and wetlands. So it is not just a minimum required flow that is needed, it is a regime of varying flow conditions. This adds to the complexity of 'allocating' flows to the environment during periods of water supply stress.

QUANTIFYING ECOLOGICAL RESPONSES TO VARIOUS WATER ALLOCATION POLICIES

One approach to quantifying the relationships between water regimes and ecosystem responses is to link hydrologic attributes (that can be managed) to the quality of the habitat of key species indicators. The use of these habitat suitability index methods tends to be concentrated in the northern hemisphere and in developing countries influenced by the work of ecologists in the United States and Europe. More holistic approaches are being applied in the southern hemisphere, especially in South Africa and Australia (Tharme, 2003).

Environmental flow assessment (EFA) methods are termed holistic if they address the management of all non-pristine river ecosystems, all major abiotic and biotic components of the ecosystem, and the full spectrum of flows and their temporal and spatial variability (King and Brown, 2006). This typically requires the use of various models or modules of a larger ecosystem response model, such as:

1. a biophysical module designed to maximize understanding of an aquatic ecosystem and predict the effects of flow change on the stream, wetland, lake or river,
2. a social module designed to maximize understanding of how people use the water resources and to predict how they would be affected by changing flows and qualities,
3. a module used to compile scenarios of hydrologic changes and the impact on people, and
4. an economic module in which the costs as well as the benefits of development scenarios can be identified and evaluated.

The EFA approach makes the condition of the water body a priority management issue while still considering economic benefits. It is designed to identify the trade-off between economic development benefits and the maintenance of sustainable ecosystems. EFA implementation is not an issue for managers alone; scientists need to work side by side with managers to ensure its success and usefulness (Marchand, 2003).

MANAGEMENT ACTIONS AND CHALLENGES

Human society is served in the long term by ecosystem sustainability. We humans must

develop coherent policies that more equitably allocates water resources between natural ecosystem function and societal needs. Our welfare depends on it.

How can society extract the water resources it needs while not diminishing the important natural complexity and adaptive capacity of freshwater ecosystems? The requirements

of freshwater ecosystems are often at odds with human activity, although this need not always be the case. Our present state of ecological understanding of how freshwater ecosystems function allows us to elaborate the requirements of freshwater ecosystems

regarding adequate quantity, quality, and timing of water flow. Effective and timely communication of these requirements to a broad community is a critical step for including freshwater ecosystem needs in future water allocation decisions.

For scientific knowledge to be implemented science must be connected to the political decision making process. Scientists must explicitly identify and incorporate aquatic ecosystem needs in national and regional water management plans and policies. They must include watersheds as well as water in those plans and policies so that water resource allocation decisions are viewed within a landscape, or systems context. Scientists must educate and communicate across disciplines, especially among engineers, hydrologists, economists, and ecologists to facilitate an integrated view of water resource management. Regional environmental managers must include restoration efforts and protect the remaining freshwater ecosystems using well-grounded ecological principles as guidelines. All stakeholders must recognize and acknowledge the dependence of human welfare on naturally functioning ecosystems. All must assist in the development of coherent policies that equitably allocate water to maintain functioning natural ecosystems as well as meeting other societal needs (Hinrichsen, Robey and Upadhyay, 1997). Clearly more research is needed to help identify just how this can best be done in specific situations in the face of non-commensurate quantitative and qualitative performance measures.

CONCLUSION

Ecological processes are often viewed as occurring in remote and exotic places, not as essential to our daily lives, or strongly influenced by our actions. Ecosystem sustainability requires that human society recognize, internalize, and act upon the interdependence of people and the environment in which they live and are a part. This will require broad recognition of the sources and uses of water for human health, societal and ecological needs. It will also require taking a much longer time view of water resource management and its associated infrastructure.

Water delivery systems, including dams, are developed with lifespans of decades, and some operate over a century. Aquatic ecosystems have evolved over much longer periods of time, and their sustainability must be considered for a long period to come. Governmental policies, mass media, and market-driven economies all tend to focus more on perceived short-term benefits. Local watershed groups interested in protecting their natural resources provide a first step toward long-term stewardship. They need to be matched by state and national policies that recognize that fundamental human needs for water will continue on forever (or certainly into the distant future) and can only be sustained through decisions that preserve the life-support systems in the long term.

Conflicting uses, as critical or desired as they are, that have negative impacts on the environment can not be sustained. Especially in times of water scarcity, the environment may have to suffer some because of higher priority uses, but it can not suffer for long. By satisfying the need for naturally varying flow regimes, and reduced pollutant and nutrient inputs, natural aquatic ecosystems can be maintained or restored to a sustainable state that will continue to provide the amenities and services society requires and has come to expect. Managers are challenged, especially in times of water stress, to meet both humans and ecosystem needs, now and in the future. And with increasing population pressures and climate change impacts, periods of water stress will likely increase in duration and intensity.

It is indeed time to focus our best and brightest scientists and policy makers on how best to allocate our increasingly variable and uncertain water supplies to meet increasing demands in a way that optimizes water for life.

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MANAGEMENT TECHNOLOGIES FOR SOIL AND WATER RESOURCES IN RIVER BASINS OF THE CROSS-BORDER REGIONS. A CASE OF NERETVA RIVER VALLEY (CROATIA)

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ABSTRACT

Inappropriate management of a coastal aquifer, highly sensitive to disturbance, may lead to its destruction as a source of fresh water much earlier than other aquifers that are not connected to the sea. Estuaries and river deltas are one of the coastal areas most at risk from human activities worldwide, and many of them are intensively-farmed arable lands. Neretva River Valley is located in the southern part of the Croatian Adriatic coast. Agriculture mainly involves growing of citrus and other Mediterranean fruits, as well as early vegetables, regularly applying irrigation. Irrigation, as a regular growing measure, has led to significant increase in water abstraction, giving rise to growing environmental problems. The research program was set out to develop and validate appropriate knowledge and technologies to improve the production capacity of the available soil and water resources of the region through two main research program components: (*i*) land resources surveys and inventory and (*ii*) soil and water management in saline conditions. Appropriate technologies for the management of saline soils should be developed and adopted, as well as recommendations for the improvement of irrigation schemes. Networking between countries and research centers dealing with soil and water management is inevitable in preventing problems especially trans – boundary pollution.

INTRODUCTION

The decline in availability of freshwater for irrigation due to its allocation to other sectors (urban and industry), especially in arid and semi-arid regions such as the Mediterranean basin, has resulted in intensive use of waters of poor quality. Furthermore, inappropriate management of a coastal aquifer, highly sensitive to disturbance, may lead to its destruction as a source of fresh water much earlier than other aquifers that are not connected to the sea. Besides, large hydrotechnical interventions such as construction of dams, hydroelectric power plants and other hydrotechnical structures can also change the water regime within a catchment area, and consequentially lower the quality of water for different purposes. Estuaries and river deltas are one of the coastal areas most at risk from human activities worldwide, and many of them are intensively-farmed arable lands. All the mentioned combinations occur in the Mediterranean part of Croatia as well as in most Mediterranean and other parts of the world. Water management that focuses on issues such as water allocation and water quality almost always have a cross-border component. Neretva River Valley is located in the southern part of the Croatian Adriatic coast. The most of the catchments area spreads to the neighbouring country. Delta of the Neretva River is a hydro-ameliorated area being intensively used nowadays as a fertile agricultural land. Agriculture mainly involves growing of citrus and other Mediterranean fruits, as well as early vegetables, regularly applying irrigation. Irrigation, as a regular growing measure, has led to significant increase in water abstraction, giving rise to growing environmental problems. Both the quantitative aspect and the problem of water quality and pollution in Neretva River Valley are continuously increasing, whereas agriculture certainly is not the only player disrupting the water cycle and quality (*Romic and Romic, 2007*). Based on all variables mentioned, the research program was set out to develop and validate appropriate knowledge and technologies to improve the production capacity of the available soil and water resources of the region. In order to achieve this goal and purpose in the most efficient way, research in soil and water management is carried out under two main research program components, namely (*i*) land resources surveys and inventory and (*ii*) soil and water management in saline conditions. This program included water quality monitoring, land resources survey, one field trial and two greenhouse experiments.

METHODS

Study Site

The research was carried out in the Neretva River Valley (Fig.1) in the Mediterranean part of Croatia (43°00´N, 17º30´E). The Neretva River runs 225 kilometers and only 22 km through Croatia. The upper river flows swiftly through a mountainous landscape, while the last 30 km spreads into an alluvial delta before emptying into the Adriatic Sea. The Neretva's lower course and delta were shaped by high waters that periodically washed down from the mountains, bringing dissolved organic substrate, the sedimentation of which created fertile soil. In the lower valley in Croatia, the Neretva River splinters into multiple courses, creating a delta covering approximately 12,000 hectares. The delta in Croatia has been reduced by extensive land reclamation projects, and now flows in just three branches, a drop from the previous 12. The marshes, lagoons and lakes that once dotted this plain have disappeared and only fragments of the old Mediterranean wetlands have survived. Nowadays, the main river-bed in the downstream part is under the strong influence of the Adriatic Sea and that is why physical, chemical and ecological processes are similar to those in estuaries.

The area is semi-arid with a Mediterranean climate of hot, dry summers and wet winters. Most rainfall occurs in the period from October to April, with an annual average (1980-2000) of 1230 mm. The mean annual air temperature is 15.7°C, with the highest (25.2°C) in July. Annual Penman-Montheith reference evapotranspiration amounts to 1,196 mm, the highest of 191 mm occurring in July. Climatic conditions are favorable for the field crop production throughout the year. The most of about 6,000 ha of land are used for the field vegetable production and citrus fruits growing, along with irrigation as an obligatory growing measure.

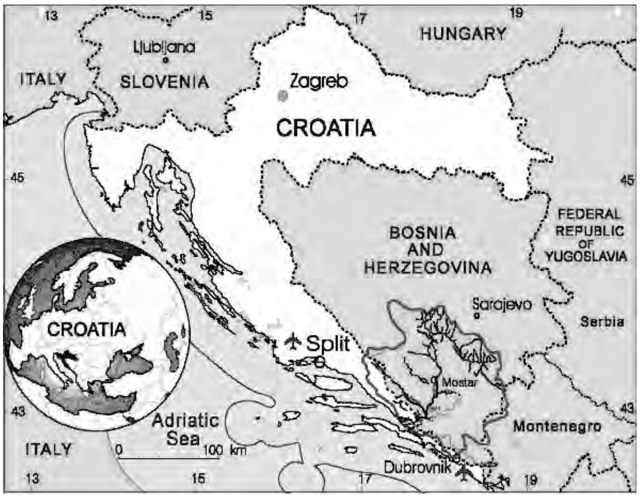

Fig.1: Study area.

Source: SAS Institute Inc. 2004. SAS/STAT User's Guide, Version 80.2. SAS Institute Inc.: Cary, NC.

Water Quality Monitoring

The surface water monitoring program was established in 1997 on 22 locations considered to be potential sources of irrigation water in the Neretva River Valley. Standard protocols for sampling, sample stabilization and analysis were adopted for all water quality variables, pH, electrical conductivity (EC dS m^{-1}) and ionic composition (*APHA, 1992*). The obtained data were statistically processed using the computer program SAS (*SAS Institute Inc., 2004*).

Land Resources Survey

Due to special interest in the region from both an environmental and agricultural point of view, a multi-element pedo-geochemical survey was carried out as a part of a national geochemical mapping project covering agricultural land. The second part of the land resources survey aimed to investigate the potential of predicting salt content in soils with hyperspectral data (ASTER satellite imagery acquired in 2006) (Fig. 2). Salt-affected areas were detected using a normal supervised classification method. Corresponding cropped areas were detected from NVDI (Normalized Difference Vegetation Index) values using an unsupervised method. Field samples and agricultural statistics were used to estimate the accuracy of the classification. Historical data concerning irrigation and drainage as well as the groundwater table were used to analyze the relation between changes in soil salinity and land and water management practices.

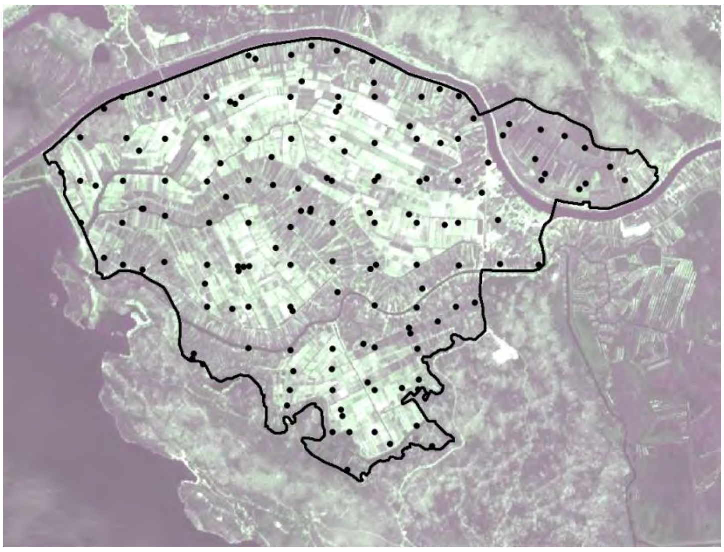

Fig. 2: Surface soil sampling locations (ASTER satellite imagery acquired in 2006).

Experimental Settings

Field trial

The first trial was carried out in 2003 on the experimental plots in the Neretva River Valley which were adjacent to commercial vegetable fields. Soil was classified as Gleysol hydroameliorated (*FAO*, 1990), non-salinized, of uniform physicochemical characteristics. Effects of different irrigation treatments on the growth, yield and mineral composition of the leaf tissue were assessed on watermelon plants. Two irrigation systems - drip and sprinkler, and three saline irrigation treatments (S3, S5 and S7) plus a non-saline control (S1) were tested. Irrigation water of the average ECw of 1.1 dS m^{-1} was pumped from an open watercourse. The saline water was obtained by adding commercial sea salt to the irrigation water. Three dosing units (Netafim dosing system) were used to provide accurate salinity control and water samples were taken in 10-days intervals to be analyzed by standard analytical methods for pH, electrical conductivity and ion composition (*APHA, 1992*). The ECw value was controlled at each irrigation by collecting samples from emitters or sprinklers in particular treatments. Electrical conductivity of irrigation water was measured using a portable EC metre. Irrigation was applied at 2-3 days intervals. Soil samples were taken twice during the experiment. Plant growth parameters were measured during the growing season. Mineral composition of plant tissues was determined, as well as the yield.

Greenhouse Experiments

Two experiments were set up in a polyethylene greenhouse located at the experimental station on the University of Zagreb Faculty of Agriculture (Croatia) in 2004 and 2006. The first one was aimed to test the hypothesis that organic matter decreases the bioavailable Cd^{2+} pool and therefore restricts its phytoextraction. The effect of four salinity levels (0, 20, 40 and 60 mM NaCl) and three Cd levels (0.3, 5.5 and 10.4 mg kg^{-1}) in peat soil on mineral accumulation and distribution as well as vegetative growth and fruit yield parameters of muskmelon (*Cucumis melo* L.) were assessed. The second experiment was done on radish (*Raphanus sativus* L. var. *sativus*, cv. Tarzan).

RESULTS AND DISCUSSION

Soil cannot be considered a simple mechanical filter, but rather a complex system of the mineral origin acting as an active exchanger of the different ions. Therefore, it is very important to know the quality of water that is applied by irrigation. Monitoring of the water quality in addition to the adequate management may certainly prevent the damages on the agricultural land and crops. Analyses of the data obtained by the water quality monitoring showed that salt concentrations in surface waters of the Neretva River Valley changed substantially during the year as a result of the hydrological regime, demonstrating a spatial as well as a temporal variability of the water electrical conductivity and sodium and chlorine concentrations (Fig. 3).

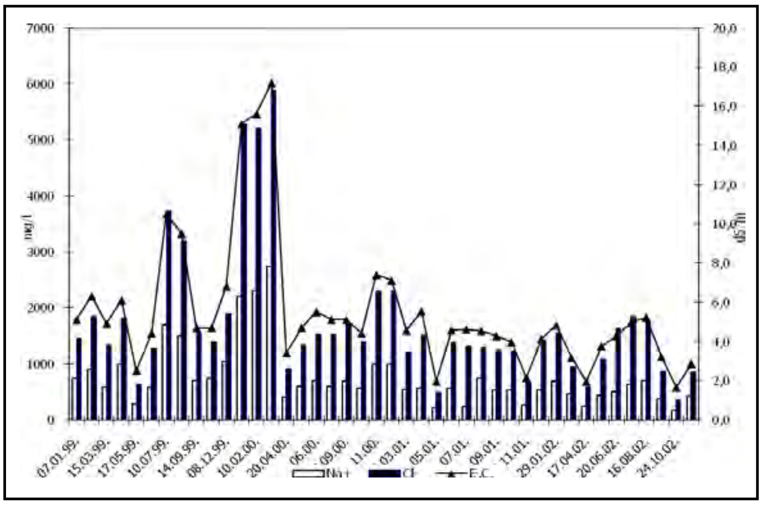

Figure 3: Electrical conductivity, sodium and chlorine concentration in sampled surface water on the location Modric canal (1999-2002).

Application of saline water requires adequate management (*Rhoades, 1992*). Three ways of agricultural soil salinization were determined in the Neretva River valley: by capillary rising of the saline groundwater, irrigation with water of inadequate quality, and bringing out saline sediments to soil surface with ameliorative practices (*Romic et al., 2007*). Therefore, the second topic referred to the sustainability of the existing land use practices, and was aimed at the development and testing of a generic framework for assessing ecological risks associated with farming practices in the Croatian coastal part. The first experiment was set up with the aim to determine the influence of increasing salt concentrations in irrigation water using different irrigation systems (sprinkler and drip) on: crop growth, changes in soil solution composition, changes in leaf tissue mineral content, and changes in crop yield. Saline irrigation reduced the crop growth and thus had detrimental effects on yield. Application of saline water rapidly changed the ion composition of soil solution. Significant changes in Ca, Na and Cl concentrations in soil solution were determined parallel to increasing the irrigation water salinity. The experiment has shown as well that salinity affects nutrient uptake and accumulation and also nutrient partitioning within the plant (Table 1).

Table 1. Content of dry matter and mineral composition of watermelon leaves in the treatment with drip irrigation*

Treatment	Dry matter	Mg	Ca	K	Na	Cl
	%	g/kg				
S1	12.8a	4.6a	113.8a	18.6a	3.9a	10.0a
S3	13.0a	4.2a	120.2a	14.2ab	13.8b	18.3ab
S5	12.9a	4.6a	116.2a	11.7bc	25.6c	25.4b
S7	11.2b	6.0b	118.9a	8.4c	31.8d	42.8c

*The same letter within columns indicates no significant difference at $P \geq 0.95$.

Saline water irrigation resulted in soil salinization as well, causing mainly accumulation of calcium, sodium and chloride (*Romic et al., 2008*). In the case of drip irrigation, increasing water salinity reduced potassium uptake by plants, but enhanced sodium and chloride uptake. Despite the salt-induced yield reductions, the implication for applying water of poor quality using drip irrigation is clear (*Ondrašek et al., 2006*). This is especially valid in the regions with high annual precipitations, occurring mostly during the winter. Beside the usual agricultural management, the possible harmful effects of salt accumulation in soils may thus be prevented also by natural leaching.

Rational management of soil salinization requires an understanding of how soil salt concentrations vary across the land. The key to successful management of salinization is the early recognition of salinized soil; implementation of methods to combat incipient salinization, such as improved irrigation, drainage, and farming practices; and monitoring of salinized land on a regular basis. Conventional techniques of identifying and monitoring salinized land are time-consuming and rather expensive. Therefore, the potentials of remote sensing for identification and monitoring of soil salinization have been used and Chemical analysis of 152 samples collected from the surface soil in the Neretva River delta area shows that salt content was low on average, but very high in certain areas with electrical conductivity exceeding 11dS/m. Dominant chemical in the saline soil was NaCl. Multivariate models were established between soil salt contents and multispectral data (ASTER image). Our results indicate that multiple linear regression (MLR) technique that included soil salinity data and multiple predictors including ASTER satellite image, DEM and distance from sea and open channels did not show a strong prediction capacity. Anyhow, some of the results indicate that remote sensing may be a useful tool in evaluating and improving land and water management practices in this particular region.

Estuarine sediments are frequently rich in contaminants transported from land. Also well known is the ability of sediments to faithfully record environmental impact, including the heavy metal contamination, on fluvial systems over time. For the Neretva estuary, the main source of contaminants is industries in the upper part of the catchment area. The lower part is an intensively agricultural region, producing generally vegetables and fruits, and salinity poses an increasing threat in the Neretva estuary, since the major route of human exposure to toxic elements is via consumption of vegetables grown on contaminated soil. Soil salinity, especially increased concentration of dissolved Cl^- ligands, significantly influences solubility of some trace elements like cadmium (*Ondrašek et al., 2009*). Results of the greenhouse experiment with muskmelon grown on Cd-enriched peat provide evidence that cadmium transfer from saline and contaminated organic soil to edible fruity tissue is low and not mediated by NaCl salinity. These results suggest that (i) muskmelon appears to have low capacity to take up and transport Cd from roots to fruits, and/or (ii) to translocate Cd via phloem from developed leaves to fruits, suggesting that phloem mobility of Cd in muskmelon is relatively poor and unaffected by NaCl salinity (*Ondrašek et al., 2009*). When radish plants were tested, it was shown that cadmium uptake and leaf deposition was markedly enhanced by NaCl, whereas Cd translocation and hypocotyl accumulation was up to 6-fold lower and not influenced by NaCl salinity.

Conclusion

As a conclusion, appropriate soil and water conservation technologies for protection and proper conservation of productive soils and rehabilitation of salinized soils should be fostered and monitored. Appropriate technologies for the management of saline soils should be developed and adopted, as well as recommendations for the improvement of irrigation schemes. Networking between countries and research centers dealing with soil and water management is inevitable in preventing problems especially trans-boundary pollution.

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WATER RESOURCES MANAGEMENT OF THE WETLANDS IN TURKEY

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ABSTRACT

Turkey, at present, has about 250 wetlands. Internationally known are 76 and they extend over 1,295,456 hectares and located on the routes of the immigrant birds and fish. At present, 9 of them are operated and protected by the International Ramsar Agreement. Due to the state policy and accordingly the laws and regulations in act before the 1970's, about 8.4 % of the total wetlands in Turkey were dried and converted into agricultural plots, flood control zones, and malaria eradication zones. Flood control measures taken during the period of 1940-1970 adversely affected the stable ecosystems of 17 wetlands covering a total area of 143,956 hectares.

Water related problems faced in wetland management in Turkey can be listed as: water scarcity due to the recent global warming; depletion of groundwater levels below wetland due to uncontrolled pumping, build up of extensive drainage canal networks, and reservoirs on rivers feeding wetlands, sand and gravel quarries; pollution due to wastewater and solid waste deposition areas neighboring the wetlands; illegal hunting and fishing; sudden reed fires; soil and channel erosion; and wrong operation techniques.

The wetland protection awareness and related studies by both non-governmental and governmental organizations started at the beginning of the 1980's. The Ministry of Environment was established in 1991 and "Wetland Protection Regulation" was declared in 2005. The protection policy, initiated in 1970, has focused on the sustainability of biodiversity of existing wetlands. The Bern Agreement (Agreement of Wild Life Protection) was signed by Turkey in 1984.

The aim of this study is to present the historical development of environmental management concept in Turkey, starting from the Ottoman Period, and the ecological problems of the natural wetlands of Turkey. In this sense, some facts and figures about the wetlands of Turkey are presented simply to describe the different types of problems of Turkish wetlands. A set of constructive comments are exemplified on water resources management of natural wetlands with

reference to state water management policy. Additionally, current laws and regulations related to wetlands and some projects about wetland protection are presented. EU Water Framework Directive implementation studies during the transition period for Turkey are described. Several cases (including the Amik Plain and Lake Wetland, European Union Water Framework Directive implementation at Büyük Menderes River Basin, World Bank GEFII Project at Sultansazlığı Wetland, European Union Life Project at Uluabat Lake and World Wild Life Foundation project at Tuz Lake Basin, Maritza River and Göksu Lagoon) are summarized and presented as case studies. Turkey, being aware of the importance of biological diversity and sustainability, and having a high eco-tourism potential in and around wetlands in the country, has to make an integrated protection and preservation program of wetlands and minimize the potential problems.

1. INTRODUCTION

Wetlands can be defined as "Areas that are inundated or saturated by surface or groundwater frequently or for a duration sufficient to support and that under circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions and generally wetlands include swamp, marshes, bags and similar areas" (Lyon, 1993). On a global scale, wetland desiccation studies began at the end of 1800's in order to stop malaria in the world. For example USA lost nearly half of its wetlands because of this reason (Özesmi, 1997). Spain lost more than 60% of its wetlands in the last 50 years (Gallego and Fernandez, 1999). Wetland desiccation by drainage canals began in the early of 1940's in Turkey and in the last 50 years a total of 57% of wetland areas have been converted into agricultural area (Caliskan, 2008). Significant efforts have been made for wetland reclamation over the last 15-20 years, both by the government and NGOs.

The aim of this study is to describe the wetlands and provide insight about the water resources managements of the wetlands. Information about the present wetlands of Turkey had been collected in order to describe the problems of the wetlands. Additionally, current laws and regulations concerning the environment and wetlands with some examples about wetland preservation are given. EU Water Framework Directive implementation studies during the transition period for Turkey are described. The wetland of Amik Lake, Büyük Menderes River Basin, Sultansazlığı, Uluabat Lake, Tuz Lake, Maritza River and Göksu Lagoon are presented as case studies.

2. ENVIRONMENTAL CONSERVATION IN THE WORLD AND IN TURKEY

2.1. Environmental Protection in the World

Starting from the 1970's globally, a series of international agreements for the protection of birds, wild life, biology, oceans, wetlands, ozone layer, and air pollution control, water quality control and nuclear pollution control have been signed and ratified by many counties.

The following international organizations have in a way been active in environmental and ecological problems on a global scale. These include UNDP (United Nation Development Program), FAO (Food and Agricultural Organization), WMO (World Meteorological Organization), WHO (World Health Organization), UNESCO and HABITAT under the umbrella of United Nations (UN). Also IMF (International Monetary Fund), EC (European Community), DECD (International Economic Cooperation and Development), NATO and volunteer organizations like Green Peace are rather active (Gürer ve Gürer, 2005). The Ramsar Convention (convention regarding internationally important wetlands) was signed in 1971. Habitat Meeting was held in 1972 at Stockholm. World Environment Development Commission was founded by UN in 1982 and after 4 years this commission published a report "Our Common Future." Rome Convention (Single European Act) was signed in 1987. According to this convention natural resources, human health and the environment must be protected. Limoges Statement, which was published in France in 1990, expresses the importance of national environmental law education in the universities of the developed and developing countries. A UN Conference on Environment and Development was held in Rio De Janeiro in 1992. The Rio Declaration had 27 basic principles regarding the environment and development (Öztürk, 2007). International Water and Environment Conference was held in Dublin in 1992. In 1992, EU European Council declared the "Habitat Directive," which includes a range of wetland systems in its list of habitats for priority protection and this directive also includes an obligation to undertake environmental impact assessment for activities planned around the wetlands. The directive is about the conservation of natural habitats, wild fauna and flora (Pearce, 1996; EEA, 2006). Bonn Convention (convention about migratory species and wild animals) was signed in 2004 (GNF, 2004). The 13th Conference of UN Climate Change Framework Convention and the 3rd Conference of Kyoto Protocol were both held on 3-15 December 2007 at Bali and a roadmap was formulated to tackle the climate change (Maden, 2008).

2.2. Environmental Institutionalization of Turkey

2.2.1. Historical background of environmental studies in Turkey: Clean environment was important for the Ottoman Empire, for example the Sultan Mehmet I took precautions in order to prevent the pollution at the Golden Horn (Haliç Bay). He banned agriculture and forestry activities around the Golden Horn. During the period of Sultan Süleyman the Magnificent, the first environment law in the world had been declared in 1539. According to this law, solid waste disposal and waste water discharge at the urban area were banned and development plans of the cities were revised in order to protect the environment. Tannery plants in Jerusalem were moved outside of the city in order to prevent the bad odor. Sewage pipe lines were constructed in 16th Century at Istanbul. Gedikpaşa Bath wastewater collection pipe line was constructed in 1568 (Öztürk, 2007). Wetland reclamation studies began in the 19th Century, consisting of wetland mapping and wetland drainage studies. Lake İznik and Büyük Menderes River were cleaned in the 19th Century. During the Ottoman Empire period, flood control studies were initiated at the end of the 19th century, according to the regulation declared on 7 January 1890. According to another regulation, which was declared on 26 December 1901, urban development at forest zone was banned. Also, some studies on natural disasters preventions such as earthquake, flood and storm were systemized during the Ottoman Empire period. Environmental protection studies were financed by the Ottoman treasury, charitable foundations and local people (Öztürk, 2007).

2.2.2. Present state institutions on environment: Ministries concerned with the environment are:

-Ministry of Environment and Forestry
- The Ministry of Culture,
- The Ministry and Tourism
- Ministry of Agriculture
- The Ministry of Public Works and Settlement,
- The Ministry of Health
- The Ministry of Interior: Municipalities

In the Ministry of Environment and Forestry, the main service units are:

- General Directorate for environment management
- General Directorate for environment impact assessment and planning
- General Directorate for erosion control and reforestation
- General Directorate of forest-villager interactions
- General Directorate for nature protection and national parks
- Directorate for research and development
- Directorate for international relations and European Union Office
- Directorate for education and printing
- Directorate of Conservation of Cultural and Natural Resources
- General Directorate of National Parks

Within the structure of the Ministry of Environment and Forestry, in addition to the regular ministry works and personnel, a series of expert groups were set up such as: Environmental Higher Board, Environmental Council and Local Environmental Units.The work definition of this ministry can be summarized as:

- Protection and improvement of the environment
- Optimum utilization and protection of the natural resources of rural and urban areas
- Preservation and improvement of the natural flora and fauna of the country
- Prevention of environmental pollution

- Preservation and enhancement of forests
- Improvement of the economy and living conditions of the villagers living within and / or at close neighborhood of national forests
- Development of forest industry.

Besides the above listed state organizations, there are other state organizations and scientific organizations concerned with the environmental issues, such as;

-General Directorate of Conservation of Cultural and Natural Resources
-General Directorate of State Hydraulic Works
-General Directorate of Bank of Provinces
- Scientific and Technological Research Council of Turkey (TÜBİTAK)
- Prime Ministry, State Planning Organization
- Environmental Engineering Departments of the Universities
- Environmental Research Centers

Being the main institute in Turkey in charge of planning and managing of water resources development projects with integrated approach, especially in recent years, General Directorate of State Hydraulic Works of Turkey (DSI) keenly observes the possible negative impacts on environment. DSI has adopted the principle of sustainable development in all water related projects (Gürer ve Gürer, 2005).

2.2.3. Nongovernmental (volunteer) organizations on environmental issues: In recent years, especially in the developed countries, the non governmental organizations are more involved and work for the environment and give the impression that they are more sensitive to the environmental problems (Gürer and Gürer, 2005). In Turkey, many non-governmental organizations were formed; NGO's which are working on international and national level are actively participating in the discussions concerning environmental problems and policies and protection concepts. Some of them are;

- The Society of Nature and Animal Protection in Turkey (founded in 1955)
- The Foundation of Environment Protection and Greening (founded in 1972)
- The Society of Natural Life Protection (founded in 1975)
-Foundation of Environmental problems (founded in 1978)
- Foundation for Protection and Promotion of the Environmental and Cultural Heritage (ÇEKUL) (founded in 1990)
- The Turkish Foundation for Combating Soil Erosion, For Reforestation and the Protection of Natural Habitats (TEMA) (founded in 1992)
-The Foundation of Environmental Education (founded in 1993)
-World Wild Foundation (WWF) Turkey (founded in 1996)

-The Society of Bird Research (founded in 1998)
-The Society of Environment (DOĞA DERNEGI) (founded in 2000) (Gürer and Gürer, 2005).

2.2.4. International agreements signed by Turkey: Turkey signed the Bern Agreement (wild life protection) in 1984, the Rio Agreement (biological diversity) in 1992, the Ramsar Agreement (wetland protection agreement) in 1994, the UN Climate Change Framework Convention in 2004, and the Kyoto Protocol in 5 February 2009.

The concept of environment conservation is very important for EU. European Environmental Agency (EEA) was set up on 7 May 1990 according to the regulations of European Union (EU), in order to create a data base and thematic reports, to work on integrated environmental evaluation, to support the periodic reporting system, to build infrastructure for monitoring, and finally to set up the administrative units. All members of the EC and some of the European Free Trade Association (EFTA) countries are members of EEA and they are connected by the thematic network of European Information and Observation Network (EIONET). (Öztürk, 2007). "Polluter pays" principle was accepted at Maastricht EU Convention in 1992. The Importance of the concepts of sustainable development and environment protection was declared at Amsterdam EU Convention in 1997. The EU publishes "Environmental Action Program (EAP)." The 1st EAP covers 1973-1977, the 2nd EAP covers 1977-1981, the 3rd EAP covers 1982-1986, the 4th EAP covers 1987-1992, the 5th EAP covers 1993-2000 and the 6th EAP covers 2005-2010. These action plans concern human health, climate change, biodiversity and waste management (Yasamis, 2001). The EU planned to combine all directives concerning the environment in one comprehensive regulation. The European Union Water Framework Directive (WFD) was accepted in December 2000. WFD regulates integrated water management of Europe (Akar and Koç, 2007). At present, EU-WFD implementation studies continue. Since the implementation of EU Water Framework Directive, Turkey has enforced various directives such as: integrated pollution prevention control, wild bird, waste water treatment, nitrate, solid waste, etc. EU WDF textbook includes the following items regarding wetlands: Item 8 states that "EU Commission adopted a communication to European Parliament and the Council on the wise use and conservation of wetlands." Item 16 states that "Further integration of protection and sustainable management of water into other Community policy areas such as energy, transport, agriculture, fisheries, regional policy and tourism is necessary." "Common principles are needed in order to improve the protection of Community waters in terms of quantity, quality, sustainable water use, protection of aquatic and terrestrial ecosystems and wetlands," according to Item 23 of WFD. Actually, the purpose of the EU-WFD is to protect and enhance the status of aquatic ecosystems, terrestrial ecosystems and wetlands regarding to their water needs and to promote sustainable water use based on a long term protection (Official Journal of EC, 2000). In October 2000, Turkey and EU signed an agreement and Turkey became a member of EEA and EIONET. This agreement was ratified by Turkish parliament on 23 January 2003 with the law No: 4794 (Öztürk, 2007).

2.2.5. Present juristic structure: As in many fields of life, environmental considerations in Turkish society have been taken into the state administrative structure. Starting from the establishment of the new Turkish Republic in 1923, almost all the institutions responsible for environment were in the structure of municipalities (Municipalities Law No: 1580), city councils and village leaders. By the laws of municipalities and general health, "Environment and Public Health" are guaranteed by the state in Turkey. The first environmental organization in Turkey was set up with the government decree dated 27.07.1978, and No: 16041 as "Environment Under secretariat" and became responsible for all of the political decisions related with the environmental issues and also the coordination between national and international organizations. In the 1982 Turkish constitution, it is stated that "everybody has the right to live in a healthy and stable environment. It is the duty both of state and the people to improve the environment, protect the environment and prevent the environment's pollution." The Turkish state issued the first environment law on 11.08.1983.

Starting with the 4th five-year period State Development Planning (DPT) report, covering the period of 1980-1985, the environmental problems have been listed in development plans. For example in the 7th report covering the period of 1996-2000, all the arrangements related to the development and protection of environment, are given under the headlines of: 1. Current situation, 2. Purpose, principles and policies, 3. Juristic and institutional arrangements. The 8th report ,covering the period of 2000-2005, states that a sustainable development approach is important for human health, environmental protection and economical development, and the environmental politics of Turkey, and it must be integrated with the social and economical politics of Turkey. According to this plan, all stakeholders must work together in order to solve the environmental issues, and environmental politics of Turkey must be in accord with the international and EU standards. The 9th report,covering the period of 2006-2013, states that "Polluter pays" principle is important for the environmental protection and this puts responsibility on Turkey according to UN Climate Change Framework Convention. Additionally, the report states that the development of an urban infrastructure and environmental protection are important for the social and economical development (www.dpt.gov.tr).

The Ministry of Environment was established in 1991 and wetland protection studies began in Turkey. The first "Wetland Protection Circular" was issued in 1993. Laws and regulations which have relationship with the wetlands and environment can be listed as "Groundwater Law (1960, revised in 2006)", "Groundwater Regulation (1961)", "Fishery Law (1971)", "Environment Law (1983)", "National Parks Law (1983)", "Environmental Impact Assessment Regulation (1993, revised in 1997 and 2008)", "Water Pollution Control Regulation (2004)", "Solid Waste Control

Regulation", "Wetland Protection Regulation (2005)", "Urban Wastewater Treatment Regulation (2006)" "Money punishments Circular for the polluters (2006)", "Environmental Noise Assessment Regulation (2008)", "Air Quality Assessment and Management Regulation (2008)", "Air Pollution Control Regulation (2008)", "Air Pollution Control at Industrial Area Regulation (2008)", "Packing Waste Control Regulation (2008)", "Swimming Water Quality Regulation (2008)" and "Environmental Landscape Planning Regulation (2008)". "National Wetland Commission" was established in 2000 and National Wetland Strategy Plan for 2003-2008 was prepared. This commission prepared wetland management plans for Göksu Lagoon, Manyas Lake, Uluabat Lake, and Gediz Delta before the end of 2006. Wetland management plans of Sultansazliği, Kizilirmak Delta, Burdur Lake, Eber and Aksehir Lake, Erzincan Wetlands, Adiyaman Lake and Yumurtalik Lagoon are under preparation by the same commission. The Ministries of Environment and Forestry were united as one ministry with the law dated on 01 May 2003 (www.milliparklar.gov.tr).

3. Important Wetlands of Turkey and Their Problems

Turkey has about 250 wetlands, at present. 9 of them are protected by the International Ramsar Agreement. Meric Delta, Uluabat Lake, Tuz Lake, Sultansazligi Wetland, Göksu Logoon, Büyük Menderes Delta and former Amik Lake are selected as case studies and shown in Figure 1.

3.1. Former Amik Lake

The wetlands of former Amik Lake (*Figure 1*), near Hatay city, used to cover a total area of 31,000 ha before being desiccated in the 1940's for flood control, and the plain was converted to cotton fields. Desiccated area was given to the poor farmers. The former wetland area is partly flooded in wet years. There is an airport construction area at the location of former Amik Lake (Caliskan, 2008).

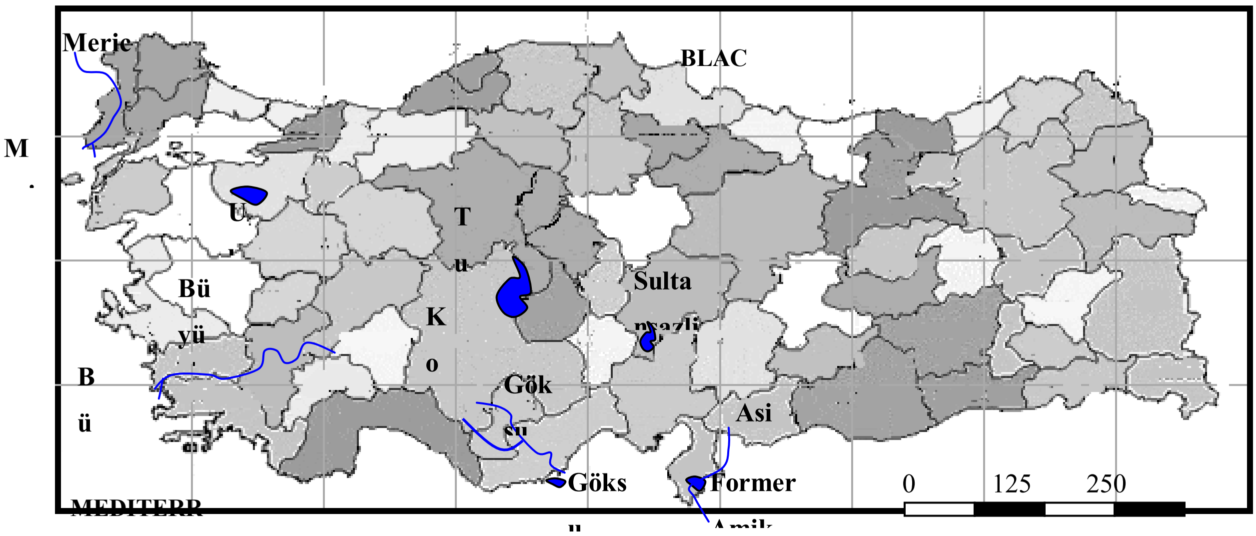

Figure 1: Some important wetlands of Turkey (modified after Yildiz, 2007).

3.2. Tuz Lake (Salt Lake) and Wetlands of Konya Closed Basin

At present Tuz Lake (*Figure 1*) lost half of its area because of the climate change both at the Konya closed basin and Tuz (Salt) Lake Basin. Groundwater level drops about 1 m each year and sinkholes similar to those of the Dead Sea zone, Israel, were formed. Pollution is a big threat to the groundwater and also the lake water. Almost all domestic and industrial wastes from surrounding towns like Sereflikochisar, Kulu, Cihanbeyli, Eskil and Aksaray are discharged into lake without any treatment. Several provinces began planning wastewater treatment plant projects (Köse, 2008). There are many wetlands at Konya Closed Basin. For example Esmekaya and Hotamis Wetlands dried entirely, Akgöl Eregli Wetland dries during dry season and there are water scarcity and pollution problems at Beysehir, Sugla, Kulu, Samsam and Meke Lakes which are placed at Konya Closed Bain. One of NGO; WWF-Turkey started a project called as "Towards Wise Use of Konya Closed Basin" in order to provide conservation and wise use of water resources and wetlands of Konya Closed Basin. (Tektaş, 2004).

3.3. Sultansazlıgi Wetland

At Sultansazligi Wetland, located at Develi closed basin (*Figure 1*), almost 90% of the total wetland area was dried due to agricultural use of the incoming water. All stakeholders in World Bank GEFII project try to solve the water shortage and wetland water pollution problem. Turkish State of Hydraulic Works planned inter-basin water transfer from the Zamanti basin by using Zamanti (Gicik) tunnel to supply irrigation water needs at Develi closed basin. Additionally Sultansazligi Wetland will be fed by the water which will be transferred from Zamanti River. Sultansazligi has been protected by Ramsar Convention. Sultansazligi Wetland is important for the migratory birds. (Gürer, 2003; Yildiz, 2007).

3.4.Uluabat Lake

Uluabat Lake is placed at Susurluk Basin (*Figure 1*), the main problem of this lake is pollution. Additionally, water shortage is a significant problem due to unauthorized water diversion for rice plantations from inflowing Mustafa Kemal Pasa Creek. Total lake area was 165 km^2 in 1965. The lake's area dropped down to 116 km^2 in 2002. Uluabat Lake is one of Ramsar Conservation area. NGOS and other stakeholders try to solve the environmental problems of Uluabat Lake. WWF-Turkey, Ministry of Environment and Forestry and other related stakeholders prepared an environment management plan for 1998-2002. This plan was the first participatory and functioning management plan of Turkey. Additionally Globe Nature Fund (Germany) and WWF-Turkey added Uluabat Lake into "Living Lakes Project". This project has been financed by EU Life Program. Coordinator of this project for Uluabat Lake is WWF-Turkey (Gattenlöhner, 2006; Gürer ve Yildiz, 2008).

3.5. Büyük Menderes Delta

The Büyük Menderes Delta is located at the southern part of Izmir city, near the Aegean Sea (*Figure 1*). The main problem of this delta is water pollution because untreated industrial wastewater (mercury, cadmium and chromium from leather industry) flow through Büyük Menderes River (EEA, 2006). In order to conserve this river and Büyük Menderes Delta; a consortium lead by a company from Netherland has provided support to the Turkish Government for the implementation of Water Framework Directive (EU-WDF). Büyük Menderes has been selected as pilot area for WFD Implementation Project. This project has national and regional levels. Büyük Menderes River Basin Management, which is based on sustainable and integrated water management, had been prepared according to European WFD requirements (TNWP, 2008).

3.6.Meric (Maritza) Delta

Meric (Maritza, Evroz) River is located at the northwestern part of Turkey (*Figure 1*), this river flows at the borders of Greece and Bulgaria. Water level in Maritza Basin decrease because of increasing water needs. The Meric River is evaluated as one of the polluting source of Aegean Sea. Cooperation among the riparian countries (Turkey, Greece, and Bulgaria) is important for the solution of quantity and quality problems of the Meric River (Gürer and Gürer, 2005).

3.7. Göksu Lagoons

Göksu Wetland is placed at Göksu Delta near the Mediterranean Sea (*Figure 1*). Göksu Wetland consists of the Paradeniz Lagoon (salt water), the Akgöl Lagoon (fresh water) and reed-field area covering total 2,130 ha. This wetland has been protected by the International Ramsar Agreement. Göksu wetland is important for the migratory birds. Seal and sea turtles live at this zone (www.cevreorman.gov.tr).

CONCLUSIONS

Historical background of Turkey about environment, state and non-governmental organizations dealing with the environment are presented in this study with the current laws and regulations concerning the environment. Additionally EU Water Framework Directive implementation studies at Turkey, wetland problems such as water scarcity and pollution are described. The environmental conservation studies, at some wetlands which are selected as case studies, are also introduced.

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COMBINATION OF CATCHMENT BASIN MODELING AND ECONOMIC ANALYSIS TO DETERMINE OPTIMAL REHABILITATION STRATEGIES FOR MULTIPLE USE TRANS-BOUNDARY STREAMS

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ABSTRACT

This paper deals with a hydro-economic modeling of the Alexander-Zeimar River basin, which is a transboundary river originating in the Palestinian Authority (PA) and flowing through Israel to the Mediterranean Sea. Since the 1950's, the river has become a sewage outlet, used by Israelis and Palestinians alike. The major purpose of the study was to estimate the costs and benefits derived from the restoration plan which has been conducted in the river since the mid 1990's. Another goal was to examine further cleanup efforts. In order to achieve these goals, the net benefits of different cleanup strategies both with and without cooperation between IL and PA were compared.

Three aspects of the system were examined: river hydrology, pollution abatement costs, and pollution abatement benefits. A hydrological model was developed, which made it possible to trace pollution transport along the river, and to examine the effects of possible reduction measures. This gave the opportunity to test how reduction in pollution is related to costs and benefits.

Benefits were derived by different methods: Water diverted to agricultural uses was assigned the shadow value of water in the region. The remaining clean water in the river provided a non-market benefit, which had to be estimated by non-market valuation methods. Two such methods were used: Travel Cost Method (TCM), to estimate the situation in 2005, and Contingent Valuation Method (CVM), to estimate future water clean up efforts.

The Cost Benefit Analysis (CBA), with respect to the 2005 *vs.* 1995 situations, revealed that treating all major pollution sources resulted in a positive net benefit of $0.5 \cdot 10^6$ US$/y. Of this sum, about $2.67 \cdot 10^6$ US$/y are non-market net benefits. Financially, the river is a net loser by $2.18 \cdot 10^6$ US$ annually, but socially there is a net gain. With respect to future water quality upgrade, it was found that the best alternative was to treat both of the river's main focal points: the "turtle bridge" (IL) and the Peace Park (PA). It was estimated that the net benefit in such case would reach about $1 \cdot 10^6$ US$, while treating either one of the two separately would create a lower positive net benefit.

INTRODUCTION AND BACKGROUND

The Alexander-Zeimar River runs for about 44 km, from the western side of the Samaria Mountain Belt across cultivated areas and past towns of the Coastal Plain to the Mediterranean Sea (Figure 1). The Alexander River is the name given to the lower section of the river, which runs through the coastal plain within Israel (IL), while the upper, Palestinian (PA) section is known as Wadi Zeimar. The basin is small (about 500 km^2) but heavily populated (total population of 600,000 inhabitants, Figure 2), with two major towns, Nablus (PA) in upper part of the river and Netanya (IL) close to the river mouth.

Domestic as well as industrial wastewaters (some raw/untreated) have been discharged into the Alexander-Zeimar River and have introduced considerable pollutant loads over the past 40 years. These have degraded the water quality and the ecosystem of the river, turning it into an open sewage canal.

Figure 1: Map of Israel and the Palestinian Authority showing the Transboundary catchment basin of Alexander-Zeimar River

In 1995, a master plan was put forth to restore the Alexander River. Its main focus was to treat the problems in the river's drainage basin and to eliminate the pollution sources affecting the river (Friedler & Juanico, 1995). Ten year onwards (2005), the execution of the plan significantly improved the quality of the river's water and preserved wide areas along the banks for recreation. However, there is still some considerable work to be accomplished in order to fully rehabilitate the river. In addition, while the master plan dealt with the lower part of the system, no rehabilitation activity was initiated in the upper section of the river, in Wadi Zeimar.

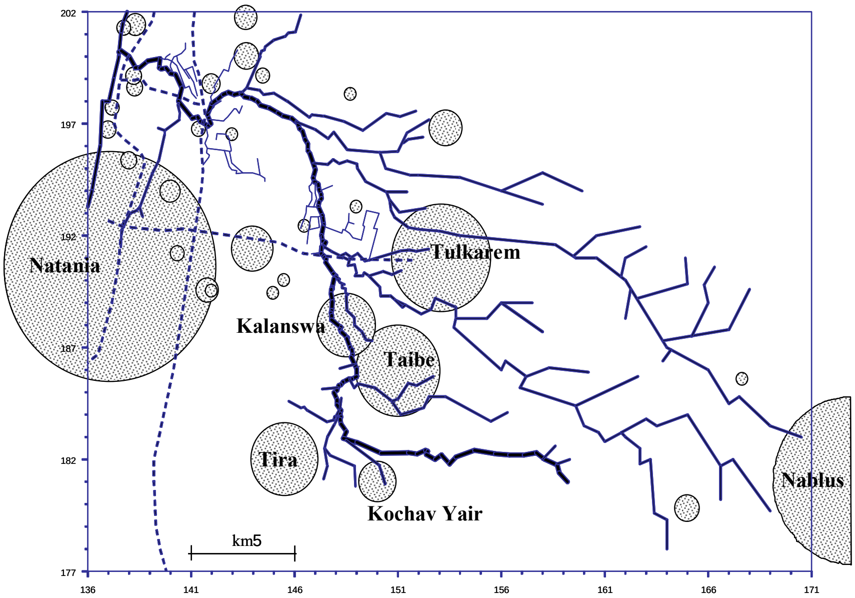

Figure 2: Population distribution in the Alexander-Zeimar River basin (Sizes of circles are proportional to the population in each town/city)

RESULTS AND DISCUSSION

The study had two major tasks:

1) To review the effectiveness of work already executed in both sides of the river (the Palestinian Authority's and the Israeli sides) on a cost benefit basis. This included an assessment of the demand for water services, the management of pollution, the improved environmental value of the river in terms of recreational use, and the establishment of an effective management plan.

2) To analyze the effectiveness of future management scenarios both in the Israeli and the Palestinian sides.

A prior step of this analysis was to collect all available data regarding water quality, water quantity and pollution sources in the river basin for a given baseline year. 1995 was chosen as this baseline year, since it was the last year before the rehabilitation program was initiated. The past situation (which was named the basic scenario) was compared with the 2005 situation.

The data collected served as input for a suite of three models developed by ESS GmbH (Environmental Software and Services, Austria) as part of the OPTIMA project:

1) WRM Water Resources Model – basin wide hydrological model;

2) RRM – Rainfall-Runoff Model, the output of which serves as input to the WRM model;

3) STREAM - A dynamic water quality model that utilizes WRM scenarios, sharing the network and daily flow data generated by WRM.

The models were quantified and calibrated for the Alexander-Zeimar River basin. The topological structure of the river under the two scenarios (1995 and 2005) is depicted in Figure 3. Water quality at the turtles' Bridge (one of the focal points of the river), as predicted by the STREAM model for 1995 and 2005, is presented in Table 1. It can be seen that for all three parameters modeled, the water quality in the river in 1995 was worse than the Israeli regulations required for river water quality. On the other hand, in 2005 (ten years into the rehabilitation program) the average concentrations of BOD and D.O. were better than the required standards, with a Biological Oxygen Demand (BOD) average of about 9 mg/L (<10) and an average Dissolved Oxygen (D.O.) of 5 mg/L (>3). However, even in 2005, the microbial quality of the river water failed to meet the required microbial quality, as indicated by the findings of Faecal Coliform concentrations that were higher than the maximum allowed concentration by 2 orders of magnitude on average. This, and the high fluctuations in the water quality stresses the need for further improvement.

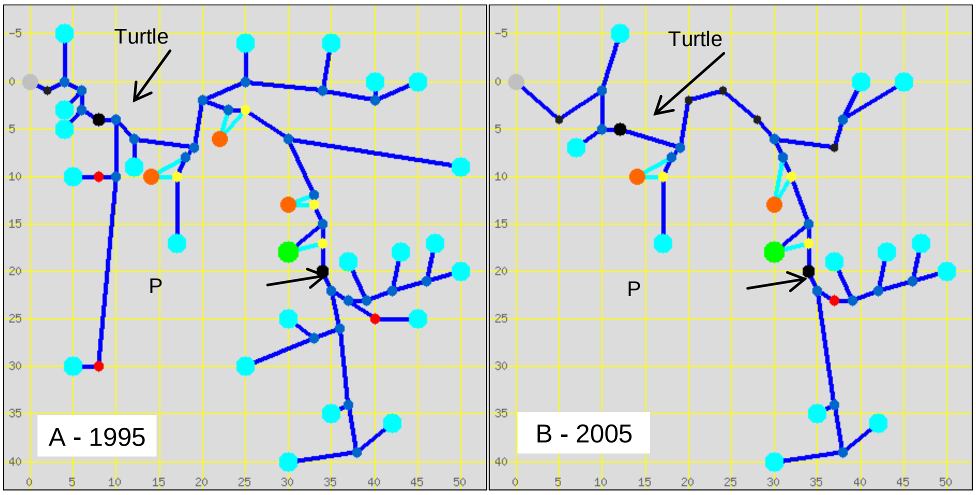

Figure 3: Topological structure of the Alexander-Zeimar basin as represented in the WRM, RRM & STREAM models

A – 1995 – The basic scenario (before rehabilitation)

B – 2005 – 10 years into the rehabilitation (it can be noted that many pollution sources were disconnected from the river, as indicated by the simpler topological structure)

The efficiency of the rehabilitation efforts to date was assessed by performing a cost benefit analysis conducted *ex-post* facto, used when a project is already under way. This approach made it possible to test if the investments in rehabilitation were successful, both from an overall point of view as well as from individual stakeholders' points of view. It did not, however, lead to the finding of an optimal investment program. A valuation study of the recreational use of the river was performed. A zonal travel cost model (ZTCM) was employed (Bockstael *et al.*, 1989; Bowker *et al.*, 1996; Willis, 1991). This was based on 300 people surveyed at the site, who were asked about their location of origin, the frequency of their visits to the river, and provided some socio-economic data.

Table 1. Water quality in Alexander-Zeimar River near the turtles' bridge focal point 1995 *vs.* 2005

Parameter	1995			2005			Israeli Regulations
	Avg	Min	Max	**Avg**	Min	Max	**Avg**
BOD [g/m3]	**68**	4.8	190	**9.1**	negligible	280	**10**
F. Coli [CFU/100ml]	**6.6E+6**	7.8E+4	4.5E+7	**2.4E+4**	negligible	1.4E+5	**200**
D.O. [g/m3]	**2.4**	0	6.5	**5**	0	8	**3**

The total annual costs of rehabilitation of the river (from 1995 to 2005) were estimated at $6.22 \cdot 10^6$ US$/y, while the total direct benefits were calculated to be $4.04 \cdot 10^6$ US$/y (Table 2). Thus, based on these figures, the river actually loses money every year. However, when the indirect costs and benefits of tourism are considered, then a positive *net* benefit of about 500,000 US$/y is produced. It should be emphasized that the tourism benefit is the non-market value of the river for tourists, which represents the social value of the river.

Table 2. Cost benefit analysis of the 1995-2005 rehabilitation effort

	Use	Description	Cost / benefit [10^6 US$/y]
Costs	Agricultural Demand	Amortized Capital Costs	0.36
		Operation & Maintenance Costs	1.2
	Supply – start nodes	Amortized Capital Costs	0.7
		Operation & Maintenance Costs	1.3
	Pollution Abatement	Amortized Capital Costs	0.71
		Operation & Maintenance Costs	1.9
	Reservoirs	Amortized Capital Costs	0.40
		Operation & Maintenance Costs	0.10
	Total Costs		**6.22**
Benefits	Agricultural Irrigation		3.8
	Landscape irrigation		0.19
	Other		0.05
	Total Direct Benefit		**4.04**
Net Benefit (direct only)			**-2.18**
Tourism		Cost	0.63
		Benefit (non market value)	3.3
Net Benefit (including indirect benefit)			**0.49**

Scenarios explored for future development considered either an attempt to reach the water quality regulations separately at each of the two focal points (Turtles' Bridge and Peace Park, Figure 3), or to work towards an integrative solution, whereby the requirements would be met at both of the focal points jointly. To reach water quality standards at the peace park, would require upgrading the Tul-Karem (PA) WWTP and the construction of an extra chlorination unit (PA), at a total cost of $1.07 \cdot 10^6$ US$ (Table 3). The cost of meeting water quality regulation standards at the Turtles' Bridge alone was estimated at $0.66 \cdot 10^6$ US$, while overall cost of meeting the water quality requirements in both points was about $1.16 \cdot 10^6$ US$.

Table 3. Costs associated with meeting water quality regulation standards at the focal points of the Alexander-Zeimar River

Action Needed	Peace Park (PP)	Turtles' Bridge (TB)	PP + TB
Tertiary treatment of Tul-Karem WWTP	0.46	-	0.46
Chlorination unit - Excess discharges of Tul-Karem WWTP	0.61	0.65	0.65
Chlorination of effluent of Kalansawa-Tnuvot reservoir	-	0.05	0.05
Total	**1.07**	**0.66**	**1.16**

* All costs in 10^6 US$

Analysis of possible future scenarios could be conducted by ZTCM ,since given their hypothetical status ,they would require an *ex-ante* analysis. Therefore, to perform this analysis, the Contingent Valuation Method (CVM) was employed, in which possible future scenarios were shown to a representative sample of visitors and they were then asked about their willingness to pay for the given water improvement scenario (Hagen *et al.*, 1992; Mitchell, 2002). Figure 4 depicts the willingness of the sampled population to pay distribution. From the willingness to pay survey, the value of future development with respect to stricter water quality standards was calculated to be $2.2 \cdot 10^6$ US$. As there is no way to divide the extra benefit between the Peace Park and the "Turtles' Bridge," it was assumed that the added benefit would be equally shared.

Based on the costs described in Table 3 and the benefit derived by the CVM method, it was possible to calculate the *net* benefit for the different alternatives. It is interesting to note that investing in the two sites together was the preferred option (Table 4). Nevertheless, investing in either focal point alone also passed the cost benefit test. Investment in the Peace Park alone has only a negligible net benefit, while the better option is to invest at the Turtle Bridge site. Taking into account that the Peace Park can contribute to more peaceful life conditions for Israelis and Palestinians along the river, it may be concluded that the shadow price of peace in this situation is $0.60 \cdot 10^6$ US$, compared to the investment in Turtle Bridge alone.

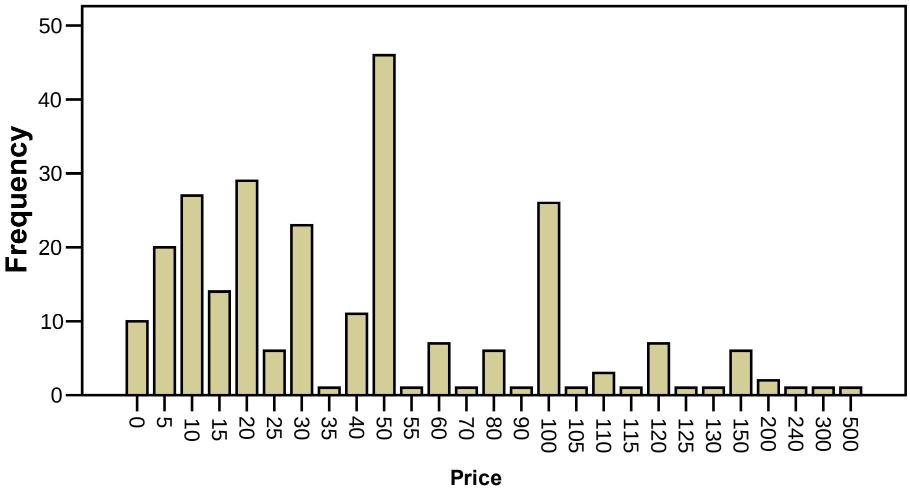

Figure 4: Willingness to pay distribution

Table 4. Cost-benefit analysis of meeting water quality regulations in the focal points of the Alexander-Zeimar River

	Peace Park (PP)	Turtles' Bridge (TB)	PP+TB
Costs	1.07	0.66	1.16
Benefits	1.10	1.10	2.2
Net Benefit	**0.03**	**0.44**	**1.04**

* All s in 10^6 US$

Conclusions

This case study dealt with managing a cross border river in which there is a strong interdependence between different users. The major concern in the Alexander-Zeimar River is water pollution. We have conducted two economic analyses. The first one tested the 10 year long process, conducted between 1995 and 2005, of rehabilitating the river. The second analysis tested future scenarios of meeting stricter water quality standards, which would enable more water use along the river.

In order to perform the first analysis the entire river system was modeled from a hydrological point of view. Then the costs associated with the rehabilitation project period were estimated. These costs were compared with benefits derived from the rehabilitation project, including the categories of market and non-market benefits. Market benefits were calculated from the shadow price of the wastewater removed from the river and diverted to agricultural use, while the non-market benefits were derived by the Travel Cost method. The *net* benefit was estimated to be about $0.49 \cdot 10^6$ US$/y.

To perform the second economic analysis, the incremental costs associated with stricter water quality standards were estimated. These were measured at the two focal points of the river, namely the Turtles' Bridge (IL) and the planned Peace Park (PA). The costs associated with these stricter standards were contrasted with the benefits. This time there were only non-market benefits involved and, since it is a hypothetical scenario, the CVM was used to estimate these costs. The major conclusion here is in line with that of the first economic analysis: undertaking both projects seems to be the best alternative. If we restrict ourselves to only one project, the Turtles' Bridge is the better option. However, in order to foster cross border cooperation, the alternative cost of creating a Peace Park is about $0.6 \cdot 10^6$ US$

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Session 7: Advances in Soil-Water-Plant Modeling

MODELING FOR RISK MANAGEMENT AND ADAPTATION SCIENCE IN AGRICULTURAL ECOSYSTEMS AND ENVIRONMENTAL POLICY

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ABSTRACT

Water is arguably the most critical resource for agriculture. Increasingly, competing claims for water lead to disputes and conflicts in many parts of the world. The causes of water shortages are multi-faceted, ranging from natural climate variability and climate change to higher demand due to increased population pressure and governance issues. This water debate is a typical example of an issue of high importance and considerable social relevance that needs to draw science out of its disciplinary comfort zones: the issue crosses many levels of temporal, spatial and disciplinary scale and requires scientific approaches that facilitate such scale transition.

In maintaining a viable agricultural sector, science must contribute to providing effective and socially acceptable solutions to overcome issues such as water shortages. For example, engineering-based water saving techniques, biotechnology and adaptive farm business management strategies all offer a range of potential adaptation options that should be assessed in

terms of their broader environmental, economic and social consequences and in terms of their locations- and situation-specific feasibility. Such assessments require "systems thinking" – the ability to quantitatively consider the consequences of proposed systems changes, across a wide range of temporal, spatial and disciplinary scales. Modeling assists in ensuring that technological innovations go hand-in-hand with changes in water management via ex-ante, probabilistic evaluation of technology by management interactions, i.e., models can become essential tools for operational risk management.

For examples across these various scales, we discuss how modeling approaches can be used to evaluate efficacy of potential innovations at various levels of integration: from genetic engineering to cropping systems management and policy setting. We show how through modeling, scale-specific knowledge can be integrated to generate insights into complex system interactions such as the production consequences of alternative biochemical photosynthesis pathways (C_3 vs C_4); predicting phenotypic expressions of complex traits in breeding programs; optimizing crop management via functional-structural plant modeling, quantifying G×E×M interactions in a changing climate and using models to optimise farm business designs. We show how all these measures need to be assessed taking the prevailing environmental policy into account. We conclude that a more formal attention to the emerging field of adaptation science might be helpful in this context.

INTRODUCTION

Systems thinking acknowledges that in dynamic systems, components interact, creating behaviours and outcomes that can be very different from viewing these components in isolation. Systems thinking places equal importance on understanding dynamic interactions between parts as on understanding the functions of the parts themselves. The system of interest (and its outputs) needs to be viewed and evaluated holistically, including the key linkages and interactions between system components. For agro-ecosystems it is particularly important to identify the leverage points where management can influence systems behaviour and where technological options can either provide incremental or transformative improvements. Successful technological and managerial innovations need to go partner with adaptive risk management and an equally adaptive policy environment (Nelson et al., 2008). Ex-ante, model-based evaluation of such technology by management - policy interactions can be helpful in better understanding the myriad of potential adaptation options. Frequently, model output is used to evaluate alternative management options or technologies probabilistically (e.g., Hayman et al., 2007; Landis et al., 2008). Used in such a way, models then become essential tools for operational risk management (Meinke and Stone, 2005).

Agricultural systems bear many of the hallmarks of complex, adaptive systems (CAS) that generally have three key characteristics: (i) order emerges rather than being predetermined, (ii) the history of the system is largely irreversible, while (iii) the system's future can only be predicted probabilistically (Dooley, 1997). Cause and effect relationships become increasingly intangible as a system becomes more complex and open (Nelson et al., 2007). In extreme cases, there may be "no scientific basis on which to form any calculable probability whatever. We simply do not know!" (Keynes, 1937, p. 214). For plant-based systems, which are generally regarded as intermediate in terms of their complexity and openness, effective integration across various scales is further challenging due to their intrinsic interdisciplinarity (ranging from genetics, molecular biology, plant physiology to plant nutrition, soil sciences, hydrology and social sciences, to name just a few disciplines). This is further complicated by the frequent lack of empirical data[12] needed to test hypothetical options. Under such circumstances, models can often replace traditional, *in vivo* approaches to data collection (i.e., experimentation) with *in silico* approaches that enable a rapid ex-ante assessment of the likely outcomes of alternative management or decision scenarios. Although such models can be difficult to apply because the type of information they contain often differs from traditional methods of deductive decision analysis, new approaches based on inductive reasoning and large ensembles of *in silico* experiments now allow for the systematic evaluation of alternative policy or management options (Lempert, 2002). Such *in silico* approaches complement and add value to experimental approaches that remain essential at all aggregation levels of the system. System modeling allows us to ask the critical "what if"-questions needed to investigate the impact of choices in agro-ecosystems management and policy. Here we explore some of the possibilities that simulation modeling provides in determining options suitable for crop production under water limitation.

RESULTS AND DISCUSSION

(1) Crop Systems Biology – From Cells to Plants

The new discipline of crop systems biology (a) brings the information from functional genomics to the crop level, (b) introduces true biological mechanisms in many current crop models, (c) better explains the organization of the whole crop and its response to environmental conditions, (d) fills the vast middle ground between '-omics' and crop physiology using models, and (e) promotes communication across scales. As a discipline, crop systems biology simulates complex crop-level traits relevant to global food production and energy supply by linking 'omics'-level information, biochemical understanding, and crop physiological component processes. For

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[12] Empirical data is often lacking due to either the impossibility of experimenting on the real system or simply because of a lack of resources.

instance, Yin and Struik (2008) showed that a successful genetic modification to equip the rice plant with C_4 photosynthesis would enable it to substantially increase biomass production.

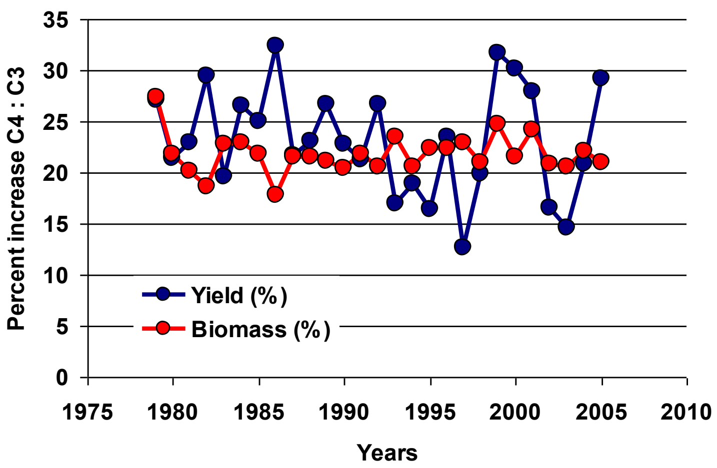


Fig. 1: Simulated yield and total biomass increases (t ha^{-1}) of irrigated C_3 vs C_4 rice if grown in Los Banos, Philippines, during the dry season based on historical climate records 1979 – 2006.

This modeling work entailed incorporating equations for C_3 and C_4 photosynthesis, combined with a stomatal conductance model, into the mechanistic crop model GECROS. They found that for the same amount of nitrogen uptake, the grain yield advantage of C4 rice (average 23%) varied considerably, depending on climatic conditions even when sufficient irrigation water was supplied (Fig. 1). This is considerably less than the 50% hoped for by Mitchell and Sheehy (2006). Higher grain yield advantages of C_4 rice can only be expected at the cost of higher nitrogen inputs. Essential in crop systems biology is to properly map the organization levels and the communication systems between these levels for the different key processes, from the molecule or gene, all the way up to the crop (Hammer et al., 2006). For example, Chenu et al. (2008) implemented an hourly time-step model of leaf growth response to temperature, leaf-air vapour pressure deficit, and soil water deficit into a daily time-step crop model. This model allowed existing knowledge about the genetic controls of leaf growth to be scaled up, to allow evaluation of genetic impacts on crop yield given different drought environments. Modeling tools based on crop systems biology can generate important crop physiological insights and lead to investigation of important societal issues, such as improving food security or zinc supply for human nutrition in rice-based diets (e.g., Jiang et al., 2008). Further, systematic evaluation at this level of integration can also contribute to scientific debates such as the recent emergence of "plant neurobiology" that Struik et al. (2008) critically reviewed.

(2) Functional-Structural Plant Modeling– From Form to Function and Back

Plants respond to their environment by adapting their functions (e.g., light interception, photosynthesis, transpiration, N allocation) as well as their structure or architecture (e.g., buds either break or remain dormant; size, shape and orientation of organs). Functional-structural plant models (or virtual plant models), explicitly describe the development over time of the three-dimensional (3-D) architecture or structure of plants as governed by physiological processes, which, in turn, are driven by large scale environmental factors (Vos et al., 2007). Such models offer options to develop a coherent research program aimed at advancing plant (or genotype) × environment × management interactions. They show promise as (a) a research tool in plant sciences, (b) a new tool supporting plant management decisions and (c) a support tool in plant breeding through exploring morphological and functional aspects of plant ideotypes. For instance, Evers et al. (2007) developed a 3-D wheat model in which local light interception determines the outgrowth of a tiller, providing feedback mechanisms between organ and whole crop phenomena of growth and development (Fig. 2). Such models can then be used to investigate, for instance, competition for resources. In the case of intercropping, different crops can act competitively and synergistically – at the same time. *In silico* studies are needed to clarify how functional-structural plant interactions in intercrops at the organ level affect plant structure and functioning, while experiments are indispensible to estimate the net effects of such interactions robustly, and provide a reality check for the modeling. For instance, the (partial) shade provided by different companion crops generally reduces overall biomass accumulation of the understory crop, but can also lead to quality improvements (e.g., coffee) that might (in economic terms) more than compensate for the loss in production volume (Vaast et al., 2006).

Fig. 2: Example of a virtual wheat canopy, using L-systems; model based estimation of red : far red ratio in the 3D structure. Developing tillers are highly sensitive to this ratio, hence tillering is strongly influenced by plant architecture (from Chelle et al, 2007).

(3) Ecology of Mixed Plant Systems – Lessons from the Past

Modern, mechanized agriculture has largely led to monocultures, often associated with low biodiversity and often sub-optimal resource use efficiency. The recent emergence of the cereal grain (especially maize) as a supposedly "economically viable" resource for ethanol production has increased this pressure considerably (Landis et al., 2008). The excitement around biofuel has also led to proposals to establish large plantations of toxic and slow-growing weed species such as *Jatropha* with potentially negative impacts on the health of workers and local environments. There is ample evidence that systems that are more diverse, e.g., agroforestry systems, mixed grass swards or (relay) intercrops, are more productive than monocultures, because they are better able to capture the available resources of light, water and nutrients (Zhang et al., 2008). Further, plant mixtures have been shown to be more resilient to biotic stresses arising from pests and diseases (Wolfe, 2000) and abiotic stresses such as climate variability (including low-frequency fluctuations). Nevertheless, contrary to Eastern countries, such as China, mixed plant systems are rarely exploited in the West, with grass-clover mixtures in organic agriculture a notable exception. The simplification of agricultural systems as expressed in short crop rotations and monocultures, is largely driven by industrial demands for uniform raw material, scale enlargement in the generation of modern starting material and the practicalities of increasingly mechanized crop management, although it is well known that diversification and inclusion of perennial species in cropping systems can increase robustness against biotic threats, reduce erosion, make the landscape more attractive, provide ecosystems functions, such as biological pest control, and possibly sequester carbon. With only few case studies available, the generic understanding of resource use in mixed cropping systems is incomplete, the technological advances to manage such systems are in their infancy and there is only a limited capacity to calculate, explain and predict the benefits of mixtures compared to single species. Any potentially negative side effects of mixed cropping on the ability to use crop rotation as an effective tool for the management of soil-borne pests also need to be resolved. Yet, mixed systems may be indispensable, in order to meet the rapidly increasing demand for multifunctional use of available land. This highlights an important knowledge gap that can be filled by proper combination of *in vivo* and *in silico* experimentation of mixed plant systems.

(4) Designing Climate-robust Cropping Systems – Towards *Adaptation Science*

Social sciences in combination with systems modeling can create “social capital” by (a) upscaling from an understanding of crop physiological responses to field-scale environmental conditions and (b) downscaling from an understanding of global climatic conditions to “quantities” that motivate farmers: farm income and the long-term sustainability of their resource base (Meinke et al., 2006).

Simulation modeling provides an effective means of bridging the inevitable disciplinary divides by creating new insights and helping decision makers at all scales to evaluate alternative options. Stakeholders can then engage in informed discussions about these alternative options, negotiate a desirable consensus outcome, and then engage in a process of innovation by design. To be most effective, modeling should be conducted in an open, transparent and participatory style that creates legitimacy for the approach and fosters global collaboration and communication.

The impact of climate change on many natural and managed systems is now beyond doubt (Rosenzweig et al., 2008). Amongst the managed systems, agro-ecosystems are arguably the most climate-sensitive sectors in our global economy (Easterling et al., 2007). Many developing countries remain heavily dependent on agriculture for national income, food security and employment, while agriculture occupies a special place in the national psyche of many developed nations (Meinke et al., 2007). Hence, any successful efforts to reduce the vulnerability of this sector to climate-related risk are likely to lead to considerable benefits, both economic and social. Particularly in developing countries, farmers' coping capacity is limited by (a) lack of resources, (b) lack of knowledge and c) institutional barriers. Nonetheless, adaptation has become a critically important aspect of risk management. We define adaptation as a set of actions undertaken to maintain the capacity to deal with current or future predicted change. The challenge is to determine the composition of an optimal "set of actions."

Deliberate actions to modify systems can be viewed as a collection of enabling technologies and their management. The knowledge component behind these enabling technologies can be termed *Adaptation Science*, a special form of sustainability science[13], occupies the boundary space between science and society and builds social networks that connect agricultural and climate science with decision makers and institutions thereby creating social capital[14]. It is a scientific approach that helps practitioners to determine the best mix of technical or managerial options, including when, where and how to use these enabling or transformational technologies. Adaptation science is designed to allow practitioners and policy makers to negotiate policy by management responses from a position of knowledge in addition to their experience, tradition and intuition (factual knowledge can never be expected to be the sole or even major driver for decision making; Gardner, 2009). Used effectively, the approach aligns policy intent with management practice. It helps to avoid or at least discourage "perverse" policy incentives such as subsidizing poor or unsustainable management practices and is an important step towards the implementation of the principles of adaptive governance (Nelson et al., 2009). Adaptation Science also helps to reduce costs associated with risk and change management by supporting informed decision making. It has the potential to increase enterprise profitability and environmental performance through early assessment of management alternatives. Research includes investigation of better and more relevant ways to use new and enhanced climate information (including climate forecasts; e.g., Lo et al., 2007; Maia and Meinke, 2008). It also considers natural resource implications in conjunction with impacts on crop production and quality and deals with farm-enterprise issues in addition to crop and cropping systems issues (e.g.,

[13] Sustainability science integrates social, environmental and economic research within an interdisciplinary planning, action and policy framework. It pays equal attention to how social change shapes the environment and how environmental change shapes society (Clark and Dickson, 2003).

[14] Social capital includes the institutions, relationships and norms that shape the quality and quantity of a society's social interactions. The approach is based on the understanding that providing relevant and credible information can motivate people to take pro-active management decisions. 'Good' climate risk management depends on various dimensions of social capital, namely peer groups, networks, trust, collective action, social inclusion, information and communication. These dimensions capture both the structural and cognitive forms of social capital (Meinke et al., 2006).

Nelson et al., 2007). Although technological progress in one discipline can sometimes trigger quantum leaps (e.g., the introduction of synthetic fertilizer), in most cases multidisciplinary problems require multidisciplinary solutions and a focus on integration of disciplinary-based science (Howden et al., 2007). An example is genetic engineering for conferring pest resistance in crops. Although this technology has undisputed economic and environmental benefits, its system-wide implications are still insufficiently understood for the technology to gain the broad-based societal endorsement needed before it can be fully implemented. While much of the component science has been done, a better understanding and communication of the risks and benefits of this technology is still needed. Analogous to the science – policy relevance gap (Meinke et al., 2006; Nelson et al., 2008), a similar chasm remains unbridged between science and society. Adaptation science might be a consolatory step towards reducing this gap.

Proactively designed adaptation does not come easily to a sector that values tradition and whose decision needs are rarely met by the climate change science community. Adaptation requires changed attitudes and practice by all participants, including the science and policy communities (Nelson et al., 2009a,b) and the recognition that science will only ever provide partial answers to societal problems (Jasanoff, 2007). The pervasive nature of ongoing climate variability and future change poses a particular challenge: climate is a widely acknowledged risk factor for most agricultural activities, but without being the sole or even dominant driver for most of them. Yet without due consideration of climatic impacts, the dual goals of agricultural production – profitability and sustainability – cannot be achieved. Conversely, the considerable opportunities that are created by more favourable climatic conditions and new, climate-related policy measures often fail to translate into real benefits.

Adapting to climate change combined with providing the policy frameworks that facilitate sound adaptation is essential for the economic survival of our agricultural sectors. Yet decision makers' research needs on both sides – practice and policy – are often neglected as their interests cross disciplinary and institutional divides. In the worst case, this lack of informed research leads to maladaptation, as shown by unintended consequences on grain prices of policies to encourage the recent expansion of biofuel production. Bridging the practice – science – policy divide requires all three players to adapt. Proactively designed and sustainable adaptation action will only occur if and when climate-related risks are treated holistically in conjunction with other drivers of risk (e.g., market, environment or social risks), supported by policies that take multiple domains and outcomes (e.g., sustainable development) into account. Hence, we call for adaptation science to provide integrated vulnerability and viability assessments that are policy relevant and trigger regionally specific and enterprise-appropriate adaptation responses.

Here we briefly review three examples of adaptation science in action. They each highlight a perceived paradox in the approach: to gain "robustness" at a systems level requires access to a mix of enabling technologies that are often, when viewed in isolation, highly specialized and potentially vulnerable, especially under highly variable conditions. Yet, used knowledgably they can contribute to more robust outcomes at the next higher level of integration. The examples were deliberately chosen to cover a wide range of spatial and disciplinary scale.

The first example draws on work by Chapman et al. (2000), who demonstrated applications of a crop model to both characterize drought stress impacts and to evaluate the relative value of different adaptive traits on the success of plant breeding programs. The timing and intensity of drought stress in different years can have greatly varying impacts on crop growth and yield. These impacts interact for genotypes that vary in traits such as flowering time, transpiration efficiency and stay-green characteristics. In order to screen germplasm for broad adaptation to drought, plant breeders conduct large-scale multi-environment trails for several seasons, with the aim of sampling seasonal conditions that vary both spatially and temporally. These trials are conventionally analysed by assuming that each location is representative for an environment-type. However, in drought-prone environments, it is unlikely that the few seasons encountered at these locations during a trial represent the true frequency of all possible season types. Using a simulation model for sorghum, Chapman et al. (2000) characterised the stress environments for each location and season and then analysed the results by environment type (mild terminal drought, bi-season drought or severe terminal drought in ratio ca. 1:1:1) rather than location. Even when a “reasonable sample” size was used (3 years x 6 locations of testing), the proportions of the three different drought types that were sampled in any given period of three years could differ greatly from the longer-term expectation. When used to characterize routine breeding trials, the classification of a real trial into an environment-type can be used to “weight” the trial results according to the expected occurrence of that environment-type in the temporal and spatial climate record. This improves the efficiency of a breeding program in identifying better-adapted cultivars for given patterns of drought stress. An extension of this work has included the simulation of the breeding process (crossing and selecting of progeny) itself (Chapman et al., 2003). To enable this capacity, the genetic controls of different traits (e.g., flowering response to temperature, transpiration efficiency, stay-green) were assigned to individuals in populations of sorghum lines. Different breeding processes and strategies (e.g., for specific or “random” environment types) were compared. These showed how different traits are accumulated during the breeding process in different environments, hence allowing traits and breeding methods to be prioritized for specific environment types. Once such improved cultivars are available, seasonal climate forecasting can assist farmers to select the appropriate cultivars for the most likely environment type at a location. While each of these new cultivars would be particularly well-adapted to one specific environment type, farmers would be able to select a mix of cultivars representative of the frequency with which specific environmental conditions are expected to occur at a particular location, hence improving robustness at the farm systems level.

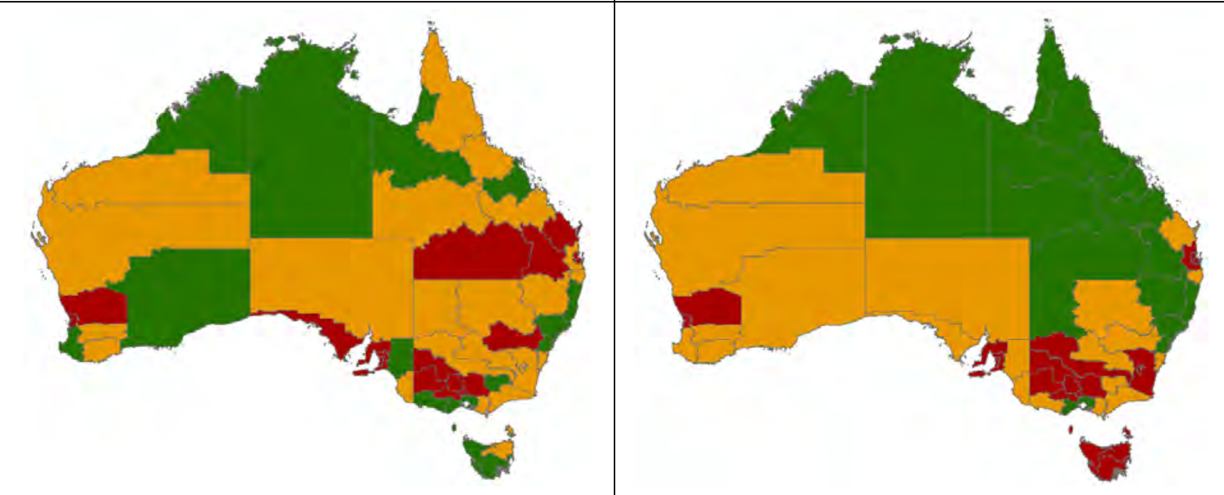
The second example is based on work by Rodriguez et al. (2007) who directly involved farmers in the identification of research questions and the parameterization of a whole farm model (APSFarm) that constituted a virtual representation of their farm business. They found that, in response to changes in their external environment (e.g., drought, market volatility, input costs, etc.), farmers continuously and intuitively adapt their management. Yet, quantitative information about alternative options can influence intuitive decision making and help farmers to “dream up” better adapted options. Many of these *in silico* derived options are innovations that lack an empirical knowledge base that would normally be required for sound decision making. Providing that the models and the science team behind them is perceived by farmers as salient, credible and legitimate (Cash et al., 2003; Meinke et al., 2006), farmers will be able to replace the lack of hands-on experience with model-based experience of systems behaviour. Equipped with such “synthetic” knowledge, farmers can now chose the most appropriate adaptation action, be it an incremental technological variation or a more transformational change in the farm business. Rodriguez et al. (2007) concluded that more than ever before there is an urgent need for the generation of more holistic approaches in the analysis of farm businesses together with the identification and quantification of key drivers of the system. This helps less experienced farmers to more quickly acquire relevant information that translates into actionable knowledge and ultimately into practical wisdom. The thus generated farm business scenarios can include the potential impacts of new management actions, new technologies, changes in climate and markets and helps farmers to adjust to the new rules of the farming game.

Given that any environmentally-induced deviation from a single “best” strategy would, by definition, reduce farm business performance, plasticity in farm management, (i.e., flexible and opportunistic farm business tactics and strategies) can provide a powerful base for adaptation actions within the existing farm system structure. Plasticity might enable farmers to respond better to environmental shifts, thus ensuring their long-term economic and environmental viability (in this context, plasticity is defined as the capacity of a system to vary in behaviour according to variable external conditions). The model is then used to test the hypothesis that farm businesses which exhibit contrasting levels of intrinsic plasticity in their tactical and strategic management will achieve different levels of resilience when exposed to a stressor such as a changing environment (e.g., climate). Rodriguez et al. (2007) simulated the impacts of a range of climate change scenarios on the annual operating return and economic risk of two real-farm case studies from Queensland, Australia, with contrasting levels of plasticity. Results indicate that a higher degree in the plasticity of farm business management leads to more capacity to manage changes in climate.

Additionally, there are feasible changes in external conditions that require consideration of more than incremental changes to existing farming systems, i.e., transformational change such as changing land use, changing location and major changes in the balance between off-farm and on-farm investment (Howden et al. 2007). Simulation models in tandem with participatory processes are able to systematically map out the conditions in which such changes may be needed and the varying consequences of different transformation options in terms of social, environmental and production values.

In our final example, Nelson et al. (2009a,b) reconciles supply and demand for integrated vulnerability assessments in Australia. They review policy demand to identify attributes that vulnerability assessments need to have in order to be policy relevant. Their conclusion is that conceptual understanding has progressed to the point where it is no longer acceptable to confuse or substitute hazard or impact modeling for integrated vulnerability assessments when providing policy advice. Policy relevant assessments integrate the hazard/impact and adaptive capacity dimensions of vulnerability in ways that inform action to reduce vulnerability and build adaptive capacity. Effective assessment processes create diverse options for managing uncertainty, and support science-policy engagement processes that enable policy advisers to reconcile trade-offs between contended values. Specifically, they show how policy relevant vulnerability assessments flow from institutional structures and incentives that facilitate collaboration between scientists from diverse disciplines and agencies. Nelson et al. (2009a,b) use bioeconomic modeling to provide policy relevant climate impact assessments that are integrated with a composite index and enables policy makers to identify practical options for building adaptive capacity. In the process, they show that exclusive hazard/impact modeling can lead to entirely erroneous conclusions about the vulnerability of agricultural communities (see also Kokic et al., 2007 and Nelson et al., 2007). Via examples, they demonstrate that Australian agricultural communities that are vulnerable to climate variability and climate change tend to be vulnerable for a complex set of interacting environmental, economic and social reasons. Fig. 3 provides but one example of how this information might be used by policy makers to target the most vulnerable regions given further expected climate changes across the continent.

Change in pasture growth (2030) vs. adaptive capacity	Change in farm incomes (2030) vs. adaptive capacity



33% least vulnerable	33% moderately vulnerable	33% most vulnerable

Fig. 3: Vulnerability of broadacre agricultural communities across Australia to climate change.

CONCLUSIONS

A sound assessment of options for productivity increase must take external boundary conditions such as the basic principles of production ecology, the policy environment and the general socio-economic setting into account. This will allow establishment of benchmarks to compare the current levels of productivity to those that would be achievable via technically feasible and socially acceptable changes in farming practices.

To lift the productivity of a diverse system, practitioners must understand the context of specific constraints and opportunities of systems components (e.g., legumes and their role in crop rotations). This requires knowledge derived from agricultural systems science in order to quantitatively assess management by environment interactions that account for spatial (e.g., soil fertility) and temporal variability (e.g., rainfall) as well as stakeholder knowledge in terms of the operating context and practical synergies and barriers to implementation (e.g., Howden et al., 2007). The knowledge component behind these enabling technologies is what we define as *Adaptation Science*, a special form of sustainability science that occupies the boundary space between science and society to build social networks that connect agricultural and climate science with decision makers and institutions, thereby creating social capital. Such knowledge will help farm managers to view a given location as a temporal sequence of different environments at different scales that will sometimes be dry, sometimes wet, sometimes difficult to reach, sometimes accessible, with variable access to resources, infrastructure and markets. For most of these individual conditions (=environments) science can offer enabling technologies and management options that perform well if conducive conditions are met, e.g., both conventional and genetically-engineered pest-resistant seeds will only perform well if water and nutrients are also in reasonable supply. While the latter seed type may provide increased benefit in good seasons (via savings in pest management), there is also a potentially greater risk of economic loss in climatic "failure" seasons, due to the higher purchase cost of such seed. Therefore a holistic approach to risk management requires a) a good understanding of these different environments that define a region, including their frequencies of occurrence and how this may change with climate change, return intervals of extreme events and their predictability, b) access to enabling technologies that would likely perform best in each environment type and c) modeling frameworks that help to integrate and make sense of the myriad of potential options and scenarios.

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DETAILED MODELING AS AN ESSENTIAL STEP IN DEVELOPING NEW ANALYSIS TECHNIQUES: THE ISOTOPE PAIRING TECHNIQUE (IPT) CASE STUDY

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ABSTRACT

The Isotope Pairing Technique (IPT) is a tracer method for measuring denitrification rates in sediments, which can be implemented in a flow-through cylinder setup. In this work, a numerical transport model of the nitrogen processes in sediments was constructed to investigate this application of the IPT. A comparison between the IPT and the numerical model demonstrated large potential errors (over 200%) in the calculation of the denitrification rates under certain experimental conditions and particularly when there is a high ambient concentration of nitrate in the water column. The errors are related to an incorrect representation of the diffusion flux of the nitrate from the water column by the IPT and an assumption that the ratio of the nitrate isotopes is constant over the denitrification zone allowing for a binomial formation of nitrogen gas isotopes. With an error in the estimation of the denitrification rates inevitable for certain experimental conditions, the numerical model was used to determine the most applicable range of the IPT. An important outcome of the study is the emphasis on the importance of numerical simulations in understanding processes in order to avoid potentially large errors in experimental work.

INTRODUCTION

The isotope pairing technique (IPT) is a tracer method, developed to measure denitrification in sediments (Nielsen 1992). IPT is advantageous as it allows for the separate quantification of coupled nitrification–denitrification (D_n) of the nitrate produced by nitrification in the sediments and the denitrification of NO_3^- which diffuses into the sediments from the water column (D_w). The IPT can be used in a variety of set-ups (Steingruber et al. 2001) and can be used in conjunction with other methods to determine the kinetics of denitrification in sediments. A large proportion of the IPT studies implement a batch mode assay (Herrman & White 2008; Minjeaud et al. 2008; Rao et al. 2008), a destructive in-situ set-up, however non-destructive sampling methods are also presented as an option in flow-through or benthic chamber set-ups (Master et al. 2005; Risgaard-Petersen et al. 1998; Risgaard-Petersen et al. 1994).

The Isotope Pairing Technique

The two most significant sources of nitrate for denitrification in sediments are the nitrate produced by coupled nitrification - denitrification (CND) in the sediments (D_n) and the nitrate which diffuses into the sediments from the water column (D_w).

The nitrate molecules from both of these sources diffuse into the anoxic layer of the sediments, undergo denitrification and produce nitrogen gas which is mostly of the light isotope ($^{28}N_2$), composed of two ^{14}N molecules which is naturally more abundant (Figure 1 - modified from Steingruber et al. 2001).

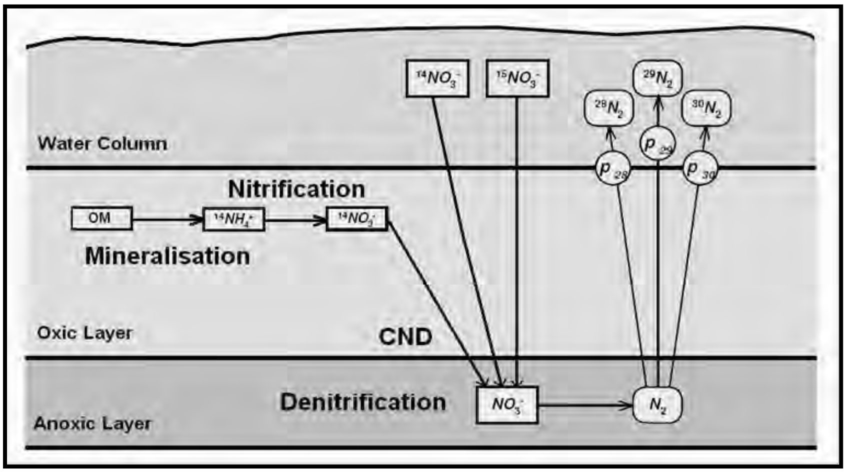

Figure 1: Nitrogen Processes in Sediments.

The IPT was originally derived by Neilsen (1992) to separately quantify the two paths of nitrate denitrification in a batch mode assay with application to traditional flow through systems. The method, as described in the original paper, replaces the ambient nitrate ($[^{14}NO_3^-]_w$) in the water column with the isotope labelled nitrate ($[^{15}NO_3^-]_w$) such that CND is the only possible source of $^{14}NO_3^-$ denitrification and the water column is the only source of $^{15}NO_3^-$ denitrification (assuming that the natural abundance of $^{15}NO_3^-$ is insignificant compared to the enriched $^{15}NO_3^-$ concentration). Denitrification of the two isotopes of nitrate result in the formation of three nitrogen gas isotopes; $^{28}N_2$, $^{29}N_2$ and $^{30}N_2$ and by measuring the production of the heavier nitrogen isotopes $^{29}N_2$ (pr_{29}) and $^{30}N_2$ (pr_{30}) via isotope ratio mass spectrometry (IRMS), the denitrification rate of $^{15}NO_3^-$ can be calculated. In order to calculate the denitrification rate of $^{14}NO_3^-$ a statistical probability distribution needs to be assumed, in the IPT case a binomial distribution is chosen. Neislen (1992) suggests that the differentiation of the two sources of denitrification can also be achieved where there is an ambient concentration of $^{14}NO_3^-$ in the water column, if the frequencies of the $^{14}NO_3^-$ and $^{15}NO_3^-$ are known by measuring the NO_3^- concentration before and after the addition of $^{15}NO_3^-$. Steingruber et al. (2001) formulated a factor ε which represents this isotopic nitrate enrichment for the case where there is ambient $^{14}NO_3^-$ in the water column ($[^{14}NO_3^-]_w$) and is used as a correction factor to account for the production of $^{28}N_2$ and $^{29}N_2$ from nitrate from the water column. The IPT thus offers two simple equations to calculate D_n and D_w

$$D_n = (pr_{29} + 2pr_{30}) \cdot \left(\frac{1}{\varepsilon} - 1 + \frac{pr_{29}}{2pr_{30}} \right) \quad \textbf{(1)}$$

$$D_w = (pr_{29} + 2pr_{30}) \cdot \left(\frac{1}{\varepsilon} - 1 \right) \quad \textbf{(2)}$$

$$\varepsilon = \frac{[^{15}NO_3^-]_w}{[^{14}NO_3^-]_w + [^{15}NO_3^-]_w} \quad \textbf{(3)}$$

using the rate of production of the two measured nitrogen gas isotopes and the value of ε (Equations 1 - 3). A complete derivation can be found in either Neilsen (1992) or Steingruber et al. (2001). The objective of this study is to determine the applicability of the IPT with emphasis on IPT experiments conducted in a flow through set up where the depth profiles of concentrations and rates of processes are significant.

METHODS

A numerical simulation of the nitrogen cycle in sediments was developed based on the model presented in Cook et al. (2006), with a few minor changes to represent the conditions in the flow through technique applied in research by Master et al. (2005). The one dimensional numerical model was formulated in COMSOL Multiphysics and run with an interface to Matlab. Partial differential equations for $^{14}NO_3^-$, $^{15}NO_3^-$, NH_4^+ and O_2 were generated to represent the mass balances of each of the species (summarised in Table 1) including aerobic mineralisation, ammonification, nitrification and denitrification as the source/sink reaction terms (summarised in Table 2). The constants for the reaction rate equations are chosen to match as closely as possible the literature range for the sediment processes and the values are presented in Table 3. The domain was defined such that the water-sediment interface was zero, increasing positively in the downwards direction. The only transport phenomena included is diffusion. The mass balance equations are presented in their time-dependent form to allow flexibility in the modeling, however, in the current simulations steady state was achieved and so the left hand term of the equations is equivalent to zero.

The numerical model was run and the nitrogen gas production (pr_{29} and pr_{30}) at each depth along the domain was extracted and was inserted into the IPT calculations (Equations 1 – 3) to generate values for D_n and D_w. The results given by the application of the IPT were then compared with the numerical model to see how closely the IPT predicted the simulated nitrogen production in a 'known' scenario. This internal comparison between the numerical simulation and the IPT calculations meant that the exact calibration of the model was not essential to obtain the required conclusions (Middelburg et al. 1996a) and therefore the model was not calibrated to any real sediments. If different values for the reaction rate parameters are chosen, then the results of the study will be different, however the comparison between the model and the IPT will yield similar conclusions about the applicability of the method.

The numerical model was run originally for concentrations of $^{14}NO_3^-$ and $^{15}NO_3^-$ of 192 and 60 mmol m^{-3} in the water column respectively and thereafter for concentrations of both NO_3^- isotopes between 20-200 mmol m^{-3} to determine the effect of the concentrations of the nitrate isotopes on the precision of the IPT calculation.

Table 1. The Processes Represented in the Numerical Model

Species	Equation	Key
$^{14}NO_3^-$	$(n)\frac{d([^{14}NO_3^-])}{dt} = \nabla \cdot \left(D_{NO_3^-}\nabla[^{14}NO_3^-]\right) + R_{nit^{14}} - R_{den^{14}}$	n=porosity; D_x=Diffusion of species x
$^{15}NO_3^-$	$(n)\frac{d([^{15}NO_3^-])}{dt} = \nabla \cdot \left(D_{NO_3^-}\nabla[^{15}NO_3^-]\right) - R_{den^{15}}$	[X]=Concentration of species X
$^{14}NH_4^+$	$(R_{ret})\frac{d([^{14}NH_4^+])}{dt} = \nabla \cdot \left(D_{NH_4^+}\nabla[NH_4^+]\right) + R_{AM} - R_{nit^{14}}$	R_{nit}=Nitrification rate; R_{den}=Denitrification rate
O_2	$(n)\frac{d([O_2])}{dt} = \nabla \cdot (D_O\nabla[O_2]) - R_{AR} - 2R_{nit^{14}}$	R_{AM}=Ammonification rate; R_{AR}=Aerobic respiration rate; R_{ret}= Retardation factor

Table 2. The Reaction Rates Represented in the Numerical Model

Process	Expression
Aerobic Respiration	$R_{AR} = R_{\min(0)}e^{(-\beta z)}\frac{[O_2]}{[O_2]+k_{AR}}$
Ammonification	$R_{AM} = \gamma R_{\min(0)}e^{(-\beta z)}$
Nitrification	$R_{nit} = k_{nitm}\frac{[O_2]}{[O_2]+k_{nitsat}}[^{14}NH_4^+]$
Denitrification of $^{14}NO_3^-$	$R_{den14} = K_{denit}\frac{k_{denO_2}^{inh}}{[O_2]+k_{denO_2}^{inh}}\frac{[^{14}NO_3^-]}{[^{14}NO_3^-]+k_{denNO_3^-}}$
Denitrification of $^{15}NO_3^-$	$R_{den15} = K_{denit}\frac{k_{denO_2}^{inh}}{[O_2]+k_{denO_2}^{inh}}\frac{[^{15}NO_3^-]}{[^{15}NO_3^-]+k_{denNO_3^-}}$
Retardation	$R_{ret} = \left(1+\frac{\rho_d k_d}{n}\right)$

The model

The output profiles for the sedimentary nitrogen processes in the top ten millimeters of the sediments of the model are demonstrated in Figure 2. Aerobic respiration occurs only in the oxic zone as does nitrification. The nitrification rate is closely linked with the concentration of ammonium in

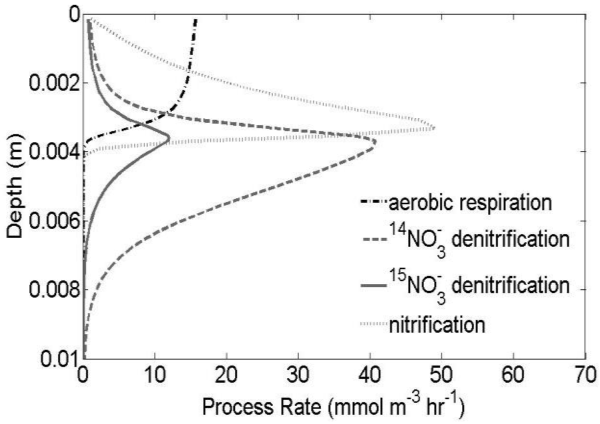

Figure 2: The Nitrogen Processes Represented by the IPT

the oxic zone. The peak of nitrification is directly above the denitrification peak.

Table 3. The Reaction Rate Constants

	Units	Value	Description
R_{OMCarb}	mmol m^{-3} hr^{-1}	16	maximum rate of the mineralisation of carbon organic matter
β	m^{-1}	1/8	a constant to fit the mineralisation profile
k_{AR}	mmol m^{-3}	5	half saturation constant for O_2 limitation of aerobic respiration
γ	-	1/15	net production of NH_4^+ in relation to C mineralised
k_{nit}	mmol m^{-3} hr^{-1}	0.6	Monad nitrification constant
k_{nitsat}	mmol m^{-3}	15	half saturation constant for O_2 limitation of nitrification
K_{denit}	mmol m^{-3} hr^{-1}	1	denitrification constant
k^{inh}_{denO2}	mmol m^{-3}	5	half saturation constant for O_2 inhibition of denitrification
k_{denNO3}	mmol m^{-3}	1	half saturation constant for NO_3^- inhibition of denitrification
ρ_d	g cm^{-3}	1.3	bulk density
k_d	cm^3 g^{-1}	1.4	soil-water partitioning distribution coefficient
n	-	0.45	sediment porosity
D_{O2}	m^2 hr^{-1}	$1.7x10^{-6}$	diffusion rate of oxygen
D_{NH4+}	m^2 hr^{-1}	$1.5x10^{-6}$	diffusion rate of ammonium
D_{NO3-}	m^2 hr^{-1}	$1.5x10^{-6}$	diffusion rate of nitrate

RESULTS

The equations of denitrification allow a small amount of denitrification in the oxic zone of the sediment, which represents the anoxic micro-sites where the coupled nitrification – denitrification occurs.

Comparison with the IPT equations

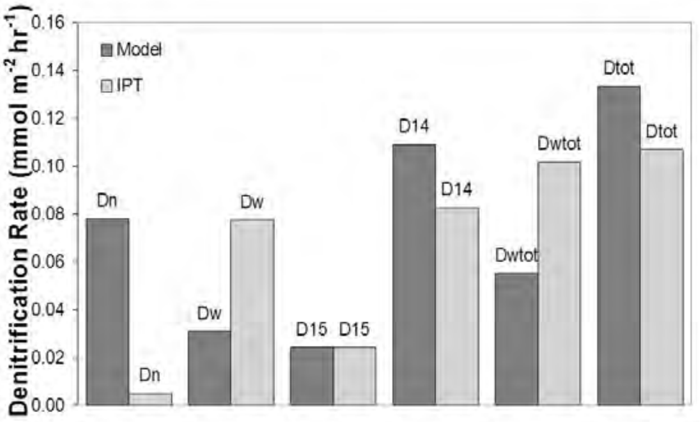

Figure 3: A Comparison between the denitrification rates from the Model and the IPT.

The Isotope Pairing Technique Calculations

applied to the output of the numerical model (pr_{29} and pr_{30}) significantly underestimate the denitrification from nitrate from nitrification (D_n) (0.078 mmol m^{-2} hr^{-1} vs 0.0051mmol m^{-2} hr^{-1}) and significantly overestimate the denitrification of $^{14}NO_3^-$ from the nitrate of the water column (D_w) (0.03 mmol m^{-2} hr^{-1} from the model vs 0.078 mmol m^{-2} hr^{-1} from the IPT) (Figure 3).

The Effect Of The Nitrate Concentrations

The denitrification rates, D_w and D_n, as given by the model (D_m) were compared to the rates calculated by the IPT (D_{IPT}) to give the relative difference (θ);

$$\theta = \frac{D_m - D_{IPT}}{D_m} \tag{4}$$

The value of θ for $^{14}NO_3^-$ and of $^{15}NO_3^-$ concentrations between 20-200 mmol m^{-3} are plotted in Figure 4. At concentrations of $^{15}NO_3^-$ above 120 mmol m^{-3} and $^{14}NO_3^-$ concentrations under 80 mmol m^{-3} the value of D_n is most accurately calculated. The value of D_w was most accurately represented for the $^{14}NO_3^-$ concentrations at the limits of 20 and 200 mmol m^{-3}. There is little overlap between the regions where D_n and D_w are best represented by the IPT calculations.

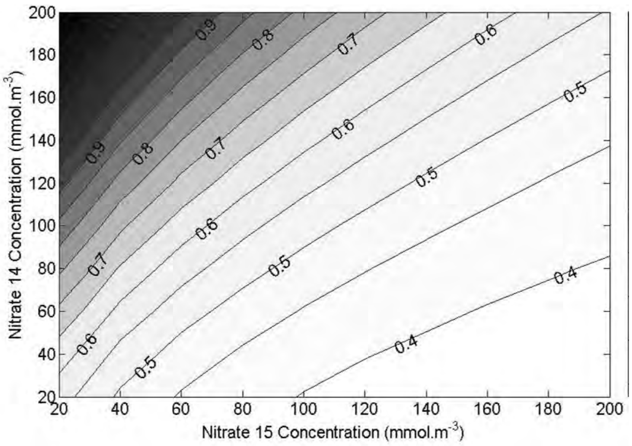

Figure 4: A Comparison between the Model and the IPT for a Range of Concentration Boundary Conditions.

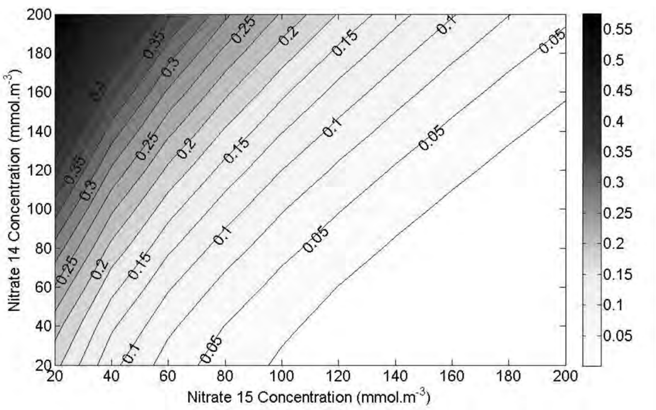

Figure 5: The Comparison for a Range of Concentration Boundary Conditions with Dw measured.

A case with a measured $^{14}NO_3^-$ flux

It was found that when the flux of $^{14}NO_3^-$ into the sediments was measured, giving an accurate value for D_w then the error in the IPT calculation of D_n is reduced. Figure 5 shows than in the lower right hand corner of the graph with the higher concentrations of $^{15}NO_3^-$ and lower concentrations of $^{14}NO_3^-$ the observed error is an order of magnitude smaller.

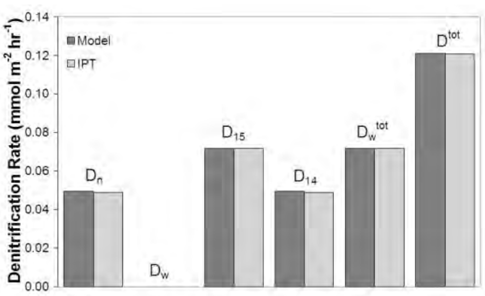

Figure 6: The Comparison for the Case of No Ambient $^{14}NO_3^-$

A case with no ambient $^{14}NO_3$

$^{-}$In the case where there was no ambient $^{14}NO_3^-$ in the water column, then the IPT calculations very accurately predicted the denitrification rates in the sediments as noted in Figure 6. The denitrification rates calculated for D_w are negative, indicating an efflux of nitrate into the water column from the sediments.

DISCUSSION

The differences between the IPT calculations and the results of the numerical model indicate that the application of the IPT in its original form is limited to a specific region of concentrations. As the IPT calculations are dependent on only three variables p_{29}, p_{30} and ε, the differences between the model and calculations is a direct effect of either the value of ε or the binomial distribution. In the discussion the explanation of the inconsistency is investigated.

The Calculation of ε

The original definition of ε (Equation 3) states that the flux of the $^{14}NO_3^-$ from the water column is proportional to the difference in the concentrations of $^{14}NO_3^-$ + $^{15}NO_3^-$ present in the water column before and after the enrichment of $^{15}NO_3^-$. However, diffusion is represented by Fick's law, which states that it is the gradient and not the concentration differences which are required to estimate the diffusive flux of NO_3^- into the sediments. The concentration gradient at the water-sediment interface is not dependent on the amount of nitrate in the water column, but rather on the difference between the concentration in the water column and the concentration at the surface of the sediments. As there is a source of $^{14}NO_3^-$ from nitrification within the sediments, the $^{14}NO_3^-$ concentration gradient is decreased. Therefore, proportionally less $^{14}NO_3^-$ can diffuse from the water column into the sediments than $^{15}NO_3^-$. For the accurate calculation of D_n, then D_w needs to be calculated by defining ε as a ratio of the fluxes into the sediment, such that;

$$\varepsilon = \frac{dC_{[^{15}N]}/dz}{dC_{[^{14}N]}/dz + dC_{[^{15}N]}/dz} \quad \textbf{(5)}$$

However, this is not easy to achieve as it requires a mass balance of the isotopes over the water column and the differences between the inlet and outlet concentrations are potentially very small and difficult to distinguish.

The Binomial Distribution

The denitrification rates are calculated by the IPT under the assumption that the ratio between the $^{14}NO_3^-$ and $^{15}NO_3^-$ is constant throughout the denitrification zone, so that the total amount of $^{29}N_2$ and $^{30}N_2$ produced is binomially distributed. Since the profiles of the nitrate concentrations are non-linear and variable with depth, the binomial distribution needs to also be applied as a function of depth. This is possible with the numerical model however the IPT calculations examine integral quantities and apply the binomial distribution to the total amount of nitrate denitrified. These two calculations are not similar as shown by the following two equations derived for p_{30} from the IPT such that all of the denitrification is measured and then the binomial distribution is applied (Equation 6) and for the simulation where the binomial distribution is applied for the denitrification which occurs at each depth (Equation 7).

$$\mathrm{Pr}_{30} = \frac{1}{2}\frac{\left(\int D_{15}(z)dz\right)^2}{\int\left(D_{14}(z) + D_{15}(z)\right)dz} \tag{6}$$

$$\mathrm{Pr}_{30}(z) = \frac{1}{2}\int\frac{\left(D_{15}(z)\right)^2}{D_{14}(z) + D_{15}(z)}dz \tag{7}$$

The same is true for the calculation of pr_{29}. The division by two is applied to maintain the stoichiometric ratio between nitrate and nitrogen gas. These two equations are not the same, as the integral of the squares and the squares of the integral are not equivalent. This explains the difference in the total denitrification rate for the IPT calculations and the values simulated by the numerical model which results in the underestimation of D_n even when the flux into the sediments is corrected. This difference due to the non-linearity of the depth profiles is alluded to in previous assessments of the applicability of the assumptions of the IPT (Middelburg et al. 1996a; Middelburg et al. 1996b; Nielsen et al. 1996), however a detailed mathematical analysis was not presented there leading to a confusion in the discussion about diffusion into the sediments.

Experimental Design

Despite the large differences introduced by both the definition of ε and the assumption of the linear profiles the IPT is still an attractive tool to determine denitrification rates given specified experimental design. This simulation supports Neilsen's claim (1992) that when the $^{15}NO_3^-$ concentration is high enough then more of the $^{14}NO_3^-$ will combine to generate $^{29}N_2$ reducing the error in the IPT calculation, however, due to the minimisation of the interference of the $^{14}NO_3^-$ in the water column. This leaves two options for the implementation of the experimental IPT, to use artificial water in the water column above the sediments which contains only $^{15}NO_3^-$ or to significantly enrich the $^{15}NO_3^-$ in the water column so that it is much greater than the concentration of $^{14}NO_3^-$. Both of these options has its disadvantages, when using artificial water, then other nutrients and components are removed from the water column perhaps changing the reaction rates of the nitrogen processes and when adding large amounts of $^{15}NO_3^-$ the denitrification rates differ due to the increased concentrations of nitrate in the system.

CONCLUSION

This analysis shows that the IPT calculations are not necessarily representative of the processes occurring in the sediments for all experimental conditions. Nevertheless, the IPT is an attractive technique which has been applied successfully in both batch mode assay and flow through experiments (Nielsen 1992). In the numerical transport model of the nitrogen processes in sediments, large discrepancies were observed between denitrification rates computed in the simulation and those calculated by the IPT equations. Two main issues were emphasised:

a) the misrepresentation of the diffusion flux by the concentration ratio ε

b) the non-linear depth distribution of the processes invalidating the implementation of the binomial assumption.

Further investigation of the sedimentary nitrogen processes utilising the numerical model showed that the error introduced by the IPT could be minimised with careful experimental design and adherence to the original IPT method as suggested by Neilsen (1992) by replacing the ambient $^{14}NO_3^-$ in the water column or by significantly enriching the $^{15}NO_3^-$.

Through the development of a numerical model and a comparison with the IPT, this research identified the range of applicability of the IPT method to measure sedimentary denitrification rates and serves as a caution for the incorrect implementation of the IPT calculations caused by a misunderstanding of the original design.

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NITRATE INFLUX KINETICS TO VARIOUS COMPONENTS OF THE CORN INTACT ROOT SYSTEM: DATA ACQUISITION FOR UPTAKE MODELING

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ABSTRACT

Uptake of nutrients by plants combines the root system growth and distribution, flow of water and solutes towards the root and their absorption by the root system. Different models were suggested, to account for specific uses. The recent models involve the genuine root distribution in the soil, considering plant genotype and the soil characteristics. We report here a method to measure uptake kinetics of nitrate by selected sections of corn (*Zea mays* L.) root systems, to be used in an uptake model that accounts for the root system architecture. The method is based on pieces of PVC tubes mounted on the target root section, sealed on both sides, and allowing the absorption of nitrate from the occluded solution for one hour at 25ºC. Net influx was calculated from the change in nitrate concentration with time before and after the tube mount, and the dimensions of the tube and the root section. The procedure was repeated with different initial concentrations. The Michaelis-Menten kinetics coefficients were obtained by curve fitting of the influx data against the mean nitrate concentration during the depletion. Comparing the K_m values of different root sections indicated that root classes significantly differed in their affinity to nitrate.

INTRODUCTION

Mechanistic models of nutrient uptake by plant roots appeared to be a useful tool to quantify and to explain the behavior of root systems as means of water and nutrient uptake from soils. The model types often vary according to their purpose. The list below summarizes the main types of models classified according to their structure:

1. 1-D (vertical) model: Changes in the vertical dimension only, between the soil surface and the bottom of the root zone. Accounts for soil layers, horizons, chemical and biological changes and root abundance and uptake. Example: Hutson and Wagenet 1995.
2. 'Single-Root', radial flow:
    a) Competition between roots of the same plant: Barber and Cushman 1981, Hoffland et al. 1990, COMP8 (Smethurst and Comerford 1993).
    b) Competition between plants at the root level: Yanai 1994.
    c) Moving boundaries: Reginato et al. 1990.

d) Uptake by root hairs: Itoh and Barber 1983, NST 3.0 (Claassen and Steibgrobe 1999).

e) Exudation and pH: Huguenin-Elie et al. 2003.

3. 3-D models: a typical example is the finite-element model of Somma et al. 1998.
4. Models that account for root branching and architecture: Roose et al. 2001, Dunbabin et al. 2004.

A review on mathematical modeling at different levels was recently published by Roose and Schnepf (2008).

The last type of models is in the base of the present study. Comparative analyses by Roose et al. (2001) and Roose and Schnepf (2004) indicated that some of the reasons for the under-estimation of nutrient uptake by the single-root models were due to their inefficient foraging of the soil by the root system. Accounting for root branching and architecture provided higher and more realistic nutrient uptake of barely-soluble nutrients as phosphate (Walk et al. 2006). An advanced model, named SimRoot, was developed by J.P. Lynch and his research group (Lynch et al., 1997) to simulate root system architecture growth with time and space. The model was calibrated with field and greenhouse data of roots of different genotypes, which were correlated against the controlling genes expression (Walk et al., 2006).

The present study was within the framework of an attempt to combine the root architecture with uptake characteristics of corn roots, to construct a model with nitrate uptake capacity for corn. Specifically, we report here a technique to quantify nitrate influx data as a function of nitrate concentration to different components of the corn root system.

METHODS

Growth conditions: Corn (*Zea mays* L. Dekalh DKC44-92) seeds were germinated in germination paper soaked in 0.5 mM $CaSO_4$ in a dark incubator with 28°C for three days. The seedlings were then transplanted to 30 liters hydroponics containers, twelve plants per container, with air bubbled via two aquarium stones attached to a pump. The nutrient solution contained 1.5 mM $Ca(NO_3)_2$, 0.5 mM K_2SO_4, 0.25 mM $Ca(H_2PO_4)_2$, 0.5 mM $MgSO_4$, 75 µM Fe-DTPA (diethylene triamine pentaacetate; a few grains of $Fe(NH_4)_2(SO_4)_2$ salt were also added weekly to prevent iron deficiency symptoms), and micronutrients (Hoagland and Arnon 1950). The pH was adjusted to 5.5 by KOH. The containers were placed in the greenhouse with additional light by a set of sodium and metal halide bulbs to maintain 16 hours day length. Residues of the kernels were removed nine days from germination. Two days prior to the uptake measurement procedure (see next), the plants were transferred to a nitrate-free nutrient solution for nitrate deprivation, where $Ca(NO_3)_2$ was replaced by $CaSO_4$.

Nitrate Analyses and Root Measurement: Four nitrate-deprived plants on each batch were transferred to a beaker with 1 L of 0.5 mM $CaSO_4$ + 0.5 mM K_2SO_4 solution and 100 µM KNO_3 with bubbled air for induction of the high-affinity nitrate transporter system (HATS; see Discussion). The solution was changed every hour along 6 hours. The plants were then placed in a 40x25 cm tray in a bath, which contained 2 L of $CaSO_4$ + K_2SO_4 solution at 25°C, with bubbling air. The plant leaves were illuminated by a 100 W metal halide bulb, which provided 103 µmol m^{-2} s^{-1} PAR at plant level; the roots were covered with a sheet of aluminum foil to avoid an exposure to direct light. After 20 min, a dose of KNO_3 was added to provide initial concentration between 5-100 µM on different runs. Ten minutes later, 4 cm long segments of a 3/8" (9.525 mm) inner diameter polyvinyl chloride (PVC) pipe were mounted on the target root sections: tip + elongation zone (0-4 cm), maturation zone (4-8 cm) of the seminal and the crown nodal roots, and laterals of the seminal roots (0-4 cm only). Both ends of the tube were sealed with silicon grease (High Vacuum Grease, Dow Corning®, Midland, MI, USA)* while soaked in the solution to prevent air bubbles. The solution in the bath was sampled several times along the tube mounting for changes in initial concentration (C_0, see Eq. 1) due to absorption by the rest of the root system. A dose of 25 µl gaseous oxygen was injected after 30 min to each tube to ensure an adequate respiration rate. After an hour, the roots on both sides were cut with a razor blade, the tube was pulled out of the bath and its internal content was sucked out: Each tube had a hole drilled on its side, covered with a drop of silicone sealant (Silicone II*, GE, Huntersville, NC, USA) that formed a flexible plaque, which allowed the samplings of the inner solution using a 10 ml syringe. When the pumping was completed, the grease sealant gave way to the air to enter; this was another indication for a proper sealing of the tube during the incubation. The solution samples were transferred to 6 ml vials, and got frozen without delay, until been analyzed for nitrate with high performance liquid chromatography (HPLC, Dionex: CD20 detector, GP50 pump, LC30 oven). The root sections were stored in 25% ethanol, and their length and mean diameter were measured using scanned images, which were analyzed by the WinRhizo Pro software package (Regent, Canada).

Influx calculation: Influx to each root section may be calculated by the nitrate depletion rate within the tube:

$$I_n = -\frac{V(C_t - C_0)}{A(t - t_0)} \qquad \textbf{(1)}$$

where I_n is mean net influx to the root segment, C_0 and C_t are initial nitrate concentration of the bulk solution on tube mount and the concentration within the tube at sampling time, respectively,

* Mentioning commercial names is not a recommendation, but merely for the reader's benefit.

A – the absorbing surface area of the root segment, V - volume of the solution in the tube, and t_0 and t are starting and sampling times, respectively. The negative sign in Eq. (1) denotes that a negative concentration change with time refers to positive influx to the root, assuming that uptake by the root is the only sink for nitrate in the system.

The root length that was actually exposed to the solution in the tube is uncertain, as part of the tube volume was occupied by the grease sealing on both sides. The exact volume of the solution is also unknown, as the sampled volume might be incomplete. The volume V of the solution in the tube equals the internal volume of the tube minus the volume of the grease sealing and the volume occupied by the root. Taking L as the effective root length exposed to the solution, and r as the root radius, and assuming the root length to match to that of the void:

$$V = \pi L\left(R^2 - r^2\right) \quad \textbf{(2a)}$$

and

$$A = 2\pi rL \quad \textbf{(2b)}$$

where R is the inner radius of the tube and assuming cylindrical geometry of both the tube and the root. Substitution of V and A in Eq. (1) with those of (2a) and (2b) will yield:

$$I_n = -\frac{(C_t - C_0)\left(R^2 - r^2\right)}{2r(t - t_0)} \quad \textbf{(3)}$$

Equation (3) includes the measured concentrations at the start (t_0) and at the end (t) of the depletion trial, the radius of the tube and that of the root (in fact, the r^2 component could be considered as negligible, as the two squared radii differ in 2-3 orders of magnitude; see Discussion). The uncertain values of the effective root length exposed to the solution and of the actual volume of the solution are unnecessary now, as they are expressed by measurable or provided parameters: the radius of the root may be accurately determined for a homogeneous short sections of cylindrical, young roots by the WinRhizo Pro software and that of the tube is given. That is, provided that the root length matches the length of the tube void, which is full with the solution (no air bubbles). Using units of $\mu mol\ cm^{-3}$ for the concentrations, cm for the radii and s for times will result in net-influx in $\mu mol\ cm^{-2}\ s^{-1}$.

RESULTS

Figure (1) presents the fitted curves of nitrate net-influx as a function of the external concentration, assuming that influx obeys the Michaelis-Menten kinetics. The calculated *Imax* and *Km* coefficients are presented in Fig. 2 (A and B, respectively) for the nitrate-induces (pre-treated by nitrate) plants (non-induced plants are interesting from a physiological point of view, but will not be discussed here). Although the curves in Fig. 1 vary considerably, looking at the calculated coefficients in Fig. 2 indicates that the maximal influx *Imax* is similar in the seminal roots for both sections (Fig. 2A), and the difference in the shape of the curve is due to the *Km* values (Fig. 2B). The great and more significant differences occurred in the *Km* values, which widely differed between the root classes.

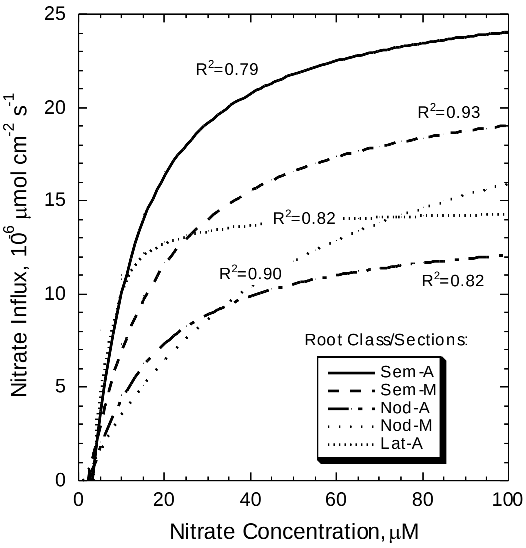

FIGURE 1: Nitrate influx to different classes (Sem: seminals; Nod: nodals; Lat: laterals) and sections along the roots (A: apical 0-4 cm; M: maturation zone, 4-8 cm from root apex) of 14-d old corn plant intact roots. The curves were fitted to influx data obtained by the nitrate depletion procedure, assumed to obey the Michaelis-Menten kinetics (see Fig. 2).

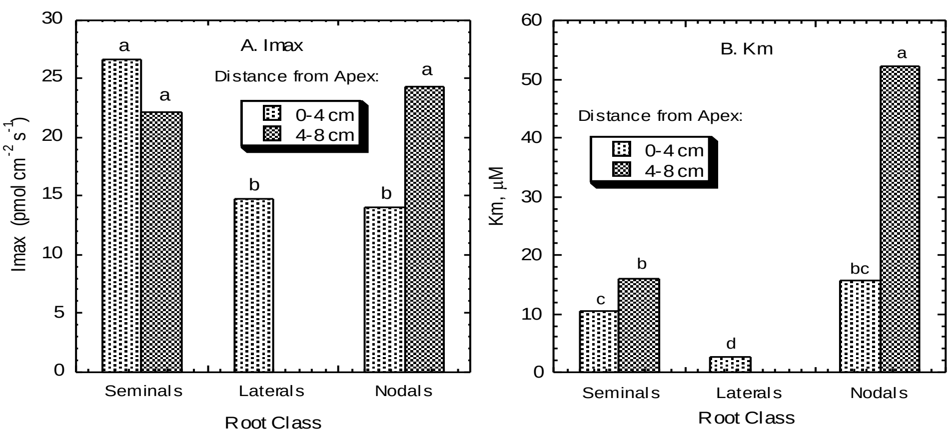

Figure 2: The calculated Imax (maximal influx, A) and Km (Michelis-Menten coefficient, B) coefficients of the Michelis-Menten influx kinetics to different classes and sections along the roots (0-4 cm apical zone; 4-8 cm from root apex, maturation zone) of 14-d old corn plant intact roots. Within each part, columns with the same letter are not significantly different ($p<0.05$) according to the paired student's t-test.

DISCUSSION AND CONCLUSIONS

Net-influx was calculated in this study by the change in concentration with time, where the volume of the solution and the absorbing root surfaces were accounted for by the tube and root radii (Eq. 3). One may wonder if the differences in the calculated influx functions are not because of differences in the radii of the different root classes, which varied widely (means of 0.82, 1.17and 0.19 mm for the seminal, nodal and lateral roots, respectively, with very small variance within each class). If that was the case, there should be a negative correlation between the radius and the *Imax* values that determine the maximum values of the different curves. Figure 2A shows that this is not the case. The more meaningful differences are those of the *Km* values for the different root classes, presented in Fig. 2B. This parameter expresses the affinity of the transport of nitrate across the call membrane of the epidermal root cells: the lower is the value of *Km* – the higher is the affinity, as half-*Imax* would occur in lower concentration.

The results presented in Fig. 2B indicate that the three root classes significantly differed in the affinity of their nitrate transporters. Two classes of genes, codes NRT1 and NRT2, are known to be involved in the High and Low Affinity nitrate Transport Systems (HATS and LATS, respectively) in plants (Epstein and Bloom 2005). Of these two groups, HATS, which is active also in low nitrate concentrations, responds to nitrogen deficiency in the plant by increasing its gene expression. The induction to this expression is by the presence of nitrate, but it would be intensified under nitrogen deprivation. The signal of N shortage moves everywhere in the plant, also to the roots, regardless of where the deficiency was sensed, but the response is mainly of HATS. Furthermore, the NRT1 gene may change its affinity to nitrate, expressed by its K_m (Epstein and Bloom 2005). We suggest that, since all plants in this study were fully induced, the differences in *Km* values of the different root classes are expression of different genes that control the HATS. Components of the corn root system do vary in their expression of genes that control their growth (Walk et al. 2006). We suggest that these variations, together with differences in nitrate uptake, could be used to manipulate the corn root system to meet differences in nitrate abundance and distribution in the soil profile.

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CROP WATER REQUIREMENTS FROM THE PENMAN-MONTEITH MODEL: SENSITIVITY TO CANOPY PARAMETERS

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ABSTRACT

The Penman-Monteith equation is widely used to calculate crop water requirements. It combines the supply of energy and transport of water vapour from the canopy. Physiological control of transpiration is taken into account by introducing a canopy resistance. Determining and modeling this resistance remains a partially resolved problem. The heterogeneity of environmental conditions and resulting non-uniform stomatal responses within crop canopies are difficult to quantify. Moreover, interactions between plant nutrition, metabolism, and water transport are highly complex and adaptive. Efforts to standardize the practical application of the Penman-Monteith equation to manage irrigation have lead to formulations compromising between scientific accuracy and practical convenience.

Aiming for a practical application of the model, a simple approach to determine canopy resistance was chosen for closed canopy conditions when the soil is a negligible source of heat and vapour. It is based on correlations between in-situ measurements of light interceptance and stomatal conductance. A radiation model was used to scale the resulting regression function from leaf to canopy level. The aim of this study was to quantify the effects of contrasting surface resistance model parameterizations on calculation accuracies.

The study was conducted in commercial corn fields near Witzenhausen in central Germany. Maize was planted and managed according to standard optimum practice. The crop experienced typical summer weather fluctuations of the region and was not irrigated. Model outputs were tested against independent sap flow measurements in maize stems.

The computation error decreased significantly at an hourly time scale when the radiation model was driven in multi-layer instead of single layer mode. The application of a dynamic light response function further increased the calculation accuracy of the model. Interactive effects of

canopy geometric and stomatal parameterization modes on model performance were not observed.

The Penman-Monteith model was also rearranged for *a posteriori* calculations of canopy conductances using sap-flow measurements as inputs. Computation errors decreased with increasing detail of canopy parameterization, but were generally high. Measured and calculated canopy resistances followed similar values and trends under clear sky conditions, but disagreed under strongly fluctuating weather conditions.

The empirical parameterization of the transpiration model does not account for short-term perturbations within the plant system which are caused by different responses of the canopy and root fractions to dynamic changes of their respective environments. Better mathematical characterizations of causal relations between leaf and root processes controlling transpiration behaviour will likely improve the performance of the Penman-Monteith equation under practical conditions.

INTRODUCTION

Agricultural water use accounts for about 70 % of the world's total freshwater consumption (FAO Aquastat, 2009). Growing demands for food and water under increasing global environmental and economic disturbance scenarios require improvements of crop water use and irrigation efficiencies. Investing into the practical application of advanced irrigation technology, breeding of efficient and stress tolerant crops, re-designing farming systems, and optimizing water management practices are important solutions. Their implementation must necessarily be based on knowledge of environmental effects on crops water use.

The Penman-Monteith model is widely used for quantifying crop water uptake using information from agrometeorological stations. Net radiation, air humidity, air temperature and wind speed are the required input variables of the model under closed canopy conditions. Soil heat-flux must be taken into account when solar radiation reaches the soil. The parameterization of resistances to vapour flow in the laminar and turbulent air layers can be carried out based on well established theories (Kaimal and Finnigan 1994). However, determining and modeling canopy surface resistance remains a partially solved problem (Brutsaert 2005). Hydraulic (Meinzer, 2002) and chemical (Srivastava, 2002) signals propagate through the plant hydraulic system and affect stomatal aperture. The generation, propagation, and perception of these signals are interrelated with other plant physiological processes. The interrelations are reasonably well understood from a conceptual point of view, but their quantifications have not been successful so far.

Aiming for a practical application of the model, a simple approach of determining canopy resistance was thus chosen for closed canopy conditions. It is based on correlations between *in-situ* measurements of light interceptance and stomatal resistance. A radiation model is used to scale the resulting regression function from the leaf to canopy the canopy level. The aim of this study was to quantify the effects of contrasting surface resistance model parameterizations on the accuracies of transpiration calculations.

MODEL

Transpiration rates from the sunlit and shaded leaf fractions are calculated separately to account for their different contributions to total transpiration (Fuchs et al., 1987; Petersen et al., 1992). Potential transpiration was estimated with (Penman, 1948):

$$E_{p,x} = \frac{1}{s+\gamma}\left(s\,R_{n,x} + \rho c_p \frac{\left[e_s(T_a) - e_a\right]}{r_{u,x}} \right)$$

where $E_{p,x}$ is the transpiration from the leaf fraction x (Subscripts p=potential, s=sunlit leaf fraction, sh=shaded leaf fraction), s the slope of the saturation vapour pressure curve, γ the psychrometric constant, R_n the net radiation flux density at the sunlit or shaded canopy surfaces x, ρc_p the volumetric heat capacity of the air, $e_s(T_a)$ and e_a the saturation and actual vapour pressures in the air at temperature T_a, and $r_{u,x}$ the aerodynamic resistance.

The actual transpiration from each leaf fraction $E_{a,x}$ (Subscript a=actual) was calculated with (Monteith 1965):

$$E_{a,x} = \frac{E_{p,x}}{1 + \frac{\gamma}{s+\gamma}\frac{r_{c,x}}{r_{u,x}}}$$

where $r_{c,x}$ is the canopy resistance of the sunlit or shaded leaf fraction.

Stomatal resistance r_s was calculated as a function of intercepted photosynthetically active radiation PAR:

$$\frac{1}{r_s} = a\sqrt{PAR} + b\,PAR$$

where a and b are fitting parameters which were determined using data from simultaneous measurements of r_s and PAR . These measurements were carried out at regular intervals during the peak growing season until the plants started senescencing.

Two methods were applied in this study to scale stomatal resistances from leaf to canopy level:

$$\frac{1}{r_{c,x}} = \frac{1}{r_s} LAI_x$$

$$\frac{1}{r_{c,x}} = \sum_{i=1}^{4} \frac{1}{r_s} LAI_{i,x}$$

The sunlit or shaded leaf areas LAI_x were determined with a radiation model which assumed a spherical leaf angle distribution. Leaf area densities were determined experimentally and used as inputs of the second function which divides the canopy into four equally sized layers i. The sunlit and shaded areas of each canopy layer were determined with calculations of vertical beam penetration probabilities.

Total canopy resistance was calculated with:

$$\frac{1}{r_c} = \frac{1}{r_{c,s}} + \frac{1}{r_{c,sh}}$$

The outputs of this model were tested against canopy resistances calculated with the inverted Penman-Monteith equation

$$\frac{1}{r_c} = r_u \frac{\gamma \lambda E_t}{\left\{ sR_n + \rho cp\, VPD_a / r_u - \lambda E_t [s + \gamma] \right\}}$$

where E_t was determined under closed canopy conditions with the heat pulse method for measuring sap-flow in plants (Cohen and Li 1996). We emphasize that the heat pulse measures sap flow and not transpiration. Time lags are small, however, since the hydraulic charge and discharge capacitances of maize are small under unstressed conditions (Langensiepen et al., 2009).

METHODS

The studies were conducted during the 1995 and 1996 seasons in commercial corn fields (~2.7 ha sizes) near Witzenhausen in Central Germany (52.21° N, 9.51°E). Maize (cv. Helix, KWS Einbeck, Germany) was planted and managed according to standard optimum practice. The crop experienced typical summer weather fluctuations of the region and was not irrigated.

Leaf vapour resistance and photosynthetically active radiation were measured with a steady state porometer (L1600, Licor, Lincoln, Nebraska, USA). The measurement locations were sampled at random in the sunlit and shaded canopy portions. Only noon observations were chosen for model parameterization to avoid artefacts from stomatal responses to rapid changes of the air environment (Li et al., 2004).

Leaf area growth was monitored by destructive and indirect methods (LI-3100C Area Meter, LI-2000 Fisheye, Licor, Lincoln, Nebraska, USA; Lang Plant Digitizer, Kassel University, German).

Plant heights were measured with rulers. The model was exclusively applied under closed canopy conditions when the leaf area index was larger than 2.5.

Solar radiation, wind-speed, air temperature and humidity were monitored at 2m height and averaged over 30-minute intervals with a standard automatic weather station which was operated in close vicinity of the experiments (Thies Clima, Göttingen, Germany).

The sap flow of 8 randomly selected plants with same stem diameters was determined with the calibrated heat pulse method (Cohen et al., 1988). Plants were changed at weekly intervals to avoid artefacts from repeated heating of stem tissues.

RESULTS

Measured and calculated transpiration rates were highly correlated when the model was driven in single layer mode (r^2=0.89; n=4272). Differences between the root mean square errors (RMSE) of calculated transpiration minus sap flow determined under a wide range of seasonal conditions were insignificant in both years. The overall RMSE of 0.087 mm/hr is dominated by its variance component $(0.0075\{mm/hr\})^2$. Data scattering is high at low sap flow rates, particularly during morning hours. Evaporation of dew explains that the Penman-Monteith equation overestimates water uptake during this time.

PAR was significantly correlated with stomatal conductance in both years (r^2=0.96, n=928). Distances of the prediction bands from the fitting curve were large, however. Seasonal changes of the parameter values of the fitting function were thus very small. Their effects on simulation accuracies were nevertheless tested in the following analysis.

Two days with characteristic courses of meteorological conditions were chosen for testing the effects of contrasting canopy resistance parameterisations on the accuracies of transpiration simulations. A nearly parabolic course of vapour pressure deficit with maximum values of 1.5 kPa and a jagged solar radiation curve were chosen in the first instance. The second day was characterized by erratic changes of both variables. Calculated and measured transpiration rates and canopy resistances closely matched each other in the first example. This was not the case during the second chosen day when calculated canopy resistances considerably departed from the corresponding measured values. Transpiration and canopy resistance calculations were significantly improved when the scaling routine was driven in multi-layer mode.

Effects of contrasting canopy and stomatal resistance parameterization on model calculation errors are summarized in Figures 1 and 2 for daily and half-hourly time scales, respectively. The computation error decreased considerably at a half-hourly time scale when the radiation model was driven in multi-layer instead of single layer mode. This was not the case on a daily time scale, however. The application of a dynamic light response function further increased the calculation accuracy of the model. Interactive effects of canopy geometric and stomatal parameterization modes on model performance were not observed.

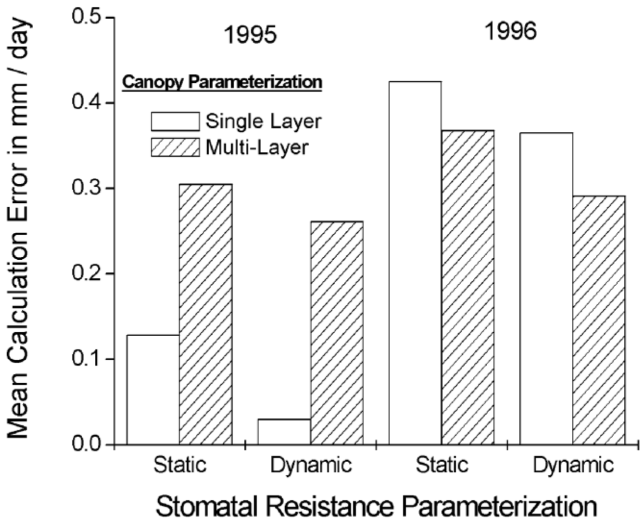

Fig. 1: Effects of contrasting canopy parameterization on the accuracies of daily transpiration computations.

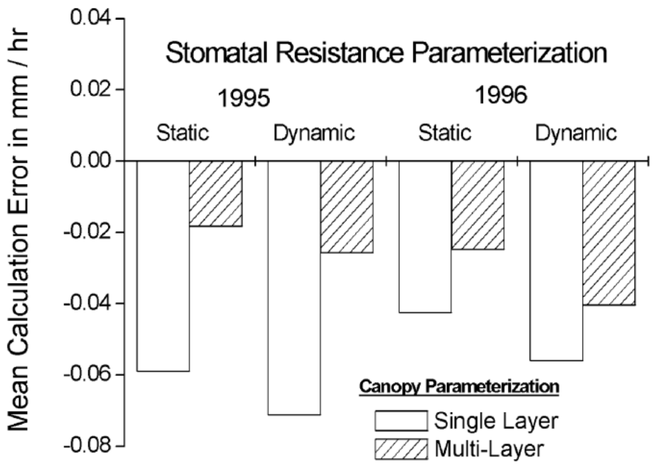

Fig. 2: Effects of contrasting canopy parameterization on the accuracies of hourly transpiration computations.

DISCUSSION

Computed transpiration agreed closely with sap flow under a wide range of weather conditions during two corn growing seasons in Germany. This observation verifies the validity of the Penman-Monteith approach, which has been also reported in a number of other studies (Burman, 2003; Brutsaert, 2005). The small advantage of the dynamic stomatal resistance parameterization in relation to the static parameterization can be explained by errors which commonly occur during porometer measurements (Turner, 1991).

The main hypothesis was that, under near-optimum water supply conditions, a more detailed characterization of the canopy light microclimate would improve the scaling of stomatal light response to the canopy level and result into better transpiration computations. The validity of this approach could not be rejected, as has been also recently shown by Irmak et al. (2008), but the magnitude of improvements was small. Disagreements between measured sap-flow and computed transpiration cancel each other out when half-hourly values are integrated over the entire diurnal course. The inconsistencies shown in Fig. 1 were likely caused by random effects.

Scaling stomatal light responses with a multi-layer radiation model was only advantageous when the model was operated at shorter timer intervals (Fig.2). We doubt, however, that this finding can be generalized. Light is the major driving factor of stomatal opening behaviour at the site in Germany which commonly receives sufficient amounts of rain and experiences vapour pressure deficits below 2 kPa during most parts of the season. Computed canopy resistance deviated by more than 100 sm^{-1} when this was not the case. This effect became most apparent when plant capacitance caused minor shifts between measured sap-flow and computed transpiration, particularly during afternoons. Scaling stomatal resistance from leaf to canopy under unstressed conditions thus cannot be based on light alone, as has been proposed by Irmak et al. (2008), since other driving factors such as VPD can become significant. The practical relevance of this finding depends on scale of observation, however. McNaughton and Jarvis (1991) provided theoretical evidence that negative feedback loops at the much greater leaf and canopy scales reduce the sensitivity of the vapour transport system to stomatal control. There is no benefit to be gained from the application of multi-layer models at these levels of observations. Sophisticated transport parameterization and sufficient computing power would be necessary, if other factors such as VPD, wind or CO_2 have to be considered in the scaling framework.

Multi-layer studies are nevertheless important if the heterogeneity of transpiration distribution within the canopy needs to be known and optimized, particularly under water stress conditions. Fluctuations in root zone water availabilities alter the relative rate of nutrient uptake and circulation, which affect the xylem sap pH and, in consequence, the partitioning of abscisic acid within the stem circulation system (Stitt, 1994). Stomata are highly sensitive to changes in abscisic acid concentrations (Wilkinson and Davies 2002). Their responses to changes in atmospheric conditions thus differ greatly within the canopy. Since these conditions are themselves also highly variable in space, quantifying the integration of stomatal opening behaviour on the plant level is a challenge. Advancements in structural-functional plant modeling will contribute to a better understanding of the underlying complexity, but the practical application of such models is not feasible due to their inherent complexity and high data demands. They provide a useful basis, however, for simpler multi-layer canopy models which can be applied in practice for quantifying the effects of soil moisture variability on crop water use.

Reductionist scaling is a measure of our ability to understand the complexity of systems. Repetitive observations of crop responses to fluctuating environmental conditions do not provide insight into the complexities of their underlying mechanisms.

CONCLUSIONS

Increasing the level of light microclimate characterization improved the scaling of stomatal light responses from leaves to canopy under near optimum soil water supply conditions. The errors of hourly transpiration computations were significantly reduced by this approach. It had little effect on the accuracies of daily transpiration calculations, however, due to the mutual cancelling of errors which occurred during daily cycles.

Multi-layer characterization of canopy resistance becomes important when the heterogeneities of transpiration distributions within canopies need to be quantified under limiting or strongly fluctuating soil moisture supply conditions.

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RELATIONSHIPS BETWEEN SOIL CARBON SEQUESTRATION AND CLIMATE CHANGE AS WELL AS ELEVATED ATMOSPHERIC CO_2 CONCENTRATION

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ABSTRACT

Soil carbon sequestration is expected to mitigate the global warming and in turn is affected by the climate change and elevated atmospheric CO_2. Effects of changes in annual average temperature and annual precipitation as well as elevated atmospheric CO_2 on soil organic carbon (SOC) sequestration for various vegetation covers were studied based on data and simulation results of CENTURY. Relationships were established between the relative changes of SOC and the relative changes of annual average temperature, precipitation, and atmospheric CO_2 concentration, as well as their inter-products for different vegetation covers. Results showed that the SOC was negatively related to the annual average temperature and positively related to the elevated CO_2 for the vegetation covers, while the SOC was positively related to the precipitation changes for soybean and corn. Using the relationships, we defined a “cutoff surface” for each of the vegetation covers, which clearly quantified the conditions for soil carbon sequestration or release under climate change and elevated CO_2. The relationships were also applied successfully to predict the SOC with weather uncertainties.

INTRODUCTION

Soil carbon sequestration can efficiently mitigate greenhouse gas emissions (Rice, 2006). Research has been conducted to study the effects of land management practices on soil carbon sequestration (Entry et al., 2002; Sherrod et al., 2003; Birdsey et al., 2006). However, the climate change and elevated atmospheric CO_2 concentrations in turn can affect soil carbon dynamics, which are still poorly understood. The atmospheric CO_2 concentration and global mean temperature are in a constantly increasing trend, as noted by the Intergovernmental Panel on Climate Change (IPCC, 2007). Under the elevated CO_2, the soil can be a carbon sink for the atmosphere (Jastrow et al., 2005; Kant et al., 2007). On the other hand, the global warming can counteract the effect of elevated CO_2 in soil carbon sequestration to some extent (Fissore et al., 2008). Therefore, the soil may act either as a carbon source or sink for the atmosphere, under the conditions of climate change and elevated CO_2 (Yu et al., 2006).

To directly describe the response of SOC dynamics to climate change and elevated CO_2, it is essential to establish relationships between the SOC and the warming effect, precipitation change, elevated atmospheric CO_2 concentrations, and others. Guo et al. (2006) provided exponential and quadratic polynomial relationships between the SOC and mean annual temperature for grassland and forestland in different annual precipitation zones. Wang et al. (2007) obtained a linear relationship between the SOC vs. annual precipitation and annual average temperature based on historical SOC data for a *Leymus chinensis* meadow steppe. Fissore et al. (2008) established a linear relationship between the SOC and mean annual temperature for hardwood and pine stands. However, important factors, such as the atmospheric CO_2 concentration and vegetation cover, have not been considered in the relationships reviewed in the literature.

The main objective of this study was to propose a simple yet comprehensive relationship, relating the SOC to the increasing annual average temperatures (warming), annual precipitation changes, elevated atmospheric CO_2 concentrations, and vegetation covers (land use). Using the relationship, we quantified soil carbon sequestration under different conditions of the climate change, elevated CO_2, and vegetation covers. The relationship was also applied to predict the future SOC amount under climate change and elevated CO_2 with weather uncertainties.

METHODS

The SOC Relationship

A simple relationship between the SOC vs. the annual average temperature (warming), annual precipitation, and elevated atmospheric CO_2 is proposed as follows:

$$\frac{\Delta SOC}{SOC} = a\frac{\Delta T}{T} + b\frac{\Delta P}{P} + c\frac{\Delta CO_2}{CO_2} + d\frac{\Delta T}{T}\frac{\Delta P}{P} + e\frac{\Delta T}{T}\frac{\Delta CO_2}{CO_2} + f\frac{\Delta P}{P}\frac{\Delta CO_2}{CO_2} \quad (1)$$

Here SOC is the SOC under the baseline climate and atmospheric CO_2 concentration (g m^{-2}), ΔSOC is the SOC change under the changed climate and elevated CO_2 (g m^{-2}), T is the baseline annual average temperature (℃), ΔT is the annual average temperature change (℃), P is the baseline annual precipitation (cm), ΔP is the annual precipitation change (cm), CO_2 is the baseline atmospheric CO_2 concentration (ppm), ΔCO_2 is the atmospheric CO_2 concentration change (ppm), *a*, *b*, *c*, *d*, *e*, and *f* are non-dimensional parameters, changing with different vegetation covers. All the changes are the differences between the values under the changed scenarios and those under the baseline scenarios.

Site Description

Nelson Farm was chosen as the study site to take the advantages of a large amount of available data and previous research results. Nelson Farm (Latitude 34°33′50″, Longitude 89°57′30″) is within the Yazoo River basin with an area of 2.09 ha. During 1930-1997, the mean annual precipitation was 90.04 cm yr^{-1} and the mean annual temperature was 15.7 ℃. Detailed land use and management of this site is described in Harden et al. (1999). In this study, we used the detailed input information for the CENTURY model set up by Harden et al. (1999).

The CENTURY Model

CENTURY consists of sub-models of soil organic matter, nitrogen, phosphorus, sulfur, plant production, and a simplified sub-model for water budget in the soil. The model can be used to simulate soil carbon dynamics in the top 20 cm of soils related to processes of fertilization, irrigation, cultivation, grazing, and fire, and simulate labeled carbon, enriched CO_2 effects, and soil incubation (Metherell et al., 1993). The effect of climate change on the SOC can be simulated using the model through input weather information.

The SOC loss processes simulated in CENTURY include soil respiration, C loss from soil erosion, and SOC leached. The SOC increase is through the net primary production, which is influenced by soil moisture, soil temperature, nutrient supply, and enriched CO_2. Soil temperature reduces production for most plant species if the temperature is off the optimal temperature (Parton et al., 1987). The elevated atmospheric CO_2 can affect the relative plant production, potential transpiration rate, the maximum and minimum C-nutrient ratios, and the root-shoot ratio. These processes have been implemented in CENTURY. More details about CENTURY are given by Metherell et al. (1993). In this work, CENTURY 4.0 was utilized.

Parameter Determination of the SOC Relationship

To obtain the parameters of Eq. (1), we conducted simulations to generate processes of the SOC dynamics under the baseline scenario and scenarios with changed climate as well as elevated atmospheric CO_2 concentrations, using CENTURY and the Nelson Farm data. The simulation time period of the scenarios was set from 1998 to 2100, to be consistent with the forecasting time period of climate change and rising atmospheric CO_2 concentration (IPCC, 2007). The baseline values of SOC from 1998 to 2100 were generated using CENTURY and the baseline data of climate and atmospheric CO_2 concentration, including the annual average temperature, annual precipitation, and atmospheric CO_2 concentration of 15.7℃, 90.04 cm, and 350 ppm, respectively (Harden et al., 1999). Based on possible changes of the future climate (IPCC, 2007), we set the annual average temperature increases by 1 and 5℃/degrees, respectively, combined with precipitation increase or decrease, both by 20% from 1998 to 2100 (Yu et al., 2006), which composed four scenarios. Each of the scenarios was combined with an increasing process of atmospheric CO_2 concentration, changing from 350 to 700 ppm during the simulation period (Wang et al., 2007). In addition, a separate scenario of 5℃/degree warming was composed with the baseline values of the annual precipitation and atmospheric CO_2 concentration. The climate and CO_2 concentration increments were assumed to linearly change during the time period (IPCC, 2007). These settings constituted one baseline scenario and five climate change and/or elevated CO_2 scenarios to be simulated. To analyze applicability of the relationship under different vegetation covers, we considered three types of plants (i.e., C_3 crop: soybean, C_4 crop: corn, and C_3 grass) in the simulations.

The simulation results of the SOC for the baseline scenario and the climate change and elevated CO_2 scenarios under different vegetation covers were used to fit Eq. (1) using multiple linear regressions to obtain the parameters. All statistics analyses were conducted employing SPSS 12.0 for Windows (SPSS Inc., 2003).

RESULTS AND DISCUSSION

Fitting Processes of the Relationship

All vegetation covers in Nelson Farm, Eq. (1) fit the simulation results very well. Coefficients of determination (R^2) for all fitting processes were from 0.964 to 0.995 (Table 1). Values of the fitted parameters in Eq. (1) for the different vegetation covers are listed in Table 1. The parameters showed that the relative change of SOC was negatively related to the relative change of annual average temperature ($a < 0$, $p < 0.001$), and positively related to the relative changes of elevated CO_2 ($c > 0$, $p < 0.001$) for all the vegetation covers; while the relative change of SOC was positively related to the relative change of precipitation for soybean and corn ($b > 0$, $p < 0.001$) (Table 1).

Table 1. Parameters and coefficients of determination (R^2) of Eq. (1) obtained by fitting the relationship with simulation results of CENTURY for Nelson Farm

Vegetation	a	b	c	d	e	f	R^2	p
Soybean	-1.328	0.127	0.265	-1.285	-0.638	0.424	0.995	0.000
Corn	-1.228	0.202	0.086	-0.058†	-0.189	0.239	0.982	0.000
Grass	-0.683	0.020†	0.120	1.418	-0.157	-0.213	0.964	0.000

†Not significant with the significant level of 0.05.

Cutoff Surfaces and SOC Calculations Based on the Relationship

Based on the combining effects of climate change and elevated CO_2 in Eq. (1), we determined the conditions that resulted in soil carbon sequestration or soil carbon release, compared with the SOC under the baseline climate and CO_2. Setting the left-hand side of Eq. (1) as zero, we obtained a curved surface, called the cutoff surface for each of the vegetation covers. Above the cutoff surface, the relative SOC changes are negative (soil carbon release), while below the cutoff surface, the relative SOC changes are positive (soil carbon sequestration). Using Eq. (1) with the parameter values in Table 1, we obtained the cutoff surfaces for soybean, corn, and grass of Nelson Farm. One example of the cutoff surfaces is shown in Fig. 1 for soybean. It was found that warming counteracted the effect of elevated CO_2 and precipitation on soil carbon sequestration. For Nelson Farm with the three vegetation covers, warming by 2.7℃ or higher (i.e., the annual average temperature > 18.4℃) would result in a negative combining effect on the SOC (soil carbon release) no matter what possible changes of elevated CO_2 and precipitation.

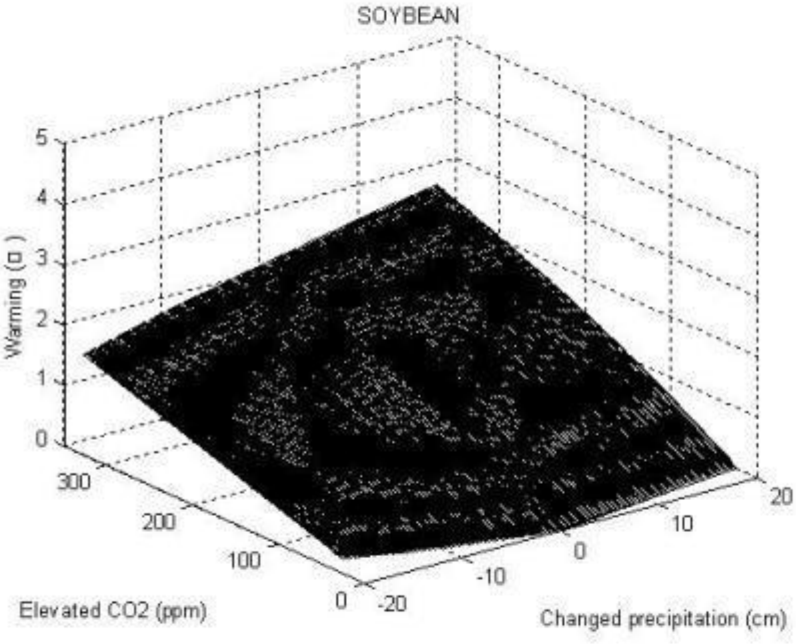

Fig. 1: Cutoff surface for soil carbon sequestration or release under the vegetation cover of soybean.

Besides the relative SOC changes discussed above, Eq. (1) can also be used to calculate the real amount of SOC changes. To estimate the average amount of soil carbon sequestration during a time period, a mean sequestration rate (*MSR*) was defined as follows:

$$MSR = \frac{SOC_c(t) - SOC_c(t_0)}{t - t_0} \quad (2)$$

where

$$SOC_c(t) = SOC(t)(1 + SOC_R) \quad (3)$$

Here t is time (yr); t_0 is the initial time (yr); SOC_0 is the initial SOC (g m^{-2}); $SOC_c(t_0)$ and $SOC_c(t)$ are the SOC values (g m^{-2}) at t_0 and t under the climate change and elevated CO_2 condition, respectively; SOC_R is the SOC relative change calculated from Eq. (1). Without considering precipitation changes, Fig. 2A, C, and E show the *MSR* values during 1998 – 2100 changing with the temperature (warming) for soybean, corn, and grass, respectively. In each figure, two cases for elevated CO_2 = 0 and 350 ppm were compared. Similarly Fig. 2B, D, and F show the *MSR* values during the time period changing with the elevated CO_2 for soybean, corn, and grass, respectively. In each figure, two cases for temperature = 0 and 5 °C were compared. Figure 2 clearly indicates that the *MSR* values increase with the elevated CO_2 and decrease with the temperature. Under the climate change and elevated CO_2, most of the *MSR* values of the soil growing soybean are negative (Figs. 2A, B), suggesting that the soil releases carbon to the atmosphere. On the contrary, the soils growing corn and grass sequestrate carbon from the atmosphere (Figs. 2C, D, E, and F). In terms of soil carbon sequestration, grass is the most efficient vegetation cover among the three.

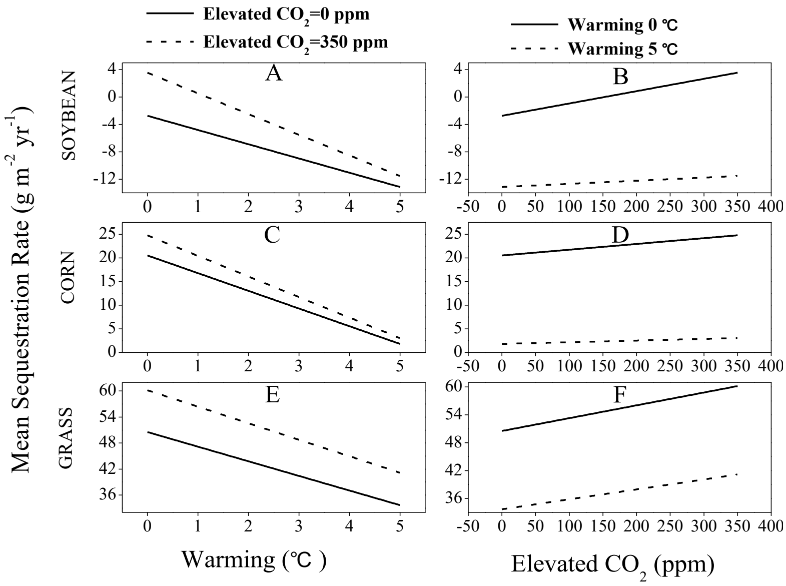

Fig. 2: Mean sequestration rates of carbon during 1998 – 2100 changing with the temperature (warming) for soybean (A), corn (C), and grass (E), and elevated CO_2 for soybean (B), corn (D), and grass (F) of Nelson Farm. Negative values refer to soil carbon release to the atmosphere.

SOC Predictions under Climate Change and Elevated CO_2 with Weather Uncertainties

For the simulations to obtain the parameters of Eq. (1), the input parameters for climate change varied linearly with time without any uncertainties. However, real measurements or future weather patterns are almost always with uncertainties or fluctuations from the general trend. Therefore, we set up several scenarios of climate changes with uncertainties. The warming patterns were set from 15.7℃ in 1998 to 2100, by increasing 1.6, 2.6, 3.4℃, respectively (IPCC, 2007), and the elevated CO_2 was assumed to be double (from 350 ppm in 1998 to 700 ppm in 2100); and these two factors were linearly changed during the simulation time period. The sequential Gaussian simulation (GSLIB, Deutsch and Journel, 1992) was used to generate the random fields of the annual average temperature and annual precipitation. Coefficients of variation used in the random field generations were 3 and 10% for the annual average temperature and annual precipitation, respectively. Combining the random fields of the annual average temperature with the warming patterns as drifts, we obtained the future warming processes with uncertainties (Zhang, 2004). We used the following equation to calculate relative errors:

$$RE(t) = \frac{SOC_c(t) - SOC_s(t)}{SOC_s(t)} \quad (4)$$

in which t is time (yr), $SOC_c(t)$ is the SOC values (g m^{-2}) calculated using Eq. (1) and the parameters in Table 1, and $SOC_s(t)$ is the SOC values (g m^{-2}) simulated using CENTURY with the temperature and precipitation uncertainties. The mean absolute relative errors between predictions using the relationship and simulation results using CENTURY for all cases were smaller than 5%. Figure 3 presents temporal distributions of relative errors between the predictions and simulation results of the SOC during the 103 years. All the absolute relative errors for grass cover were smaller than 10%, and more than 90% of absolute relative errors for soybean and corn covers were smaller than 10%, while only one error for corn was greater than 20%. The results indicated that the relationship provided reasonably accurate predictions and was robust to scenarios with particular uncertainties.

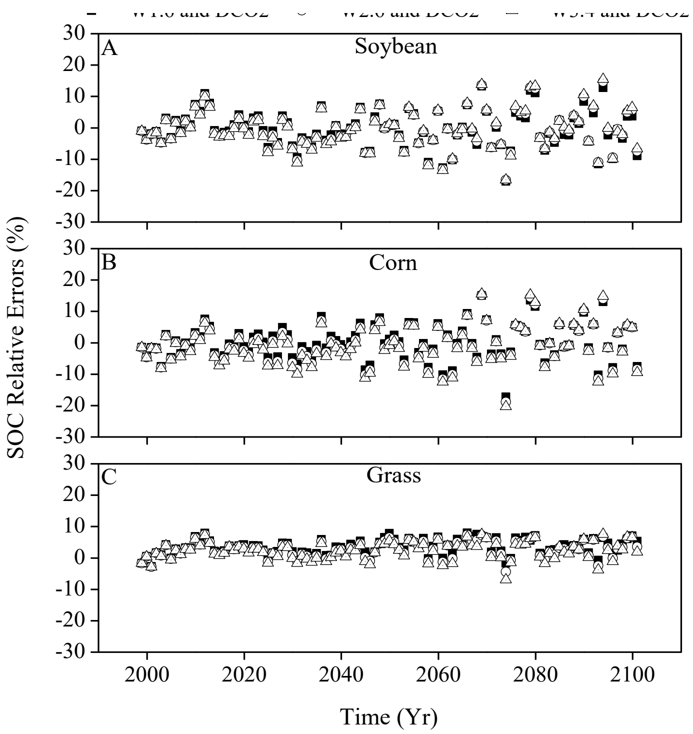

Fig. 3: Temporal distributions of SOC relative errors between the predictions using the relationship (Eq. (1)) and simulation results using CENTURY for vegetation covers of soybean (A), corn (B), and grass (C). W1.6, W2.6, and W3.4 refer to warming 1.6, 2.6, and 3.4 °C respectively, and DCO2 refers to double CO_2 concentration.

CONCLUSIONS

We proposed a simple yet comprehensive relationship between the SOC and the increasing annual average temperature (warming), precipitation change, elevated atmospheric CO_2, and vegetation covers (land use). Based on the relationship, a "cutoff surface" was defined for each of the vegetation covers, which can be used to determine various conditions of climate change and elevated CO_2 for soil carbon sequestration or soil carbon release to the atmosphere. The relationship was also applied to predict the SOC under climate change and elevated CO_2 with particular weather uncertainties. The relationship satisfactorily characterized the SOC dynamics that changed with the air temperature, precipitation, and atmospheric CO_2 concentrations under the different vegetation covers.

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Session 8: Irrigation with Reclaimed Wastewater

USE OF RECLAIMED WASTEWATER FOR IRRIGATION IN ISRAEL

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ABSTRACT

The utilization of reclaimed wastewater (RWW) in Israeli agriculture has increased in the last two decades by more than threefold, providing nowadays half of the irrigation water. The significant increase occurred in parallel to several years of drought, which stressed the importance of using RWW in a region with limited water resources. While the utilization of the RWW represents values of conservation, waste recycling and re-use of nutrients, it also exposes human beings and the environment (soil, water, plants) to salinity problems, accumulation of Boron, sodification and damage to structure (SAR/ESP), potential N and P accumulation in soil and water, undesired effects of organic constituents and health risk by pathogens. The potential threats led to a conceptual change in the attitude to RWW utilization, placing greater emphasis on the sustainable use of this source and recognizing the need to consider long-term effects much more carefully, rather than "believing" that the soil's "buffering ability" enables it to tolerate low quality RWW. Significant efforts have been devoted to (i) R&D, both in developing improved wastewater treatment techniques and agricultural and irrigation practices; (ii) Surveying the effects of RW on farmland and the environment; and (iii) Re-examining and modifying regulations. This paper summarizes the state of knowledge related to the understanding of RWW interactions with soil-plant-water and their health and environmental implications, emphasizing the need to ensure that the overall increase in RWW use occurs while sustaining high agricultural production and concomitantly preserving the water, soil and environmental quality in the region.

INTRODUCTION

There is an ever-increasing need for alternative water resources in arid and semi arid regions, where average evaporation (evapo-transpirations) significantly exceeds precipitation. A common criterion indicative of water scarcity is the amount of potentially usable water resources, where values of 1500–1700 m^3/capita/year are defined as the threshold for "water scarcity." Many Mediterranean regions including Israel have water resources below 500m^3/capita/year, indicating "severe water scarcity" (Yang et al., 2007). Average annual water potential supply over the last 75 years has been about 1400 MCM (with increasing fluctuations and a trend of decrease in the last 20 years) and the demand for fresh water is steadily increasing, from about 1500 MCM in recent years (after reducing agricultural consumption) to a projected 1750 in the year 2020. Due to water deficit, the consumption of fresh water in agriculture, the largest sector to use this source until recently, was reduced from 850-900 MCM in the late nineties to 550 in the period 2001-2007 and was further reduced, due to a continuous drought period, to 450 in 2008. The reduction of fresh water quota allocated to agriculture was compensated by a steady increase of RWW, which together with the brackish water resources increased from 350 MCM in the mid nineties to ~630 MCM in 2008! Accordingly, the percentage of RWW used in agriculture exceeded 50%, amounting to about two thirds of the treated WW country-wide. Oman and Kuwait utilize a significant proportion of their WW for agriculture; California, Florida and Mexico utilize relative large amounts of RWW for irrigation and yet these are only small fractions of the total reclamation in these regions (Hamilton et al., 2007). Other countries where the use of RWW is practiced are China, Cyprus, Greece, Iran, Italy, Pakistan and Spain (e.g., Hamilton et al., 2007; O'Connor et al., 2008). One of the critical problems associated with this reuse is the lack of common standards, regulations and guidelines for WW treatment. As a result, in many regions and particularly in less developed ones, poorly treated WW is used for irrigation (e.g., Hamilton 2007; Brissaud, 2008,).

Using RWW for irrigation introduces the valuable advantage of conserving a precious and scarce resource in regions where it is critically needed, with the added benefit of RWW containing a substantial amount of the nutrients needed by plants. On the other hand, RWW, particularly when poorly treated, poses several critical threats and disadvantages. These include salinity build up in soil and ground water; soil sodification and adverse effects on structure (runoff, erosion); boron toxicity to plants; accumulation and leaching of nutrients particularly nitrogen and phosphate; adverse effects of the active organic matter (Biological Oxygen Demand - BOD) and the hydrophobic fraction in it; potential pollution by pharmaceutical or other toxic compounds; and health problems due to inadequate removal of pathogens.

Due to awareness to the potential health, environmental and agronomic problems associated with the use of RWW, several governmental offices and agencies invested due efforts in the last two decades to act in four main directions, which are crucial for sustainable utilization of RWW. These are: i. Gaining a better understanding of RWW interaction with soil-plant-water, so as to allow improved irrigation management practices that assure sustainable agricultural production as well as consideration of concerns related to human health and environmental protection; ii The encouragement of improvements and innovations in WW treatment technologies; iii. Intensive monitoring of adverse effects on soil, water resources and agricultural products; and iv. Continuous efforts to recheck and amend legislation and guidelines for RWW users. This essay describes the state of knowledge as related to the first issue mentioned above - better understanding of RWW interactions with soil-plant-water and their health and environmental implications.

SALINITY EFFECTS

Wastewater is more saline than fresh water sources (Feigin et al., 1991; Hamilton et al., 2007; Biggs and Jiang, 2009). The additional salinity may threaten both plant growth as well as water resources' quality (e.g., Rebhun, 2004). The vast knowledge on handling water salinity has been integrated and adopted for issues related to the use of saline sources like RWW (e.g., Feigin et al., 1991; Pesond, 1992; and Roades et al., 1992). Nevertheless, salinity still remains one of the greatest concerns in using WW that is reclaimed using the more conventional and prevalent treatment technologies, which do not apply salt separation techniques (e.g., Aharoni and Cikurel, 2006; Oron et al., 2008). The National survey of RWW irrigation in Israel for 2006/7 (Israeli Water Authority, 2008) stated that about 72% of the RWW exceeds the rate of 250 mg Cl/l, indicating that 3/4 of the supplied RWW was already defined as posing medium to severe salinity problems. More than 10% of WW for irrigation was indicated as posing severe salinity threats when considering the common irrigation criteria published by Pescod (1992) or Rhoades et al. (1992). To minimize the expected salinity effects, farmers apply higher leaching fractions in areas where RWW is applied and thus the total amount of salinity leached to shallow groundwater (basically aquifers) is increased both due to higher salt content and higher LF, as demonstrated in several publications (Wallach , 1994; Rebhun, 2004; Kass et al., 2005).

SODICITY AND EFFECTS ON SOIL STRUCTURE

Normally Na content is linked to total salinity and hence its content in the reclaimed wastewater is higher than in freshwater sources, primarily, due to concentration effects (evaporation, transpiration). Yet, Na in RWW has additional enrichment sources, such as detergents, Na from human diet, and from small food/meat processing industries. It should be noted, however, that WW from heavy and chemical industries is separated from the domestic wastewater and practically not used for irrigation! Based on data of a survey of RWW irrigation in Israel for 2006/7 (Israeli Water Authority, 2008), only 8% of the RWW has Sodium Adsorption Ratio

(SAR) values between 0 and 3. This range can be defined as posing low danger to soil crusting, whereas 76% of the RWW has values of 3 to 5 (considered to pose a low-to-medium threat) and 16% is in the range between 5 and 9, which for most soils may pose severe problems and requires the use of gypsum for correction (e.g., Pescod, 1992; Rhoades et al., 1992). Sodicity values decreased significantly in RWW in the last decade, due to a new Israeli Standard (IS 438, 1999) that imposes new requirements for washing powders. Adoption and implementation of the standard marked an important breakthrough in the struggle to reduce the sodicity of Israel's water sources.

In the last five decades, there has been a substantial effort to understand soil structure deterioration and seal formation due to the use of alkaline (sodic) irrigation water (Richards, 1954; McIntyre, 1958; Shainberg and Letey, 1984;). Seal formation is attributed to two mechanisms (Agassi et al., 1981; Shainberg and Letey, 1984; Lado et al., 2005): i. Physical disintegration of surface soil aggregates, caused by the impact of raindrops; and ii. Physicochemical dispersion of soil clays, which increases with the increase in the soil's exchangeable sodium percentage (ESP) and the decrease in EC (i.e., rain). The increase in ESP is correlated with the increasing SAR (e.g., Richards, 1954; Rhoades et al., 1992).

The fact that RWW has, inherently, higher levels of SAR as compared to the fresh water it originates from, triggered investigations into the effects of RWW on soil structure deterioration and seal formation (e.g., Feigin et al., 1991; Tarchitzky et al., 1999; Mamedov et al., 2001; Agassi et al., 2003; Mandal et al., 2008). Basically it has been shown that irrigation with poor quality RWW, containing a high load of organic matter, decreased soil hydraulic conductivity (HC; e.g., Vinten et al., 1983; Magesan et al., 1999). In studies that used RWW of higher treatment quality trends were less consistent (Bhardwaj et al., 2008; Mandal et al., 2008). While, Levy et al. (1999) found little differences in HC in a comparison between RWW and fresh water, Mamedov et al. (2001) demonstrated significant adverse effects on runoff and soil loss only in loamy sand irrigated with secondary effluent. Tarchitzky et al. (1999) reported a clear reduction in the HC and effects on montmorillonite dispersion due to the use of secondary RWW. In a study performed by Agassi et al. (2003) on a loess soil (Calcic Haploxeralf) and a Grumosol (Chromic Haploxerert) it was concluded that "standard domestic effluents in Israel have no adverse effect on the hydraulic parameters and the stability of the common arable lands." In several works done later (e.g., Lado et al., 2005; Mandal et al., 2008) it was demonstrated that when slaking was the major soil structural destruction mechanism, the differences between fresh waster and RWW were negligible. Slaking occurs due to aggregates disintegration by fast wetting caused by fast release of entrapped air and differential swelling (e.g., Kay and Angers, 1999). It has been shown that in soils with relatively high clay content, where the dominant structural destruction of aggregates occurs via slaking due to relatively high rate of wetting, the effect of RWW is less pronounced or even non-existent. On the other hand, in light soils and under slow/controlled wetting (e.g., low rate irrigation), where the dominant soil structural destruction mechanism is dispersion, the adverse effects of RWW (due to higher ESP) are more pronounced. However, when the slaking mechanism is dominant in clayey soils, the adverse effects on infiltration rate (IR) can be one order of magnitude larger than in light soil (e.g., Lado et al., 2005).

In a recent work, Bhardwaj et al. (2008) demonstrated that replacing the low quality Jordan River (JR) water, which is high in salinity and sodicity, with RWW provided several advantages, including maintenance of higher HC in the arid soils investigated. However, it should be noted that the quality of the JR water was much poorer than the RWW used, due to the fact that the RWW in this region is derived from local domestic fresh water, which is of higher quality than the JR water under any criteria!

Other problems of water infiltration into soils irrigated with RWW stem from the relatively high level of organic matter (OM) and changes in soil wetting properties. These are discussed below in relation with organic constituents in RWW.

BORON TOXICITY

Boron (B) is an essential micronutrient for plants (Brown et al., 2002). However, excess B may result in a decrease in plant growth and yields, eventually having a lethal effect (Reid et al., 2004). High B concentrations are common in wastewater, originating mainly from detergents and cleaning products in domestic wastewater (Feigin et al., 1991, Tarchitzky and Chen 2004). Irrigation with RWW and particularly in arid /semi-arid areas of the world (USEPA, 2004) may be limited due to the excess B and its adverse effects on plants (Tarchitzky and Chen, 2004; Gross et al., 2005). Under low rainfall conditions, B is not leached sufficiently and may accumulate to levels that become toxic to plant growth (Reid 2007). These facts triggered numerous trials related to B toxicity, both worldwide (Camacho-Cristóbal et al., 2008) and in Israel. Part of the research was devoted to examining the effects of B in RWW (including graywater) and interactions with plants (e.g., Gross et al., 2005; Friedman et al., 2007; Yermiyahu et al., 2007) and part to soil-clay-OM interactions (e.g., Keren et al., 1985; Yermiyahu et al., 1995, 2001). The intensive focus resulted in a better understanding of B effects under irrigation with RWW. Findings triggered regulation efforts, leading to a new Israeli Standards regulation (e.g. , Tarchitzky and Chen 2004; IS-438, 1999), which resulted in a dramatic reduction of B in domestic WW from 0.65 to 0.17 mg-B/l. The findings also influenced regulation regarding the maximum allowed levels of B for irrigation, and the new allowable B level was set to 0.4 mg-B/l (Inbar, 2007). According to the last survey of RWW, in 2006/7 only 8% of the RWW used for irrigation had B levels of 0.4 to 1.0 mg-B/l, defined as medium quality by the guidelines of the Ministry of Agriculture, and less than 0.5% had low quality levels of >1 mg-B/l.

Models were developed to predict the effect of OM (including in RWW) on B availability to plants (e.g., Yermiyahu et al., 2001) generally showing that OM plays an important role in controlling B availability by binding the element and thus have an important role in reducing B uptake, particularly when OM is supplied at relatively high concentrations.

Salinity interaction with B were also intensively investigated both in relation to saline/brackish water sources and RWW, providing better insight and more accurate definitions of the salinity and B levels that can be sustained in various crops such as vegetables, grapes and citrus (e.g., Ben Gal and Shani, 2002; Yermiyahu et al., 2003, 2007).

EFFECTS OF NITROGEN

Total nitrogen concentrations in RWW used for irrigation in 2006/7 (Israeli Water Authority, 2008) was in the average range of 25-30 mg-N/l, with more than 50% at levels higher than 25 mg-N/l. Note that at levels above 25 and 40 mg-N/l, RWW is defined medium and low quality, respectively. The average amount of applied N via RWW is ~ 100 kg-N/ha. Yet, in more than 50% of the areas, the amounts can be double, implying that N supply via RWW alone may range between "sufficient to excess N" for field crops (e.g., corn for silage) or fruit trees like citrus (Haruvy et al., 1999; Shaviv et al., 2004, Tarchitzky and Co-authors, 2006). In practice, farmers apply substantial additional amounts of N-fertilizers, since they anticipate higher losses of N under irrigation with RWW (e.g., Feigin et al., 1991). This occurs also due to the continuous supply of nutrients via RWW irrigation, which takes place throughout the summer and early autumn, long after the citrus trees need N nutrition. As a result, mineral N in soil profiles of RWW irrigated citrus orchards was found to be almost double the rate found in commercial orchards irrigated with fresh water (Shaviv et al, 2004; Tarchitzky and Co-authors, 2006). The estimated levels of mineral-N in the 120cm soil profiles of the RWW irrigated soils before the winter started were in the order of magnitude of 200 to 300 kg-N/ha. This implies N levels higher than the common uptake of citrus in the region. A substantial quantity of this N is likely to be lost via leaching as nitrate or via gaseous losses, some of which (NH_3, N_2O) pose great environmental concerns.

According to Coyne (2008), conditions that enhance denitrification in soil are wet soil and/or waterlogging, application of OM, and increased pH. Such conditions are typical to RWW, as it inherently has higher pH and dissolved organic carbon (DOC) levels compared to fresh water. Indeed, increased N losses due to denitrification in RWW were found in several investigations (e.g., Master et al., 2004; Ferreira da Fonseca et al., 2007; Shigematsu et al., 2008). The higher pH and ammonium supply via RWW were also shown to increase ammonia losses (Smith et al., 1996; Master et al, 2003; Ferreira da Fonseca et al., 2007).

Evidence is accumulating in the last decade regarding increased N_2O emission due to irrigation with RWW (e.g., Master et al., 2003, 2004; Nosalewicz et al., 2005) or with effluents rich in nitrogen and OM (Barton and Schipper, 2001; Bhandral et al., 2007). The emission is ascribed both to nitrification under limited oxygen supply due to the high OM content, or to denitrification (e.g., Master et al., 2003, 2004). Under conditions of high N, OM and high water content, the role of nitrifier denitrification in producing N_2O was also shown to be of importance (e.g., Wrage et al., 2001; Baggs, 2008). The pathways of N_2O formation and the possible changes in microbial populations that are involved in nitrification and denitrification under RWW conditions may be different than in fresh water irrigation (Oved et al., 2001; Master et al., 2003, 2004). A better understanding and quantification of these processes is required, in order to allow better prediction and management of N efficiency in RWW.

The findings and observations made during the last decade clearly indicate that high levels of ammonium and OM make the utilization of RWW problematic both agronomically and environmentally. Consequently, improvements in RWW quality (lower mineral N and BOD) and efforts of farmers to better manage N supply led recently to some reduction in the total supply of N under RWW irrigation. Nevertheless, the situation must be further improved, mainly via quality improvement of the RWW.

EFFECTS OF PHOSPHORUS

Based on the assumption that P is likely to be easily fixed in the arid and semi-arid Mediterranean soils, efforts to remove this nutrient from the WW were limited. Thus, levels of non-organic P ranging between 2 to 10 mg/l are common in the RWW used for irrigation in Israel or other Mediterranean areas (Feigin et al., 1991; Angelakis et al., 1999; Tarchitzky and Co-authors, 2006). Even in the most updated regulations for RWW irrigation in Israel, the limits set for total P in RWW are 5 mg-P/l, whereas the limits for total P in RWW to be returned into streams is 1.0 mg-P/l (Inbar, 2007).

Excess P in the RWW used for irrigation led to more than double supply of P as compared to irrigation with fresh water. In addition, the higher pH and BOD levels and the potential reduction in Ca and Mg activity in RWW irrigated soils is expected to further increase P availability. Indeed, findings obtained since 1998 (e.g., Tarchitzky and Co-authors, 2006) clearly indicated a very significant increase of bicarbonate-extracted P (“Olsen Method”), from an average of 10–20 mg P /kg^{-1} in the top layers of fresh water irrigated soils to 35–55 mg P kg^{-1} in top layers of RWW irrigated soils. The effects were more prominent with the lighter soils, with drip irrigation as compared to sprinkler irrigation, and with the increase in the duration of soil exposure to RWW.

In sandy loam soils drip irrigated with RWW for 15 – 20 years, the levels of Olsen P in top layers reached 75 mg P/kg. With sprinkler irrigation of RWW under similar conditions the values were 35-40 mg P/kg and with fresh water only 10–12 mg P/kg. Levels of 20–25 mg P/kg were detected at a depth of 120 cm in the lighter soils (i.e., clay content below 20-30%) exposed to RWW, while in the heavier soils (i.e., clay content above 30%) it reached ~ 5 mg P kg^{-1} regardless of the water source.

In a recent study performed by Zohar et al. (2008), the levels of water and bi-carbonate extracted P (according to Hedley et al., 1982) in a surface layer of a Grumosol (Chromic Haploxerert) irrigated by secondary RWW were 4 and 2 times higher in the RWW irrigated soils than in fresh water. In a lysimeter experiment performed by Shaviv et al. (2007) the concentration of P collected in the drainage from maize grown on a Grumosol was almost doubled in the lysimeters irrigated with secondary RWW as compared to fresh water irrigation with similar P loading. Bicarbonate concentrations in the upper soil layers was about 0.5 meq/l higher and the pH level was higher by~0.7 units in the RWW soils than in soils irrigated with fresh-water.

The trend of increased levels of P in RWW irrigated soils observed during the last decade (Tarchitzky and Co-authors, 2006) and particularly those in the lighter soils (clay < 15%) indicate some potential for P to reach ground water and indeed poses potential threats for P to accumulate in surface water via run-off. From the agronomic point of view, accumulation of high levels of labile P in the surface soil layers may affect in the long run the availability of micronutrients.

EFFECTS OF ORGANIC CONSTITUENTS

Reclaimed wastewater contains higher concentrations of suspended and dissolved organic matter as compared with the water from which it originates. Dissolved organic matter in wastewater is highly heterogeneous with molecular masses ranging from <500 to > 5000 Da, comprised of a mixture of humic materials, polysaccharides, polyphenols, proteins, lipids, and heterogeneous molecules (e.g., Ilani et al., 2005). Penetration of such components into soils can affect important soil properties such as hydraulic conductivity and infiltration, polarity of soil constituents, soil water repellency, sorption and mobility of organic pollutants in soil, as well as microbial activity and priming effects (e.g., Ilani et al., 2005; Wallach et al., 2005; Jueschke et al., 2007; Chefetz et al., 2008).

Irrigation with low quality RWW was commonly associated with a significant increase of organic matter in soil profile (e.g., Ramirez-Fuentes et al., 2002). Due to the complexity and heterogeneity, the interactions and changes of organic constituents in soils exposed to RWW were recently examined in a more critical manner. This resulted in several important findings.

Following the reports of farmers and extension service specialists on wetting problems in soils exposed to irrigation with RWW, efforts were made to better understand the phenomenon (e.g., Chen et al., 2003; Wallach et al., 2005). A systematic study conducted by Tarchitzky et al. (2007) indicated that irrigation with RWW introduced hydrophobicity in the upper 2cm soil layers and this was related to changes in the OM characteristics on soil surface. Extractions with chloroform:methanol mixtures revealed the contribution of hydrophobic compounds to the water repellence effects. These in turn are likely to have adverse effects on soil wetting and salinity leaching efficiency.

The role of structural fractions of dissolved organic matter originating in wastewater in the sorption process of various organic compounds, which may be environmentally hazardous, was intensively studied (e.g., Ilani et al., 2005; Drori et al., 2005; Chefetz et al., 2008). It has been shown that depending on the nature of the interactions between pollutants such atrazine (herbicide), pharmaceutical compounds (PCs) or polycyclic aromatic hydrocarbons (PAHs), soil organic matter and organic constituents in WW, the transport of organic pollutants in soils irrigated with RWW can be facilitated (with a particular role of the hydrophobic groups)! This was particularly so in soils relatively poor in OM content.

Jueschke et al. (2007) showed that the organic carbon content of RWW irrigated soils seems to be depleted in the subsoil compared to freshwater irrigated fields. However, in the top-soils, the content of organic carbon was similar or even higher under RWW irrigation. It was claimed that the pronounced effects were in the deeper soil horizons with continuous input of OM to the soil. The authors hypothesized that OM in these horizons gets depleted because of the stimulated microbial activity ("Priming effect") due to fresh substrate inputs from the effluents. This effect, in the long run, may cause increased mineralization of soil OM and thus raise CO_2 emission from RWW irrigated soils.

In a recent publication, Zoller (2008) expressed concern over risks associated with endocrine disrupting chemicals (EDCs) polycyclic aromatic hydrocarbons (PAHs), alkylphyenol ethoxylates (APEOs) and their metabolites, particularly in light of the suggestion that conventional wastewater treatment technologies may not be effective enough in removing the threat of such pollutants.

To these effects of the organic constituents in the RWW, one should add also the effects mentioned above with respect to the increase of gaseous N losses (N_2, N_2O) either via denitrification or nitrification and the increased bio-availability of P associated with high OM (BOD) in RWW.

The official standards for irrigation with RWW prevailing in Israel according the regulation of Ministry of Health in 1992 (Inbar, 2007) was a BOD of 20 mg/l. In 2005, 75% of the produced

RWW complied with this the standard. Based on the experience and information gained in the last decade, the new regulations allow a BOD of 10 mg/l (Inbar 2007). According to O'Connor (2008) and Brissaud (2008), in many regions in the world the requirements are still more liberal and BOD values of 30 mg/l or higher are still used in RWW for irrigation.

PATHOGENS

The presence of pathogens in RWW was one of the first and most common concerns associated with health risks to farmers and consumers of the irrigated crops; hence, the sanitation level of RWW was and is a key issue for using this source for irrigation. Accordingly, regulation schemes were developed worldwide to address the sanitation level of RWW to be used for irrigation. Unfortunately, these differ very much, depending on the degree of development and industrialization in regions where they were developed (e.g., Brissaud, 2008). Whereas the World Health Organization recommended no more than 1000 fecal coliforms (FCs) per 100 mL for unrestricted irrigation of all crops, the Israeli regulation of RWW for “unrestricted irrigation” in agriculture is $\leq$ 10 FCs/ 100 mL. The wastewater reclamation standard in California is 2.2 coliforms/ 100 mL, whereas the US EPA guidelines are even stricter and allow no detectable FCs in 100ml (Brissaud, 2008). While adapting the level of $\leq$ 10 FCs/ 100 mL for irrigation of vegetables eaten raw, the Halperin Committee for the Israeli Ministry of Health proposed in 1999 the multiple barrier approach (e.g., Brissaud, 2008). Barriers are technical (e.g., irrigation method) or physical measures (buffer zones, soil plastic mulching) or crop characteristics (above ground fruit/crop, peel /shell protected crop) that help reduce health risks. As an example: for irrigation with very high quality RWW containing less than 10 FCs /100 mL and more than 1 mg/L of residual chlorine, no barrier is required. At the lower end of the spectrum, the use of RWW from an oxidation pond for irrigation requires compliance with 3 barriers: irrigation of fruits, an oxidation pond that accepts only domestic wastewater, and at least 10 days of retention time!

Recent studies have demonstrated that human pathogens can undergo internalization, to some extent, thus entering the plants through their roots, translocating and surviving in edible, above-ground plant tissues (e.g., Franz et al., 2006; Bernstein, 2007a,b). Some researchers stress that attention should also be given to the possibility of long survival durations of pathogenic microorganisms in soils irrigated with RWW (e.g., Jamieson et al., 2002; Bernstein et al, 2006), which might have long-term implications for food safety. The practical implications of part of these findings for food safety are still not clear, since studies reporting internalization of pathogens into roots were conducted in controlled environments, characterized by conditions different from those typical of real agronomic environments. The potential for internalization or long survival times of pathogens in agricultural fields irrigated with RWW may vary from that in controlled artificial media and should thus be investigated further in real systems.

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POTENTIAL MICROBIAL RISKS ASSOCIATED WITH UTILIZATION OF TREATED EFFLUENT FOR IRRIGATION

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ABSTRACT

Scarcity of water in arid and semi-arid regions throughout the world makes treated urban wastewater an unavoidable alternative water source for irrigation. The use of treated wastewater for agricultural irrigation may result in human exposure to pathogens, creating potential public health problems. Outbreaks of foodborne illnesses are increasingly linked to consumption of contaminated fruits and vegetables and irrigation with wastewaters. Various human pathogens are present in raw sewage water. Several bacterial pathogens, introduced through contaminated irrigation water, were demonstrated to survive long periods in soil and water, where they have the potential to contaminate crops in the field. Therefore, there is a risk of direct contamination of crops by human pathogens from the treated effluents used for irrigation, as well as a risk of indirect contamination of the crops from contaminated soil at the agricultural site. Until recently, it was generally recognized that potential health risks to consumers from edible agricultural produce irrigated with contaminated water were associated with the application of contaminated water to the aboveground, edible plant organs. However, recent studies have demonstrated that human pathogens can, to a limited extent, also enter the plants through their roots, translocate and survive in edible, aerial plant tissues. The practical implications of these new findings for food safety are still not clear, and, no doubt rely on the pathogenic microorganisms' ability to survive and multiply in water, irrigated soil, and the harvested edible crop, as well as on their ability to penetrate or adhere to plant tissue, and persist in the crop through the marketing chain.

INTRODUCTION

Water availability is the most limiting factor for the increase in extensive agricultural production required to support population growth in arid and semi-arid regions of the world. Therefore, maintained or increased production requires the utilization of marginal water for irrigation. Treated sewage effluents are becoming the main source of alternative marginal water for agricultural irrigation, due to their availability and relatively low cost. Utilization of treated wastewater for irrigation is, therefore, increasing steadily worldwide (Scott et al., 2004).

Pathogenic microorganisms present in the treated wastewaters can pose a health risk to farmers, contaminate the irrigated crops and/or be carried along to the consumers. The sanitation quality of treated wastewater is therefore a key issue in its reuse for agricultural irrigation. In addition to public health risks, treated effluents may also have detrimental effects on the irrigated crops (Feigin et al., 1991). In particular, the high salinity levels in the effluents can restrict plant growth (Lazof and Bernstein, 1998; Bernstein and Kafkafi, 2000), decrease biomass production (Neves-Piestun and Bernstein, 1991; Bernstein et al., 1993a, b; Neves-Piestun and Bernstein, 1995) and reduce yield quality (Bernstein et al., 2006). Nevertheless, many successful agricultural production systems that utilize this water have been developed (Feigin et al., 1991; Bernstein et al., 2006).

Since outbreaks of food-borne illnesses are increasingly linked to consumption of contaminated fruits and vegetables and irrigation with treated wastewater (Blumenthal et al., 1989), the potential transmission of infectious diseases by pathogenic agents is the most common concern associated with the agricultural use of treated wastewaters.

REGULATIONS CONCERNING UTILIZATION OF EFFLUENTS FOR IRRIGATION

Several regulations and recommendations have been developed around the world for sanitation quality of effluents to be used for irrigation of food crops. For example, the World Health Organization has recommended a guideline of no more than 1000 fecal coliforms (FCs) per 100 mL for unrestricted irrigation of all crops (WHO, 1989). The U.S. Environmental Protection Agency guidelines require that there be no detectable FCs per 100 mL (US EPA, 1973). California's wastewater reclamation standard is 2.2 coliforms/ 100 mL, and the Israeli regulation of effluents for "unrestricted irrigation" in agriculture is ≤ 10 FCs/ 100 mL (IMH, 2001).

Different countries have developed various approaches for the sanitation of effluents prior to their use in agricultural irrigation. While most developed countries have adopted conservative, low-risk standards based on a high technology/ high cost approach, a number of developing countries have developed a low technology/ low cost approach based on the WHO recommendations (US EPA, 2004). The notion that better health protection can be achieved not only by employing strict water quality limits, but also by adopting other practices that could provide additional barriers against crop exposure to the pathogens has been gaining acceptance (Fine et al., 2006). An example of such an approach is the standard issued by the Israeli Ministry of Health (IMH, 2001). These standards set a low coliform limit of less than 10 *E. coli*/ 100 mL for reclaimed water that can be used for irrigation of vegetables that will be eaten raw, in the absence of any additional barriers. At the same time, additional barriers, such as buffer zones between the treated wastewater and the aboveground part of the plants are required if water of a lower quality is to be utilized for irrigation. The development of the physical barrier concept relies on the accepted notion that potential health risks to consumers from the consumption of agricultural produce irrigated with contaminated water stem primarily from the attachment of human pathogens to plants via the plant's aboveground organs, and not internalization via the root system. However, recent studies suggest that human pathogens can also penetrate internal plant tissues via the root (Bernstein et al., 2007a, c; Guo et al., 2002; Solomon et al., 2002; further discussed below). The practical implications of these new findings for food safety are not yet known, but no doubt reflect the pathogenic microorganisms' ability to penetrate the plant roots, translocate to aboveground parts, and survive and multiply in water, soil, and the harvested edible crop through the marketing chain.

SURVIVAL OF HUMAN PATHOGENIC MICROORGANISMS IN SOIL AND WATER

The ability of a range of human pathogenic microorganisms to survive for extended periods of time in soils has been well-documented (Randall et al. 1999). Reddy et al. (1981) developed a first order rate constant to describe the die-off rates of several indicator organisms in soil systems. The first order die-off rate constants were 1.14 d^{-1} for FC and 0.41 d^{-1} for fecal *Salmonella* (FS). The average rate constants for specific pathogens were 0.68 d^{-1} for *Shigella* and 1.33 d^{-1} for *Salmonella*. Two to four month long survival periods for enteric bacteria in soil were reported in a review by Gerba et al. (1975). Sjogren (1994) estimated the survival times of *E. coli* to about 23 months. Since longer survival periods were demonstrated for the indicator organisms, in comparison to those of specific pathogens (Mubiru et al., 2000) more studies are needed to evaluate the persistence and fate of specific pathogenic bacteria in agricultural soils. The major factors that control the persistence of enteric bacteria in the soil environment are temperature, moisture content, pH, organic matter, bacteria type, and the presence of antagonistic bacteria (reviewed by Jamieson et al., 2002). Survival of bacterial populations may, therefore, vary in different soil and environmental conditions.

In a recent study, we have evaluated the effects of three irrigation regimes, "no-irrigation" and irrigation with or without generation of leachate, on the capacity of *S. enterica* serovar Newport to survive in a potting medium (Bernstein et al., 2007b). The duration of bacterial survival varied under the irrigation regimes employed, ranging from 4.7 to 10 weeks and was reduced by leaching. Survival duration in soils ranging 2-14 weeks (Baloda et al., 2001; Natvig et al., 2002; Cote and Quessy, 2005; Franz et al., 2005) and up to 29 weeks (Islam et al., 2004) was previously reported for *Salmonella*. A similar range of survival periods in manure-amended soils was reported for *E. coli* (Franz et al., 2005). The survival period of *S. enterica* Newport in contaminated potting media irrigated with clean water without generation of leachate was longer than when the volume of irrigation allowed generation of leachate (Bernstein et al., 2007b). Leaching reduced the concentration of *Salmonella* in the soil media, presumably due to a washing effect and, consequently, the bacteria's survival period was shortened from 70 to 33 days. In the irrigated medium *Salmonella* survived was longer than in drying medium (Bernstein et al., 2007b). The observed dependency of *Salmonella* viability upon irrigation schemes points to the need for consideration of local irrigation regimes when evaluating the health hazards associated with the utilization of effluents in agronomic production systems.

Variations in soil characteristics may account for differences in the survival of coliforms in two different soil-less media (Bernstein et al., 2006). Specifically, the high organic matter content of a coconut fiber media was suggested to facilitate the development of coliform populations, more so than the inorganic medium, perlite. The high ionic absorption capacity of the coconut fiber medium, as compared to perlite, probably allowed better bacterial sorption and adherence to the media, and enhanced development of soil-associated populations. Moreover, the physical properties of perlite, which allow better aeration, as compared with the coconut fiber media, might selectively affect population development (Bernstein et al., 2006).

Studies of bacterial transport in agricultural soil-less media (Bernstein et al., 2007b) and results of field studies (Gagliardi and Karns, 2000) demonstrated significant transport of enteric bacteria in the soil profile. The high volume of leachate (i.e., 20-50% of each irrigation event) routinely practiced in many experimental set-ups utilizing recycled effluents, which is intended to minimize salt build-up, is probably instrumental in the transport of bacteria from the irrigation water through the soil to the leachates (discussed by Bernstein et al., 2006). The ability of bacteria to be transported through soil with the mass flow of water is therefore considered to be of major importance for contamination of roots and surface- and groundwater (Jamieson et al., 2002).

In a study of an agricultural soil-less production system, we recently demonstrated that in both organic (coconut fibers) and mineral (perlite) soil-less media, the concentration of coliforms and fecal pollution indicators was low following prolonged periods of irrigation with secondary treated effluents. The irrigation water was chlorinated to the final concentration of 0.5 ppm chlorine, in accordance with the guidelines set by the Israeli Ministry of Health (Bernstein et al., 2006). The concentrations of fecal indicator bacteria in the leachates from the growing beds were not higher than those of the irrigation solutions, suggesting that specific cultures had not developed in the soil-less media. The high volume of leachate practiced in the project was probably instrumental in limiting population build-up in the soil-less medium, thereby limiting the risk of contamination of the greenhouse environment (Bernstein et al., 2006). The extent of pathogenic bacterial leaching from soil irrigated with contaminated effluents, in addition to affecting these microorganisms' survival in the agronomic land, should also be viewed in light of environmental risks associated with pathogen dispersal by drainage.

Recent evidence for uptake of bacterial human pathogens into crops via the root system, and potential contamination of the edible yield by bacteria present in the soil (detailed below) suggests that the implications of the prolonged persistence of specific pathogenic bacteria in soils may need to be considered in agricultural production systems that utilize treated effluents.

Pathogenic microorganisms associated with outbreaks of waterborne diseases throughout the world include bacteria, viruses, and parasites. Pathogens from these three groups are found in raw domestic sewage. For example, the bacteria *Shigella spp,. Salmonella spp., Vibrio cholera, various groups of E. coli, and Campylobacter sp.*; the viruses *Hepatitis A, E, Calciviruses* (Norwalk-like and others), *Rotavirus, and Poliovirus*; the protozoa *Entamoeba histolytica, Giardia lamblia, Cryptosporidium sp., and Balantium coli*; and the Helminths *Ascaris sp., Taenia sp., Necator americanus*, and *Trichuris trichuria* were all reported to be associated with contamination by raw domestic sewage and sewage solids (Kirby et al., 2003). Although the high numbers of human pathogens present in non-treated sewage decrease successively at each step of the wastewater reclamation process (Steen et al., 2000), the secondary treated effluents, which are still common for for irrigation, contain fecal coliforms that may pose a threat to public health (Maynard et al., 1999; Armon et al., 2002). There is a risk of direct contamination of crops by human pathogens present in the treated effluents used for irrigation, as well as indirect contamination of crops through contaminated soil at the agricultural site. The risk of disease transmission from pathogenic microorganisms present in irrigation water is influenced by the level of contamination; the persistence of the pathogens in water, soil and on crops; and the route of exposure (reviewed by Steele and Odumeru, 2004).

Bacterial pathogens were shown to persist in water for long periods of time. The survival duration of individual pathogens in water and wastewater varies between pathogens (reviewed by Steele and Odumeru, 2004). For example, *Shigella* spp., survive less than 30 days in water and sewage, *E. histolytica* cysts survive less than 15 days and enteroviruses less than 50 days, whereas *A. lumbricoides* eggs can survive many months. Viruses have been reported to survive and remain infective for up to 120 days in fresh water and sewage (Fong and Lipp, 2005).

Numerous disease outbreaks were associated with irrigation with untreated wastewater (for example (Cifuentes, 2000), and contaminated irrigation water was shown to be linked to outbreaks associated with the consumption of fresh produce (for example Wachtel et al., 2002b). At the same time, adherence to public health safety guidelines for the appropriate use of treated effluents in agricultural production systems has been shown to allow for the production of microbiologically safe produce (Bernstein et al., 2006).

CONTAMINATION OF CROPS BY INTERNALIZATION OF BACTERIAL HUMAN PATHOGENS INTO ROOTS

Until recently, it was generally accepted that potential health risks to consumers from edible agricultural produce irrigated with contaminated water, source primarily from the direct attachment of human pathogens to the aboveground parts of plants, and not to the root system. However, recent studies suggest that human pathogens may also be associated with underground plant organs (Natvig et al., 2002); may internalize plant tissues through roots (Guo et al., 2002; Solomon et al., 2002; Bernstein et al., 2006; Franz et al., 2006; Bernstein et al., 2007) or seeds (Natvig et al., 2002; Warriner et al., 2003; Islam et al., 2004); and be translocated to the edible, aerial plant organs, where they can persist (Samish et al., 1962; Guo et al., 2002). The use of treated effluents for irrigation may introduce human pathogens to the roots of agricultural crops. A range of human pathogens are capable of surviving extended periods of time in soils and water (discussed above), where they can act as inoculum for the contamination of crop roots.

E. Coli was reported to internalize roots of several dicotyledonous plants, including lettuce (Solomon et al., 2002; Wachtel et al., 2002a), tomato (Guo et al., 2002) and *Arabidopsis thaliana* (Cooley et al., 2003). In lettuce (Solomon et al., 2002) and spinach (Warriner et al., 2003), *E. Coli* cells were found to penetrate the vascular system, probably facilitating their long-distance transport in the plant. Fewer studies have investigated the uptake of *Salmonella* by roots. The studies available report internalization of *S. enterica* into the roots of lettuce (Bernstein et al., 2007a) and tomato (Guo et al., 2002). We have recently reported internalization of *E. coli* into a monocot plant as well (maize: Bernstein et al., 2007c).

Not all studies of root internalization have identified bacterial penetration and some of the available reports are contradictory. For example, internalization of *S. enterica* was reported in hydroponically-grown tomato (Guo et al., 2002), while in soil-grown lettuce no internalization of the bacterium was observed after 21 days of exposure to contaminated soil (Franz et al., 2005). Johansen et al. (2005), also working with lettuce and *E. coli* O157:H7, was unable to identify root penetration when the pathogen was introduced at the crop's seedling stage. In a recent study with lettuce grown in a potting medium, we observed internalization of *S. enterica* via the root and its spread to aboveground plant organs in 33-day-old plants, but not in 17- or 20-day-old plants (Bernstein et al., 2007a). The observed differences in penetration of the plant roots could be due to variations in developmental stages of the plants, growth media characteristics, concentration of the pathogen, genetic background of the specific strain used, as well as interactions with the rhizosphere community. Contamination through the root system was found to be dose-dependent (Wachtel et al., 2002b) and results of some studies suggest that the potential for root penetration is bacteria-specific (Kutter et al., 2006; Jablasone et al., 2005).

Very little information is currently available concerning the factors that affect the interactions between human pathogens and plants which result in uptake of bacteria by roots and their subsequent translocation in the plant. Similarly unknown is the variability within the root population of a single plant, in terms of permeability to enteric pathogens and resistance to bacterial loading and transport in the apoplast. Therefore, reported inconsistencies regarding contamination of vegetables by foodborne pathogens via the root system may be due to variability in the physiological traits of the different roots existing in the plant at different developmental stages, bacterial physiology, pathogen specificity or specific conditions in the rhizosphere.

CONCLUSIONS

Due to the long survival durations of pathogenic microorganisms in water and soils, the introduction of pathogenic bacteria into agronomic soils, by irrigation with contaminated effluents, might have long-term implications for food safety on crops in following years.

No data is available of human pathogens internalization of roots under agronomic conditions in the field to an extent that might affect public health. Many of the studies reporting internalization of pathogens into roots were conducted in controlled environments, which are characterized by conditions different from those typical of agronomic environments. Therefore, the potential for internalization in open field agricultural systems irrigated with effluents and hence for crop contamination may vary from that of controlled artificial media.

Several topics need to be further investigated to facilitate evaluation of the health risks associated with irrigation with treated effluents. Among these are survival of different pathogenic microorganisms present in the treated effluents in the agricultural soils, factors affecting the internalization of human pathogens into plant roots, short and long-distance translocation of the pathogens in the plant, adherence of human pathogens to aboveground plant parts and the survival and possible reproduction of pathogenic bacteria on and in the plant tissues.

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THREATS AND VIABLE SOLUTIONS FOR OLIVE MILL WASTEWATER IN ISRAEL: SOME ECONOMICAL, ENVIRONMENTAL AND PRACTICAL CONSIDERATIONS

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ABSTRACT

The majority of the olive oil industry in Israel is based on a three-phase extraction process that yields oil, olive mill solid waste and olive mill wastewater (OMW). This industry is constantly growing. Presently, about 50,000 m^3 of OMW are produced in Israel during the "on" olive harvest years. There is yet no common or widely acceptable solution for OMW in Israel and it happens that some of the OMW is released to the environment in an uncontrolled manner. This situation is extremely undesired because of possible contamination of fresh water resources as well as possible adverse effects on soil quality. Multiple economical, environmental and practical aspects need to be considered in the search for viable solutions to this problem: 1. Choosing between engineered technology and environmental/agricultural recycling approaches; 2. Choosing between a regional treatment facility and a local one; 3. Setting only a local preliminary treatment system; 4. Adopting agricultural recycling approaches, including controlled land spreading and co-composting of olive mill solid waste and olive mill wastewater; and 5. The potential advantages of moving large mills into the two-phase extraction process. Based on our analysis, cautious agricultural recycling approaches are viable and sustainable but are not necessarily cheaper than wastewater treatment technologies.

1. OLIVE CULTIVATION IN ISRAEL

The present total area of olive planting in Israel is about 20,000 ha, of them, 18,500 ha are used for oil production (Figure 1). In terms of planted area, it is currently the largest fruit tree crop in the country. The regional distribution and cultivation methods of olive oil trees are detailed in Table 1. Although the fraction of intensive olive groves is relatively small, their contribution to the total production is higher by a factor of at least 3, relative to their proportion due to their higher yields. The new development and increase in the Israeli olive oil industry is based on intensive cultivated irrigated orchards. Most of the new intensive orchards are developed in terrains with deeper soil and topography suitable for efficient operation of modern cultivation and harvesting equipment (Lavee, 2006; Israel Olive Oil Board, 2007).

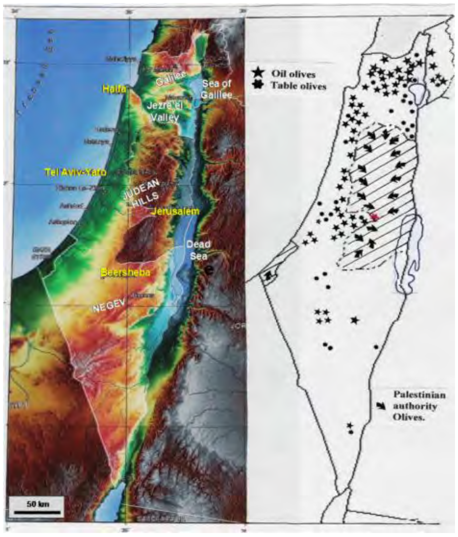

Figure 1: Distribution of oil and table olive plantations in the different regions of Israel (Source: Lavee, 2006).

Table 1. Regional distribution of the planted areas of oil-producing olive trees. The total area is about 18,500 ha (Birger and Chanoch, 2006; Lavee, 2006).

Region	**Planted area** (%)
Southern (Negev)	8.1
Central	17.8
Western Galilee	35.7
Northern (Galilee and Valleys)	38.4
Cultivation Methods	
Traditional	84.3
Intensive	14.6
Highly intensive (Hedge-row orchards)	1.1

2. Production and Consumption

During the last decade, the local production fluctuated between 2,000-4,000 and 8,000-9,000 tones oil yr^{-1} during "off" and "on" years, respectively (Figure 2). Consumption was doubled during the last decade from around 7,000-8,000 to 16,000-17,000 metric tons oil yr^{-1}. Today there is no net import of olive oil to Israel. Yet, the new intensive plantations, especially with varieties of lesser alternate bearing, may shift this production-consumption balance in the coming years.

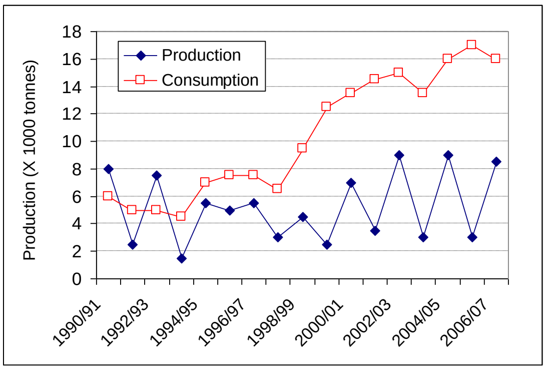

Figure 2: Yearly production and consumption of olive oil in Israel (Source: International Olive Oil Council, 2007).

3. Olive Oil Processing

Today, there are about 120 olive mills operating in Israel. A small number of mills (~10) are still operated by the traditional discontinuous pressing process. These mills have a relatively small processing capacity (less than 0.5 metric tons olives hr^{-1}). The majority (~100) is equipped with modern machinery and is operated by the three-phase continuous centrifugation process. Only a few mills are operated by the two-phase continuous process, although we see some increase in the total amount of oil produced by this method. The olive mills are geographically distributed mainly in the regions of the major planted areas (Table 2). Most of them are located in the northern part of Israel.

Table 2. Regional distribution of olive mills in Israel (Source: Israel Olive Oil Board and Israel Ministry of Environmental Protection).

Region	Number of Mills*
Southern (Negev)	10
Central	8
Western Galilee	28
North (Galilee, Carmel, Golan heights)	58

*Based on a total 104 mills reported in 2004.

4. Management of Olive Mill Wastes

4.1. The linkage between Israel's fresh water resources and olive mill wastes management

About 50,000 m^3 of olive mill wastewater (OMW) and 25,000 m^3 of olive mill solid wastes are produced annually in Israel during the "high yield" years. A good management of these wastes is crucial in a country like Israel, which is facing continuous water scarcity. The quality of drinking water in Israel can be severely affected by surface contamination throughout the drainage basin of the Sea of Galilee (about 30% of freshwater resources) and from infiltration of contaminants into groundwater (more than 50% of freshwater resources). Most regions in Israel were defined as highly or moderately hydrologically sensitive (Figure 3). This explains the extremely high awareness of national authorities to potential pollution that might be caused by uncontrolled release of OMW into the environment. Efficient and economical wastewater management is hampered by the decentralized nature of this industry. Due to the high organic load and toxic nature of OMW, direct discharge into domestic wastewater treatment plants is not allowed. Unfortunately, in some cases, either raw or pre-treated OMW are unlawfully discharged directly into sewer systems, causing problems for domestic wastewater treatment plants.

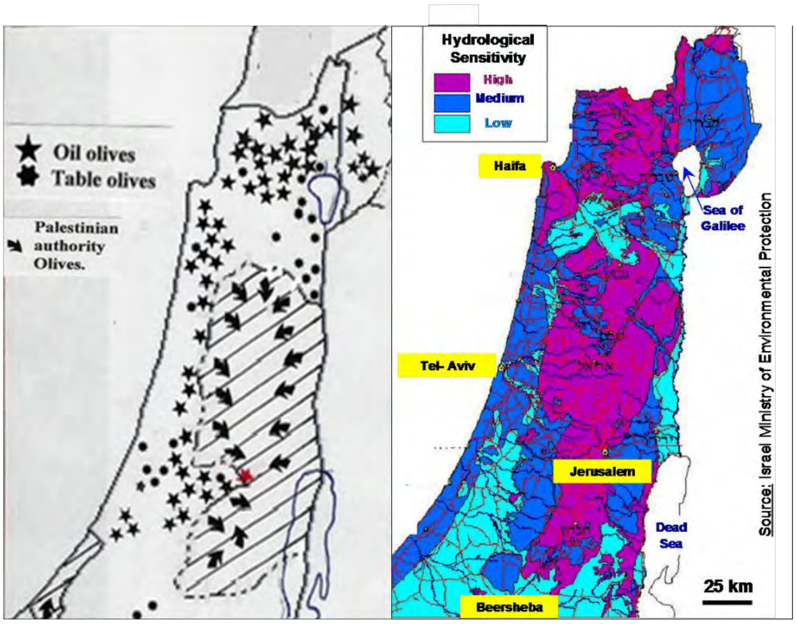

Figure 3:

Left: Distribution of olive plantations (Source: Lavee, 2006).

Right: Regions of different levels of **hydrological sensitivity (Source: Ministry of Environmental Protection).**

4.2. Currently used treatment technologies. Using recent governmental assistance, 9 mills in the Western Galilee acquired a pre-treatment floatation device (S. Capua, Ministry of Environmental Protection; Personal communication). This system is potentially capable of reducing COD values by 80-90% (Figure 4; Table 3). The final effluents, however, still contain COD values as high as 15,000-30,000 mg l^{-1}, much above the value of ~2,000 mg l^{-1} normally accepted by municipal authorities. Yet, in the absence of better solutions, the Ministry of Environmental Protection allows to discharge this pre-treated water into municipal treatment facilities after reduction of the COD by at least 70%. In some cases, the floatation device may be useful to reduce organic load and fats before land spreading *(section 4.3)*. More advanced treatment technologies are currently not employed by olive mills in Israel. Anaerobic digestion systems are at the research stage in Israel (Sabbah *et al*., 2004, 2005) and have not yet been applied on a wide scale.

Figure 4: OMW treatment using floatation technology. The system also removes solid particles and volatile organics. This technology is currently in use by two olive mills in Israel (Kisra in the north and Revivim in the south) (Source: Ministry of Environmental Protection).

Table 3. Treatment of OMW with floatation device operated in Kisra, northern Israel (Source: Israel Ministry of Environmental protection).

Concentration (mg l^{-1})	Before treatment	After treatment	% removal
COD-total	167,200	26,867	83.9
COD-soluble	53,760	16,550	69.2
Total Suspended Solids (TSS)	43,630	3,660	91.6
Fats	25,872	1,812	93.0

4.3. Controlled land spreading. The Israel Ministry of Environmental Protection allows land spreading of OMW up to 40-50 m^3 ha^{-1} yr^{-1}, every alternate year on the same plot. These recommendations are "to be on the safe side," as compared to the Italian law which allows up to 80 m^3 ha^{-1} yr^{-1}, or as compared to research results showing no adverse effects even at higher application rates (e.g., Chartzoulakis *et al*., 2007). The Ministry requires detailed documentation on spreading activities and soil analyses (EC, nitrates, total phenols) before and after application. During the last season (2008-9), the Ministry managed controlled spreading activities in the lower Galilee throughout forest trails of the Keren Kayemet le-Israel- KKL (S. Capua, Ministry of Environmental Protection; Personal communication).

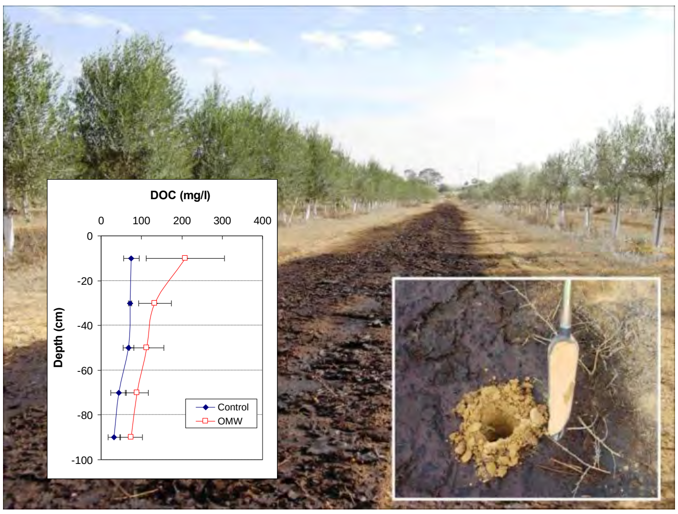

Figure 5: Dissolved organic carbon (DOC) in saturated paste extracts of soil collected from the olive plantation in Revivim. Data represent averages and standard deviations of three plots (control and OMW-applied).

More local research is being conducted to study the impact of OMW spreading on soils and crops as well as to assess potential transport of organic constituents below the root zone. Current studies concentrate on two geographical regions that are of low hydrological sensitivity: Jezre'el Valley in the north and the Negev desert highlands in the south. In a one-year study performed in Jezre'el Valley, using application rates of up to 72 m^3 ha^{-1}, divided into three successive applications (Saadi *et al.*, 2007), only a short-term increase in phytotoxicity was shown in the top 0-10 cm topsoil (expressed by root elongation of cress; *Lepidium sativum* L.). The soil was partly or completely recovered between successive applications and no further phytotoxicity was observed in treated soils as compared to control soil, three months after the last application. A survey performed in an olive orchard in Revivim (south of Beer Sheva; loess soil), where OMW is spread during the last several years, revealed penetration of organic constituents to a depth of 90 cm (Saadi *et al.*, 2009; Figure 5). More research is needed before providing the Ministry of Environmental Protection with tools for tuning up the current non-specific spreading guidelines. As long as safe spreading is assured, several agricultural-environmental benefits can be viewed. This includes the nutritional value of OMW and its potential herbicidal activity (Erez-Reifen *et al.*, 2009). Such benefits are of extra value in the context of organic and sustainable farming.

5. Viable Solutions: Some Economical, Environmental and Practical Considerations

5.1. Choosing between an engineered technology and environmental/agricultural recycling approach. We grossly divide OMW management into two main categories: I. Relying on an engineered water treatment system. Using this approach, OMW are viewed as detrimental by-products, which need to be disposed of; II. A recycling approach in which the wastes associated with the milling process (solid, liquid or semi-solid) are considered as natural valuable resources which can be utilized beneficially. We assume that the preference of one approach over another will eventually be based on economical criteria and would be affected very little --if at all-- by environmentally beneficial factors. Yet, if carbon sequestering is to be integrated in future economical analyses, then it may give an extra push to the recycling approach. Poor soil fertility in certain regions may further push toward recycling approach as well.

5.2. Choosing between a regional treatment facility and a local one. A regional treatment facility, which would be co-operated by several clustered mills, is considered in comparison with a local one. Considering the annual amount of OMW produced during the 2-3 months of the harvest season during "high yield" years (~50,000 m^3), an annual rate of ~1,000 m^3 OMW day^{-1} is expected. Assuming that ~80% of this amount is produced by mills located in the northern part of the country, it means that about 25 road tankers, 30 m^3 each, would be required daily to transport OMW to a regional facility. This transportation might be problematic, depending on local existing road infrastructure and traffic load. Local temporary storage units might be needed or some alternative solutions might be sought for part of the OMW. The cost of transportation is estimated as ~10 €/m^3 OMW. On that we need to add the cost of treatment.

5.3. Setting only a local preliminary treatment system. Due to the high cost of advanced treatment technologies, a pre-treatment device (and consequent discharge of the treated OMW into municipal treatment facilities) is in some cases accepted by the Ministry of Environmental Protection. As discussed in *Section 4.2*, nine mills in the Western Galilee have recently acquired a pre-treatment floatation device. If an investment of ~10,000-20,000 € (depending on matching governmental support) is to be divided over 10 years of mill operation with annual production of 1,000-2,000 m^3 OMW, it would come up to only ~1-2 €/m^3 OMW. Yet, as reported in Table 3, effluent quality does not meet the required standards such that, unless exclusively approved, it may not be discharged into the local sewage system. This level of treatment may still be useful before land spreading. Fats removal can alleviate some potential negative impacts on soil physical properties.

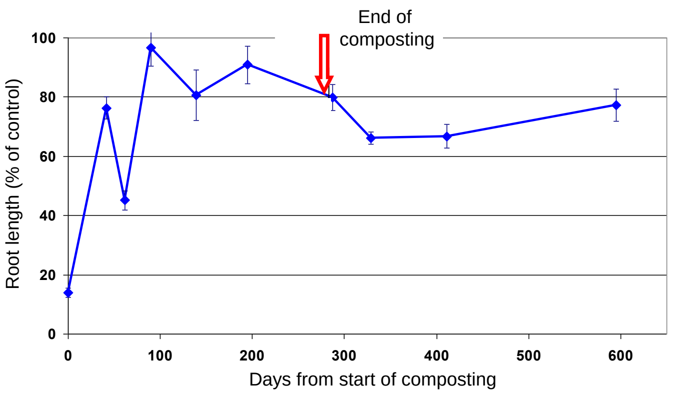

Figure 6: Phytotoxicity of compost that is based on olive mill wastes (40% olive solid waste, 30% separated cow manure, 30% olive leaves) and is irrigated with OMW. Phytotoxicity is expressed as root length of cress (Lepidium sativum) seedlings, exposed to the compost extracts, as related to water control.

5.4 Environmental/agricultural recycling. The two approaches that we consider are: I. Controlled land spreading; and II. Co-composting of solid wastes and OMW. *Controlled land spreading* is discussed in *section 4.3*. It is currently considered as a viable solution by the Israel Ministry of Environmental Protection. This approach however always seems to be criticized by hydrologists and water authorities. For this reason and for tuning the current guidelines, more local studies need to be conducted especially in regions of low hydrological sensitivity. Economically, land spreading is viable with estimated cost of about 5-7 €/m^3 OMW. It should be remembered that spreading would require additional cost of transportation for mills that are located in regions of high hydrological sensitivity. Additional concern is the need to educate workers and to perform strict control on spreading activities. *Co-composting of solid and liquid olive mill wastes* is currently at the research level in Israel and is not yet applied on a large scale (Raviv *et al*. 2009, in press). The high phytotoxicity of the raw materials is substantially reduced during the process (Figure 6). Raviv *et al*. estimated that ~0.5 m^3 of OMW can be used to wet ~1 m^3 of solids in compost piles based on olive mill solid wastes. The OMW is used to wet the piles during the thermophilic phase instead of using fresh water and the compost is essentially used as a reactor to treat the OMW. Yet, this process cannot rely only on olive mill solid wastes for three main reasons: I. Based on 1:2 solid to liquid wastes ratio in the three-phase process (Azbar *et al*., 2004), the amount of solid wastes needed to absorb the whole amount of wastewater is about 4 times higher than the amount produced in the mill. Therefore, other wastes (agricultural and/or municipal) need to be considered. II. The high cost of building a composting facility that would meet the standards required by the Ministry of Environmental Protection. These facilities also need impermeable storage structures to collect the OMW. III. The need to operate the composting facility throughout the year (slow composting processes of olive mill wastes), though the harvest season extends 2-3 months only. For these reasons, we believe that co-composting would be possible mainly in existing composting facilities, by combining OMW with assorted agricultural/urban solid wastes. There are multiple composing facilities in Israel that are already built according to the Ministry of Environmental Protection standards and seem ready to accept OMW and use it for wetting compost piles. Such facilities treat various kinds of agricultural wastes and in some cases have un-used storage volumes. Besides transportation costs (~10 €/m^3 OMW; *Section 5.3*), we estimate that the gate fee at the composting facility (tipping fee) would be in the range of 4-6 €/m^3 OMW. The total cost is thus estimated as ~15 €/m^3 OMW.

5.5. Gradual transition from three- to two-phase extraction process. Similar to the current trend in other countries, it is expected that more mills in Israel will gradually move into the two-phase extraction method. Most of the engineered systems that are developed to treat OMW cannot be applied on the two-phase wastes. On the other hand, co-composting *(Section 5.4)* seems viable for any kind of milling process. Based on the literature and the work of Raviv *et al*. (2009) on three-phase wastes, we assume that the two-phase wastes can also be successfully co-composted with other wastes in the composting facility. Another advantage is that the smaller amount of liquid produced by the two-phase process would reduce total wastes volume, and thus the cost of transportation and tipping fee. The current situation in Israel is that some modern mills can easily switch from three- to the two-phase process. If successful co-composting of such wastes becomes evident, it would trigger mill owners to go for such a transition

6. ECONOMICAL CONSIDERATIONS

Based on the cost assessment of Azbar *et al*. (2004), the cost of advanced OMW treatment is in the range of 5-10 €-cents/Kg oil. This assessment was made for mills producing ~5,000 m^3 day^{-1}, 10-years lifetime and a 1:5 (w/w) oil to OMW ratio. The cost of ~15 €/m^3 OMW estimated for co-composting (7.5 €-cents/Kg oil) is therefore within this range. Since no initial investment is needed for co-composting in existing sites, this approach can be viable also for small mills. Agricultural recycling approaches, as presented in this manuscript, seem superior over some engineered solutions. More research work is still needed, mainly to address potential agronomic values and absence of phytotoxicity in the two- or three-phase wastes composting product and practical aspects related to the use of existing composting facilities. More research work is also needed for better selecting areas that are most suitable for OMW spreading with minimum risk to fresh water resources.

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REUSE OF WASTE WATER IN AGRICULTURE: THE INDIAN EXPERIENCE

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ABSTRACT

About one quarter of the ground water resources used for irrigation of agricultural crops in India are saline and/or sodic. In states like Rajasthan and Haryana 84% and 62%, respectively, of the underground water is of poor quality. In many situations, salty underground waters also contain other toxic ions and heavy metals, such as arsenic, fluoride, selenium and nitrate etc. Continuous use of such waters for irrigation is bound to result in salinity and sodicity problems on the one hand and entry of heavy metals in the food chain on the other hand. Already 6.73 m ha in India are affected by salinity and sodicity. The estimates reveal that if the present level of land degradation continues, the country will face salt problem in about 11.7 m ha by 2025. Over exploitation of ground water for irrigation of rice and wheat cropping system in good water quality zones in Punjab, Haryana and Western Uttar Pradesh has resulted in draw down of the ground water, thus necessitating the need for replacement of shallow cavity wells (centrifugal pumps) with deep tubewells (submersible pumps). Little or limited exploitation of ground water for irrigation in poor quality ground water regions is resulting in underground flow of poor quality waters from these zones into over exploited fresh water areas. Recent surveys have revealed a shift in the ground water quality in good quality zones.

Another issue is the likely change in the share of water use in agriculture from about 85% at present to about 77% by 2025. This indicates that sustainability of agriculture in the near future will be largely determined by how well the domestic sewage and industrial wastewaters will be exploited for irrigation purpose. At present, about 83 million M^3 of industrial wastewater are generated per day in India, an amount that is expected to double in next two decades. Similarly, about 22.9 million M^3/day domestic wastewater is generated. Hardly 24% of the wastewater in India is treated.

The Central Soil Salinity Research Institute has developed and standardized guidelines and techniques for the judicious use of poor quality waters, including sewage and industrial effluents. A brief account of these technologies is cited in this paper. The issues and strategies related to wastewater use in agriculture are summarized under the following sub-heads: (i) nature, quality and distribution of poor quality waters in India, (ii) generation of sewage and industrial effluents and their scope for use in agriculture, (iii) guidelines and agronomic practices for reuse of wastewater, (iv) phyto and bio remediation approaches for detoxification of soils and waters

loaded with heavy metals, (v) experiences of US-India AKI initiative on reuse of wastewater in agriculture and (vi) future research, development and required policy initiatives.

INTRODUCTION

At present agriculture consumes about 85% of the total water, and this share is likely to be reduced to 70% by 2050. It is estimated that the present population of India of about 1.1 billion is expected to cross 1.5 billion mark by 2050. Most of the population (>50%) is expected to be settled in urban areas. The generation of wastewater both domestic and industrial will multiply. These wastewaters will contain contaminants like organic compounds, dissolved toxins and heavy metals. The domestic sewage waters are already used for peri-urban agriculture in areas adjacent to the cities since centuries because they contain sufficient quantity of plant nutrients and mostly contain biodegradable constituents. As such, application of domestic wastewater for agriculture does not pose serious threat of heavy metals and other toxic industrial constituents entry into the food chain. However, under Indian conditions there are no in-built mechanisms to keep domestic sewage water separate from the industrial effluents. In most cases these are diverted into the common storage and water carrying streams or *nallahs*. Farmers pump these waters at their convenience to irrigate agricultural crops in general and vegetables in particular. Cultivation of green fodder in peri-urban agriculture with wastewater for meeting requirements of milch animals is another important land use. Several studies conducted in these areas revealed higher concentration of heavy metals, pesticides, BHC etc. in grasses, forages, milk and animal serum. There is always a risk associated with their entry into the human body with the consumption of milk, milk products, eggs and meat.

Several estimates have been made about the total quantities of domestic sewage and industrial effluents generated in India. The estimates made by the Central Pollution Control Board (CPCB, 2000) are given in Table 1. It has been further estimate that only 72% of the total wastewater generated is collected. Of this only 24% is treated before release. It will be worthwhile to share here that sizeable parts of cities, towns and villages where running water supplies have been established, do not have any sewerage systems or sewerage system is overloaded or disfunct. A large portion of wastewater, thus, remains uncontrolled and is a source of soil and ground water pollution. This kind of disposal options ultimately affect food, nutritional, environmental and livelihood securities and calls for development of strategies for sustainable use and management of wastewaters for their use in agriculture.

Table 1. Basin-wise wastewater generation, collection and treatment in class-I cities

Name of river basin	No. of class-I cities	Volume of wastewater (MLD)		Treatment capacity (MLD)
		Produced	Collected	
Brahmani	1	17.3	13.0(75)1	NA
Brahamputra	7	178.9	91.9(51)	NA
Cavery	16	726.9	471.5(65)	396.1(51)2
Ganga	103	5812.4	4341.1 (69)	1618.9(28)
Indus	15	624.3	330.5(53)	93.8(10)
Godavari	25	634.8	467.8(74)	65.4(10)
Krishna	27	1313.8	1055.5(80)	489.0(37)
Mahanadi	9	412.9	321.9(78)	86.0(21)
Mahi	3	160.6	121.8(76)	81.0(50)
Narmada	4	44.0	22.2(51)	NA
Pennar	6	60.7	43.7(72)	12.0(20)
Sabarmati	7	651.4	532.4(82)	471.0(72)
Subarnrekha	2	280.0	210.0(75)	NA
Tapi	8	270.8	218.4(79)	70.0(26)
Coastal	29	4561.8	3858.0(85)	389.1 (85)
Punjab	10	360.5	266.3(74)	NA
Rajasthan	14	763.2	614.8(81)	27(4)
Non-major	37	908.7	525.2(58)	639.0(70)
Total	299	16662.5	11938.2(72)	4037.2(24)

Source: Central Pollution Control Board (2000)

DOMESTIC AND INDUSTRIAL EFFLUENT AND POLLUTION LOAD

It has been estimated that out of 22900 million litres per day (MLD) of domestic wastewater generated, only about 5900 MLD that accounts for 26% of the total is treated before release into different streams and water courses. Nearly 17000 MLD is disposed off untreated. Comparison of pollution load generation from domestic and industrial sources is given in Figure 1. Similarly, the volume of wastewater generated from different industries is given in Figure 2. The total wastewater generated from all major industrial sources of Indian is 83048 MLD. This comprised of 66700 MLD of cooling water generated from thermal power plants (Biswas, 2003). Out of the remaining 16348 MLD, thermal power plants generate another 7275 MLD as boiler blow down water and overflow from ash ponds. Engineering industries such as electroplating, paper mills, textile industries, steel plants and sugar mills are the other major concerns which generate significant quantities of wastewater.

WASTEWATER COMPOSITION

In case of domestic sewage the wastewater composition varies from community to community according to the living standards and diet habits. In general, all municipal wastewater contains organic matter, essential plant nutrients (like N, P, K), dissolved minerals, toxic chemicals and pathogens. At present there seems no systematic program for monitoring irrigation potential of these sources on a regular basis.

Routine measurements, in general, pertain to non-specific pollution parameters such as biological oxygen demand (BOD), suspended solids and chemical oxygen demands (COD). However, those characteristics which have direct effect on crops, soils and groundwater are rarely measured and monitored on a time scale. A number of workers in India at different locations analysed composition of raw sewage, primary treated and secondary treated sewage waters.

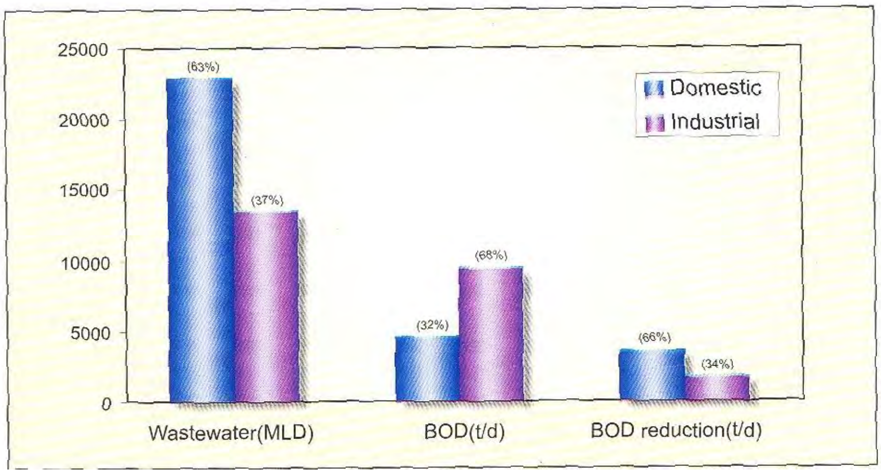


Fig. 1: Comparison of pollution load generation from domestic and industrial sources Volumes parenthesis are percent of total.

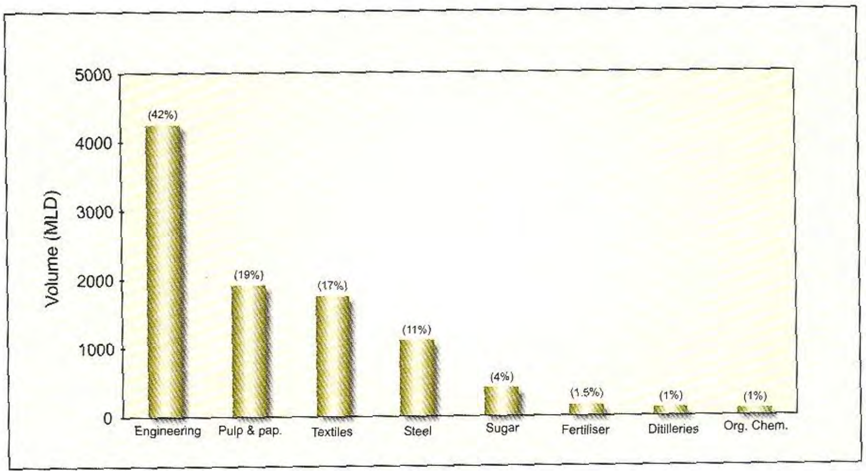


Fig. 2: Volume of wastewater generated from different industries (Total 10,215 MLD).

The compiled information is given in Table 2. Their findings reveal that sewage water contains more than 90% water. Olinya *et al.* (1998) reported that the solid portion comprised of 40-50% organics, 30-40% inert materials, 10-15% bio resistant organics and 5-8% miscellaneous substances on over dry basis. Because of presence of detergents and soaps sewage effluents are in general alkaline, have low to medium salinity and low sodium adsorption ratio (SAR). Further, these have high BOD, N, P, K, Fe, Zn, Cu and Mn. The chemical composition varies from season to season. For example, during post monsoon season the concentrations particularly of heavy metals like Cd, Ni, Cr, Pb decrease appreciably. It is reported that in general, raw sewage water contains 10^7-10^9 coliform per 100 ml, *F. streptococci* 10^7-10^8 and virus per 10^2-10^3 100 ml. Distilleries generally generate very concentrated wastewater and it is hard to treat (Trivedi, 2003). The health implications associated with the industrial wastewater are because of the presence of chemical contaminants.

Table 2. Composition of sewage at different locations in India

Location	Nagpur Untrated	Nagpur	Calcutta	Calcutta	Ludhiana	Haryana	Haryana	Dharwad	Indore	Anand	Amberpet Hyderabad
Parameters	Kaul *et al.*, (2002)		Gupta & Mitra (2002)	Adhikari *et al.*, (1994)	Arora *et al.*, (1985)	Gupta *et al.*, (1993)	Baddesha *et al.*, (1986)	Hunsal *et al.*, (1997)	Anonymous (2004)	Anonymous (2004)	Bhupal Raj (1997)
pH	7.2-7.8	7.2-7.7	7.5(8.4)*	8	6.2-7.9	7.3-8.0	7-7.5	7.6	7.1-7.5	7.1-8.1	7.1-8.5
EC(ds/m)	0.7-1.0	0.7-1.0	1.7(1.9)	1.2	0.8-1.8	0.9-1.8	0.9-2.9	0.42	0.9-2.1	1.5-1.7	2.58-4.31
SAR(mmol/l)^{½}	-	-	1.6(2.5)	2.9	-	-	1.6-6	-	1.5-3.8	-	-
BOD (mg/l)	210-340	185-305	34(78)	-	-	63-90	66-173	134	68-215	-	-
COD (mg/l)	-	-	274(212)	-	-	-	-	273	215-628	-	-
N (mg/l)	54.8-68.3	46.3	14(17)	20	-	32-70	25-98	12.1	11-64	-	31-45
P (mg/l)	8.7-11	7.2-11	0.9(1.9)	2	1.3-10	15-30	4.3-12.7	1.9	1-1.2	-	4.5-10.4
$HC0_3$(me/l)	4.9-6.4	4.6-6.5	-	61	2.8-5.1	-	4.3-11.4	-	4.3-7.2	4.6-5.1	-
Cl (me/l)	1.8-3.1	1.8-3.1	-	3.7	6-15	-	1.7-12.5	1.7	5-10.7	9-10	2.3-4.2
Ca(me/l)	1.6-2:7	1.5-2.5	3.7(5)	4.3	2.5-5.2	-	2.8-5.7	4.0	7.2-11	-	6.2-8
Mg (me/l)	0.8-1.3	0.8-1.3	5.5(2)	3.0	1.3-3.6	-	4-15.3	2.3	1.8-3.5	-	2.1-3.3
Na (me/l)	4.2-6.1	4.0-5.9	3.4(4.7)	126	-	-	3-18.4	0.6	3.5-9.2	8.2-9.2	8.6-11.5
K+(mg/l)	31-37	29-33	16(16)	19	11-45	250-500	28-152	53	19.5-54	3.4-3.7	0.6-0.8
Fe (mg/l)	1.41-1.57	1.24-137	656(449)	-	6-31	6-25	0.6-21.8	1.23	0.14-0.21	1.3-4.9	2.2-6.1
Zn (mg/l)	0.9-1:2	0.8-1.0	0.3(0.4)	-	0.5-2.6	1.6-28	0.13-0.9	0.27	0.013-0.11	0.17-0.71	0.23-0.35
Mn (mg/1)	0.14-.2	0.12-0.16	0.66(0.65)	-	0.2-0.5	0.8-2.8	0.25-0.6	0.11	0.127-0.312	0.19-2.14	1.2-3.7
CU (μg/l)	0.1-0.15	0.09-0.12	0.07(0.085)	-	0.1-0.4	0.7-6.2	0.06-0.6	0.12	0.01-0.027	0.03-0.11	0.12-0.13
Pb (μg/l)	-	-	2.9(7.0)	8	-	-	0.09	0.032	0.032-0.325	0.12-0.55	0.06-0.10
Cr (μg/l)	-	-	12(2)	1	0.28	-	-	0.0013	0.06-0.168	0.04-0.07	0.18-0.41
Ni (μg/l)	ND	ND	58(113)	8	-	0.8-3.5	0.14	ND	-	0.02-0.25	0.03-0.07
Cd (μg/l)	ND	ND	1.3(4.9)	-	0.4	0.4-0.18	0.01	ND	0.02-0.08	0.02-0.04	0.02-0.03
CO (μg/l)	-	-	6(10.5)	3	-	-	-	-	0.02-0.113	0.07-0.28	0.01-0.12

*Values in parenthesis represent those monitored during post-monsoon season

SCOPE OF WASTEWATER USE IN AGRICULTURE

Wastewaters contains sufficient amounts of organic carbon and plant nutrients and provide ample opportunities for harvesting and use for sustainable agriculture. One conservative estimate reveals that these waters have the potential to irrigate 21000 ha of land on daily basis or about 8 m ha annually. Most of these waters are available near/adjacent to the cities and can be effectively used for labor intensive high value crops like vegetables and fodder. Estimates made based upon average N, P and K contents in sewage and 70% utilization in agriculture reveal that these have the potential to contribute 380, 60, 520 and 1.4 thousand tons of N, P, K and Zn, respectively in addition to several other micronutrients. There exists a potential of one million tons of nutrients compared to total requirement of about 20 million tons of factory produced fertilizer consumption in India. It has been reported that based upon sewage water based irrigation near cities farmers usually adopt to year round, intensive vegetable production systems with a cropping intensity of 300-400 and can generate 3 to 4 times more income from a unit land than those using fresh water. It is reported that first sewage farm in India was established in 1896 at Ahmedabad followed by Poona in 1918 and Madurai in 1928. At present there are more than 300 sewage farms in India covering an area of more than 50000 ha. The average cost of sewage irrigation varies from place to place and reported to range from Rs. 75/ha at Hyderabad to Rs. 400/ha at Jaipur; with average consensus figure of Rs. 188/ha.

IMPACTS OF SEWAGE WATER IRRIGATION ON AGRICULTURE

Shende *et al.*, 1988; Hussain *et al.*, 2002; Rattan *et al.,* 2001 and Minhas and Samra, 2004 studied the impact of wastewater use on soils, crops, public health, surface and ground water and other socio-economic and environmental issues. These reviews provide an insight to adopt appropriate land use practices on areas used for sewage farming.

Soil Properties

The ultimate effect of wastewater use on soil properties in governed by the parameters like type of soil (its structure, texture and biological properties), rainfall, quality and quantity of wastewater applied and the kind of crops grown with this kind of water. The main effects will be based upon the cations, anions, total dissolved salts, specific ions and heavy metal concentrations etc. Several studies conducted in different regions of India revealed that the soil pH decreased, EC and ESP increased with continuous use of wastewater for 8-30 years (Shende *et al.*, 1988; Azad *et al.*, 1992; Gupta *et al.*, 1998 and Yadav *et al.*, 2002). However, the impact of these changes was not visible in terms of decreased productivity. In almost all cases organic carbon content increased. The long term effect of sewage irrigation on soil salinity, alkalinity and major nutrients as compiled by Minhas and Samra, 2004 is reported in Table 3. Most of these studies reveal the accumulation of N, P and K and micronutrients in the soil (Baddesha *et al.*, 1997; Prasad, 1996 and Shende *et al.*, 1998). Jayaraman *et al.*, 1983 reported improvement in total porosity, stability index and aggregate stability with application of sewage water due to increased levels of organic matter in the soil. However, Otis, 1984 and Halliwal *et al.*, 2001 reported reduced hydraulic conductivity in sewage irrigated soils probably due to accumulation of suspended solid at the surface, clogging of pores due to algal cell particles and formation of biological mat.

Table 3. Effect of sewage irrigation on soil salinity, alkalinity and major nutrients

Site/years of sewage use	Treatment	pH (1:2)	EC (1:2) dS/m	Org. C (%)	Total N (%)	Total P (%)	Total K (%)	Source
Nagpur (8yrs)	SI	8.50	0.23	1.00	0.41	0.05	0.50	Juwarkar *et al.,* (1987)
	2SI:1NSI	8.87	0.24	0.70	0.26	0.25	0.27	
	1:1	8.93	0.13	0.65	0.12	0.11	0.09	
	1:2	8.88	0.04	0.62	0.04	0.04	0.03	
	NSI	9.00	0.48	0.57	0.05	0.43	0.04	
Calcutta (50-60 yrs)	SI	7.7	0.34	0.37	0.10	0.10	0.13	Gupta & Mitra(2002)
	NSI	7.2	0.13	0.19	0.056	0.05	0.073	
Faridabad (20 yrs)	SI	8.1	4.5*	1.2	0.11	0.06	0.27	Anonymous (2004)
	NSI	8.4	3.8	0.35	0.05	0.05	0.27	
Kurukshetra (25 yrs)	SI	8.1	1.68	1.73	0.145	0.881	0.214	
	NSI	8.3	1.00	1.24	0.080	0.56	0.183	
					Av-N	Av-P (kg/ha)	Av-K	
Kaithal (15 yrs)	SI	7.7	1.9	1.3	70	78	1050	Gupta *et al*., (1998)
	NSI	8.4	3.3	0.5	42	30	188	
Narwana (12 yrs)	SI	7.7	1.3	0.8	57	74	136	
	NSI	7.8	3.0	0.3	50	4	172	
Rewari (15 yrs)	SI	8.6	0.5	0.3	70	14	-	
	NSI	8.2	0.7	0.5	77	16	-	
Hisar (8 yrs)	SI	7.5	0.5	0.7	56	43	815	
	NSI	7.9	0.6	0.5	49	34	43	
Delhi (21 yrs)	Nilothi(SI)	8.3	0.51	0.45	-	38.1	92	Rattan *et al.,* (2002)
	"(NSI)	8.64	0.47	0.25	-	16.0	219	
	Ranhola(SI)	7.86	0.64	0.66	-	22.1	49	
	"(NSI)	8.54	0.39	0.39	-	13.8	92	
	Mundka(SI)	8.13	0.82	0.51	-	30.6	138	
	"(NSI)	7.99	0.24	0.37	-	18.5	83	
Indore (30-40yrs)	SI(40y)	8.1	1.4	0.9	315	17.6	975	Anonymous (2004)
	SI(30y)	7.9	1.3	0.8	280	26.4	1345	
	NSI	8.1	0.7	0.8	280	26.4	507	
Jaipur	SI	8.9	0.12	0.55	-	-	-	Sharma *et al*., (2001)
	NSI	8.8	0.21	0.21	-	-	-	
Delhi	SI	7.7	-	0.5	-	90	273	Dutta *et al*., (2000)
	NSI	7.8	-	0.4	-	32	343	
Hyderabad	SI	5.8	4.66	0.54	570	26.2	784	Anonymous (2001)
	NSI	7.4	0.38	0.26	210	8.4	208	

*Av- represent value for available nutrient; SI: Sewage irrigation and NSI: Non-sewage irrigation

One of the major limitations for the use of wastewater to irrigate agricultural crops is the accumulation of heavy metals in the soil and then entering into the food chain. In general, heavy metal accumulation takes place in the order: Fe > Zn > MN > Cu > Cr > Pb > Cd. The critical limits for these ions have been worked out by Revira *et al.* (1996) to be 3.0, 150.0, 210.0, 300.0, 112.0 and 46.0 mg/kg for Cd, Cr, Cu, Pb, Ni and Zn, respectively. He worked out these limits for 7.0 pH soils and cautioned that their accumulation in soil should not exceed 0.15, 3.0, 12.0, 15.0, 3.0 and 30 kg/ha, respectively. Total accumulation of heavy metals in soils irrigated with wastewater in different parts of India is reported in Table 4. For example, Mitra and Gupta (1997) reported 137, 47, 18.5, 5.6, 3.9, 3.6, 2.4 and 2.3 fold increase in Cd, Zn, Pb, Cr, Co, Cu, Fe and Ni, respectively in wastewater irrigated soils near Calcutta. Similarly, 36, 86 and 46% increase in Cd, Ni and CO contents, respectively was observed in soils irrigated with sewage and effluents near Ludhiana (Azad *et al*., 1992). Arora and Brar reported higher concentration of As, Cr and Pb in heavy textured compared to light textured soils under Punjab conditions. All these studies reveal that accumulation depends upon texture, structure, water intake capacity, rainfall, depth to groundwater, quantity and quality of the effluents, frequency and method of application and distance from the source. A review of total micronutrients and heavy metal status (mg/kg) in soils receiving sewerage/industrial effluents as compiled by Minhas and Samra, (2004) is given in Table 4.

Since sewage water contains sufficient quantities of organic matter and, therefore, it is likely to increase the bacteria, fungi, actinomycetes and other microbial populations in the soil.

Soni and Singh (1994) reported higher mineralization rates of nitrogen in sewage treated soils compared to untreated soils. In some cases the microbial biomass becomes smaller when heavy metals get accumulated under increased application of sewage effluents.

EFFECT ON CROPS AND THEIR PRODUCTIVITY

The effect of wastewater use on crop productivity and quality depends upon the kind of pollutant used, relative proportions and concentrations of pollutants and the genetic build-up of the plant in terms of its tolerance limits. In general, untreated domestic sewage has a positive effect on most crops because of higher amounts of organic matter, plant nutrients and biological activity. However, sometimes imbalances of nutrients because of more N in sewage water effects the crop growth adversely. Juwarkar (1991) reported the long term effects of sewage water irrigation on several crops. His studies showed that maximum productivity in case of 15 crops was obtained with primary treated sewage followed by dilutution in the ratio of 1:1 with untreated sewage and least with well or canal water irrigated crops (Table 5). Similar results were also obtained at several other places (Chakrabarti and Chakrabarti, 1995; Mahida 1991; Singh *et al*., 1989). Studies conducted at CSSRI experimental farm indicated enhanced productivity of vegetables, fodder, grain crops and agroforestry in the range of 15-27% with sewage water irrigation compared to tubewell water irrigation Figures 3 and 4.

Table 4. Total micronutrients and heavy metal status (mg /kg) in soils receiving sewage/industrial effluents

Source	Treatment	Fe	Zn	Cu	Mn	Cd	Pb	Co	Ni	Cr	Source
Ludhiana	SI	-	-	-	-	1.1	-	24.1	43.9	-	Kansal (1992)
	NSI	-	-	-	-	0.8	-	16.3	23.6	-	
Amritsar	SI (0-4km)	30.6-28	413-182	280-85	490-360	-	-	-	-	-	Hundal and Sandhu (1990)
	"(3-16km)	28-20.6	192-112	80-28	380-300	-	-	-	-	-	
	NSI	24.9-19.8	108-68	22-10	340-260	-	-	-	-	-	
Kolkata 50-60 yrs	SI	22120	1210	198	382	3.72	385	46.6	61	164	Gupta and Mitra (2002)
	NSI	9090	26	52	446	0.04	24.2	12.0	25	24.8	
Faridabad (20 yrs)	SI	2207	261	60	241	4.2	-	-	73	79	Anonymous (2004)
	NSI	966	53	23	188	1.1	-	-	19	23	
Indore (40yrs)	SI	26.3	14.5	27.4	53.9	0.17	12.1	2.7	-	1.14	
	NSI	16.4	3.7	2.7	39.5	0.04	1.85	0.95	-	0.10	
Jaipur	SI	-	2.8-5.3	1.8-6.3	-	0.12-0.2	-	-	-	-	Sharma *et al.*, (2001)
	NSI	-	3.4	1.15	-	0.15	-	-	-	-	
Patancheru	SI	11.7	2.1	1.2	12.7	0.42	3.84	1.87	2.74	4.14	Bhualraj (2002)
	NSI	2.3	0.2	0.6	2.2	0.03	0.05	0.03	0.03	0.12	
Durgapur	IEI	-	309	41.5	-	6.1	180	-	-	-	Som et al., (1994)
Ahmedabad	SI+IEI	16.6	12.1	7.0	6.0	0.06	8.6	0.01	0.52	0.01	Patel et al., (2004)
	Papermill	14.2	7.6	3.2	8.1	0.14	27.2	0.01	0.36	0.02	
Vadodara	Refinery Eft.	11.4	1.26	2.5	17.2	0.03	0.6	0.22	0.50	0.01	
	Fert. Plant	20.6	1.10	2.1	25.2	0.02	0.36	0.20	0.88	0.01	
Permissible limits		50	2	5	10	0.5	5	2	2	2	Chapman (1975)
Toxic levels		150	20	10	-	1	10	5	5	5	Rovira *et al.* (1996)

SI: Sewage irrigation, NSI- Non-sewage irrigation, IEI-Industrial effluent irrigation

However, higher amounts of organic matter leading to high organic load (BOD) is one of the major limiting factors affecting crops growth due to low oxidation of organic matter, less nitrification and more amounts of ammonical nitrogen in soil. Studies conducted by Yadav *et al.* (2002) revealed that the rice yields improved when irrigated with waters having BOD up to 500 mg/l. However, further increase in BOD (1000 – 4000 mg/l) reduced the productivity appreciably. The normal observations are that application of N rich sewage water promotes vegetative growth, more succulence, lodging and make the crop more prone to the incidence of pests and diseases.

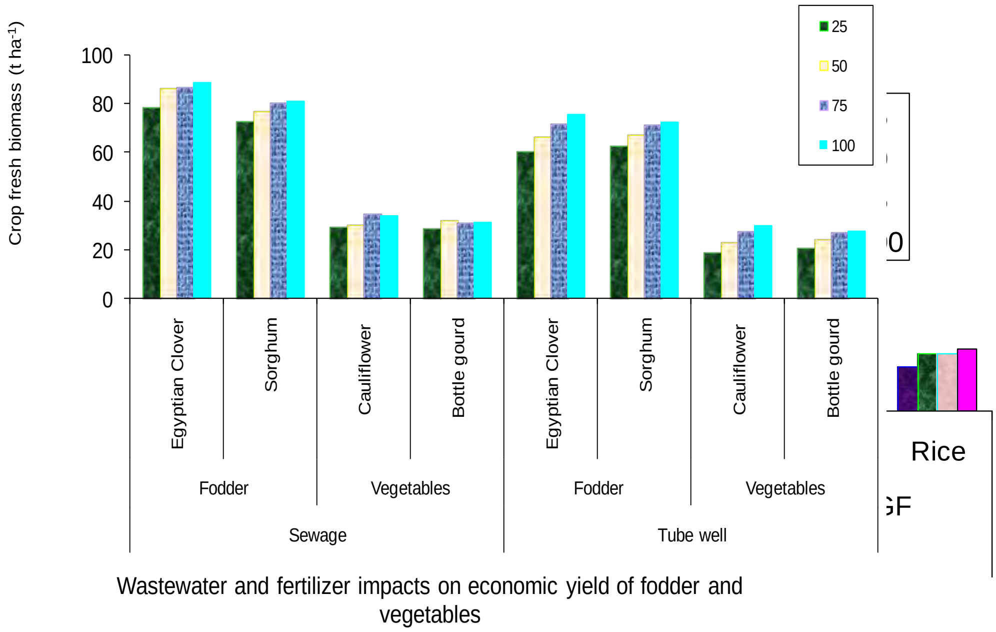


Fig. 3: Wastewater and fertilizer use in grain crops

Another serious concern is the accumulation of toxic ions in the crops and their recycling in the food chain. The effects are more pronounced in highly acidic soils having pH < 5.0 and low CEC and organic matter compared to calcareous soils with high CEC and high organic matter. Mitra and Gupta (1999) reported 2 to 40 times higher concentration of heavy metals in radish, gourd, spinach and cauliflower around Calcutta. Similarly, Brar *et al.*, 2000 reported higher accumulation of metals in leaves and tubers of potato grown on sewage irrigated soils as compared with ground water irrigated soils near Ludhiana. Singh *et al.* (1991) reported that Cu, Fe and Mn was higher in sewage irrigated while Cd, Pb an Ni were higher in refinery effluent irrigated crop.

STRATEGIES FOR WASTEWATER USE IN AGRICULTURE

The main limitation associated with the use of sewage and industrial effluents for irrigation to agricultural crops is the presence of toxic substances and the pathogens which have the potential to enter the food chain and thus adversely impacting the animal and human health. Such risks can be minimized to a greater extent by avoiding wastewater use without treatment in food crops like cereals and pulses, lettuce, cucumber and other root crops, vegetables and fruits.

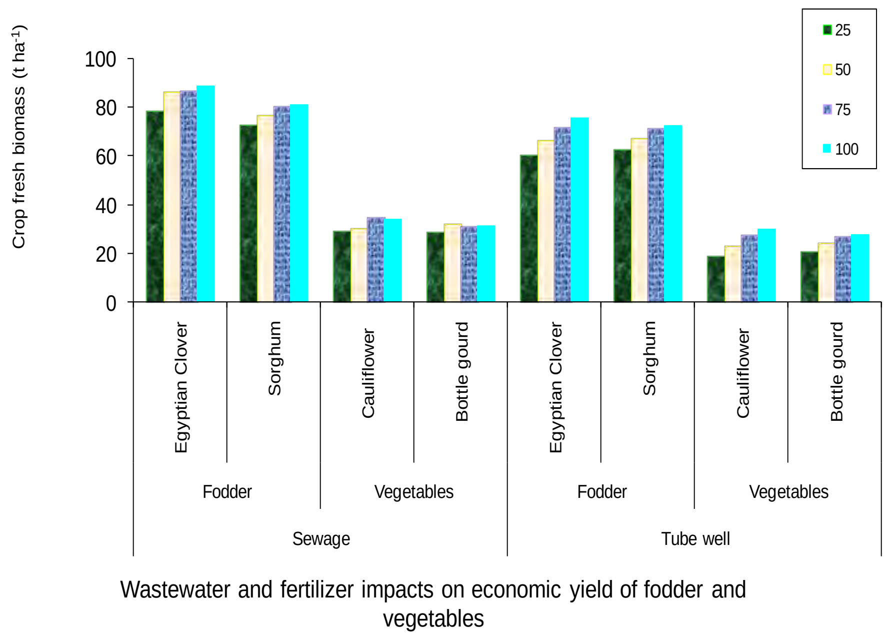


Fig. 4: Wastewater and fertilizer impacts on economic yield of fodder and vegetables.

Table 5. Crop yield with sewage amendment of soil of Nagpur

Crops	Yield (Mg/ha)			
	Well/canal water	Untreated sewage	Primary treated sewage	Diluted (1:1) sewage
Rice	3.8	3.3	4.3	4.1
Wheat	2.8	3.1	3.4	3.2
Soybean	1.6	2.1	2.3	1.9
Greengram	0.6	0.5	0.8	0.7
Chickpea	1.2	1.3	1.5	1.4
Cabbage	13.3	14.8	16.4	15.7
Cauliflower	16.4	18.2	19.7	16.9
Okra	3.1	3.4	4.8	4.0
Tomato	13.7	15.5	16.4	16.1
Brinjal	9.1	12.1	12.7	10.1
Potato	6.4	7.1	8.1	7.1
Sugarcane	42.7	44.4	48.5	43.3
Marigold	5.1	7.1	7.6	-
Daizy	8.4	9.7	11.4	-
Jasmin	3.7	3.4	4.4	4.1
Average	88	9.7	10.8	9.9

The World Health Organization (WHO) has developed standards with respect to safe use of wastewater for agricultural crops and human health and fixed the limits for toxic substances and pathogens. These guidelines are rarely followed but some of the precautions which do not involve high financial costs such as wearing of shoes and gloves while working with wastewater irrigation, regular treatment of farmers and workers with antihelmintic drugs, raising crops on bunds/ridges to avoid direct contact, if adopted reduce the pathogen load significantly. Some of the other precautions which can be followed included: removal of outer leaves in cabbage, washing with fresh water and drying in sun or shade. Effect of planting methods and washings on *F. coliform* contamination is given in Table 6. Similarly, incidence of infestation of coliform in ridge gourd vegetable crop when kept under shade or sunlight is depicted in Figure 5.

Table 6. Effect of planting method and washings on *F. coliform* contamination of sewage irrigated ridge gourd

Treatment		Fecal coliform (MPN/1000g)	
Bed planting		Range	Mean
	Middle	<2-5.0x10^3	8.1x10^1
	Side	2.1x10^2-2.6x10^4	3.4x10^2
Ridges		<2-2.4x10^4	8.5x10^2
Washings	0	1.1 x10^3-2.6 x10^5	1.3x10^4
	1	<2-3.0 x10^3	1.3x10^2
	2	<2-1.4 x10^2	1.1x10^1
	3	<2	<2
Cabbage after leaf removal	Nil	<2-3.4x10^3	1.8x10^2
	1	2-2.6x10^3	2.9x10^1
	2	<2	<2
	3	<2	<2

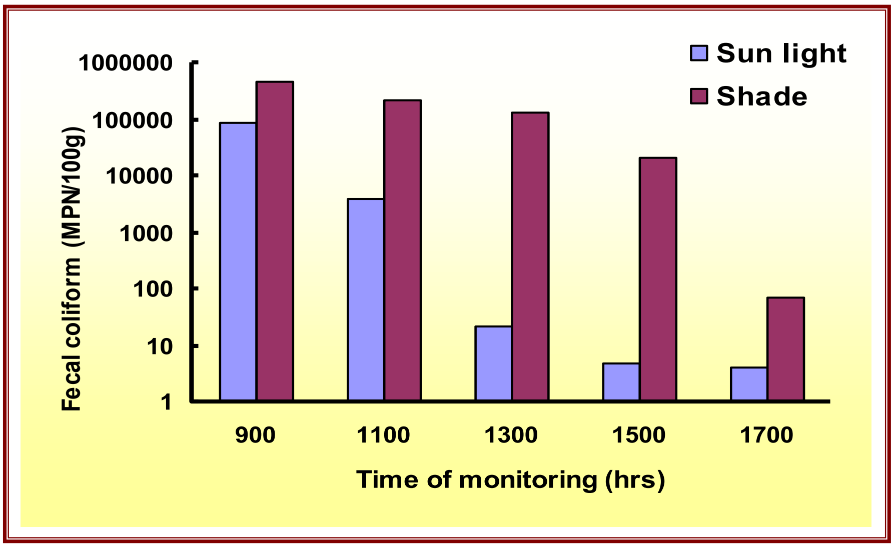


Fig. 5: Coliform contamination in ridge-gourd when kept under shade or sunlight.

The other option is to exploit sewage water use for growing non food crops. Workers at the CSSRI, Karnal have identified several flower, aromatic and medicinal crops which can be grown successfully using sewage irrigation. Amongst the flower crops marigold (*Tagetes erecta*); medicinal and aromatic plants like Uchanti (*Ageratum conzyoides*), lemon grass (*Cymbopogon flexuosus*), Nigundi (*Vitex negundo*) and Tukham Malanga (*Salvia aegyptica*) have been identified as quite promising. Cadmium (Cd) removal potential of flower crops and relative yield of aromatic grasses at different Cd levels is reported in Figures 6 and 7.

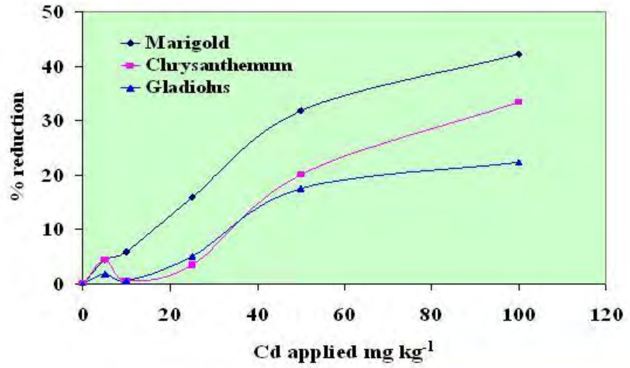
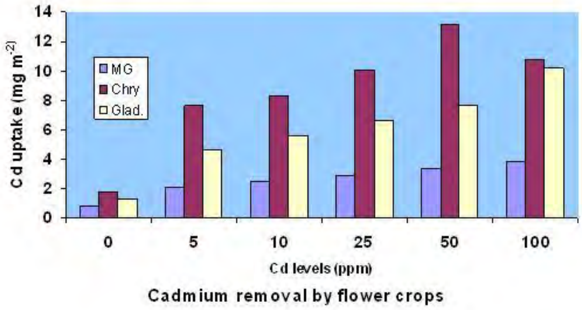


Fig. 6: Phyto-remediation through floriculture



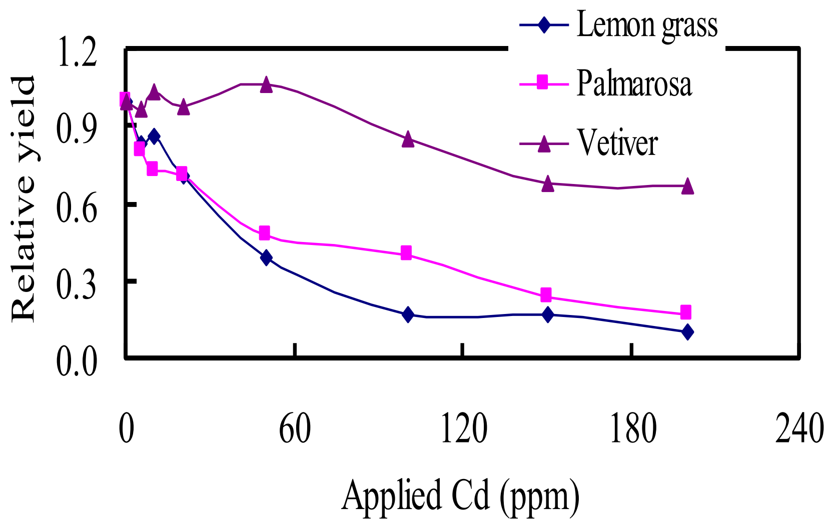


Fig. 7: Relative yield of aromatic grasses at Cd levels.

Disposal of sewage and industrial effluents for raising tree plantations for biomass production is another option of great promise. The high transpiration capacity of fast growing trees like *Eucalyptus tereticornis* can be exploited. Results of a long term experiment conducted at CSSRI, Karnal where sewage and tubewell irrigation impacts were evaluated on eucalyptus planted at different densitities revealed that this tree can transpire 30 to 70 litres of water/day. The comparison with other fast growing poplar trees revealed that poplar trees transpire at much higher rate than eucalyptus during monsoon and post monsoon period (Figure 8). Comparison of growth parameters of eucalyptus when irrigated with sewage and tubewell waters is given in Table 7. This land use option seems quite promising as forest plants can tolerate relatively higher concentration of salts, toxic elements, BOD and waterlogging stresses. Since the trees are used as fuelwood, timber, pulp, coal and even for gas production; there seems no danger due to pathogens to the workers and consumers of end products. Another advantage with this option is that abandoned wastelands can be utilized for raising tree plantations and for elective disposal of wastewater.

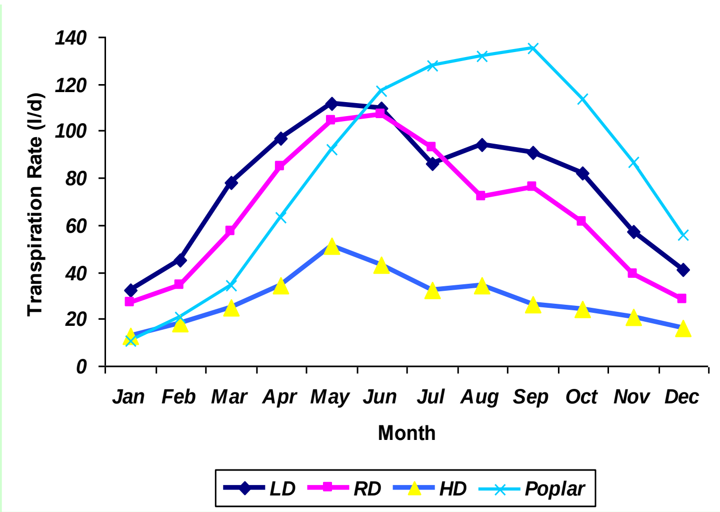


Fig. 8: Average daily transpiration rate of sewage irrigated eucalyptus and poplar; HD=High density, RD=Recommended density and LD=Low density.

Table 7. Growth parameters of Eucalyptus in June, 2008

Planting density (no.)	Plant height (m)		DSH (cm)		DBH (cm)	
	TW	SW	TW	SW	TW	SW
VHD(6530)	11.9	12.5	9.7	10.1	8.8	8.6
HD (1993)	14.1	14.6	14.2	14.5	11.7	11.9
RD (517)	15.9	16.3	17.2	17.4	15.5	16.0
LD (162)	16.6	16.8	19.0	19.3	16.8	17.0

VHD=Very high density, HD=High density, RD=Recommended density and LD=Low density

Several studies are in progress to devise bioremediation techniques for treatment of wastewater. At CSSRI, several bacterial cultures are being screened for their efficiency to reduce BOD and COD. Maximum reduction in BOD (50 to 57%) and COD (37 to 42%) was observed in unsterilized raw sewage with bacterial culture of *Enterobactor intermedius* and *Alcaligenes cupidus* in comparison to least reduction in BOD and COD in uninoculated control (12 to 14%). This indicated effectiveness of these two bacterial cultures to bioremediate wastewater under natural conditions. Similarly, encouraging results were obtained with fungal culture *Aspergillus flavus* to reduce BOD (74%) and COD (70%) of sterilized raw sewage.

US-India Agriculture Knowledge Initiative on Water Management

United States of America and India has taken a major initiative for joint research, education and capacity building initiatives for water management including reuse of wastewater in agriculture. Under this program, about 15 US universities and 20 Indian universities and research institutes are collaborating. The already approved projects under this program included water harvesting for ground water recharge and biodrainage for salinity control, sustainable water resources management, information and communication technologies for efficient water management and on farm water management for rainfed agriculture on benchmark watersheds in diverse eco-regions of India. The program is likely to provide much technical and capacity building support to water management in general and reuse of wastewater in particular.

REQUIRED RESEARCH, DEVELOPMENT AND POLICY ISSUES

- There seems strong case to segregate domestic and industrial wastewaters in each town/city. To enforce this, legal laws may be required. There is also a need to develop and implement location specific cost effective treatment technologies.
- Development of guidelines and mechanisms to decrease health risks involved in the irrigation with sewage water. Most of the vegetables and fodder crops near the cities are cultivated with sewage water and those are consumed in most cases raw by the people. A regulatory mechanism needs to be put in place for choice of crops and monitoring of toxic metals and pathogens.
- There seems need for testing and standardization of aquatic microphytes for removal of toxins. Identification, testing and culturing of microbes having bioremediation potential should be another priority research agenda.
- To develop best management practices for reuse of wastewater, multidisciplinary research teams comprising agricultural scientists, health engineers, medical doctors and animal scientists will be required. There is also a need to shift from discipline oriented to multidisciplinary team approach in wastewater management.
- Municipalities should be motivated/advised to make proper arrangement for collection, storage and reuse of such waters for growing non-edible crops like flowers, trees and other aromatic and medicinal crops.
- Sensitization of consumers through mass media about the safe use of peri-urban agricultural products grown with the use of sewage water.
- Wastewater management policy must come with a slogan “Polluter Must Pay”.

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Session 9: Advances in Irrigation

ADVANCED IRRIGATION ENGINEERING: PRECISION AND PRECISE

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ABSTRACT

Irrigation advances in precision irrigation (PI) or site specific irrigation (SSI) have been considerable in research; however commercialization lags. A primary necessity for SSI/PI is variability in soil texture that affects soil water holding capacity and crop yield. Basically, SSI/PI uses variable rate application technologies, mainly with center-pivots or lateral-move or linear irrigation machines, to irrigate prescription-specific management zones within a field by varying the application to match crop needs or soil water holding constraints. SSI/PI can avoid irrigating management zones with poor internal drainage; zones with poor crop growth or development (from fertility or salinity or other soil factors or even crop diseases); or zones with known problems (rock outcrops, physical obstructions, etc.). One limitation for SSI/PI is defining the objective function for the production goals/constraints. Examples of objective functions include optimizing overall field productivity, minimizing water use, or reducing environmental on-site or off-site impacts. The variable rate applications are achieved by a range of engineering options from variable nozzle flow rates, pulsing nozzle flows, or multiple nozzles on separate submains to vary application rates. Newer center pivot and linear machines are controlled by on-board microprocessor systems that are easily integrated with supervisory control and data acquisition (SCADA) controllers to integrate communication and variable rate application controls for

specific sets of nozzles or individual nozzles for determined management zones. Communication for center pivot or linear controllers is typically done using radio telemetry, wireless internet links, or cellular telephones.

Precision irrigation is of limited utility without precise irrigation scheduling (temporally and spatially). Irrigation scheduling has advanced considerably in the past 20-30 years with improved technology to measure soil or plant water status and, especially, within the past 10-15 years to utilize remote sensing tools. Plant or soil sensors are most often utilized to initiate or complete an irrigation event based on specific criteria. Automated weather stations are now widely used to provide basic site information on the irrigation requirement using either crop development models or simpler reference evapotranspiration (ET) data to be used with crop coefficients (Kc). Remote sensing is increasingly being utilized to measure crop water status (usually through crop surface temperature) or crop development or ground cover based on spectral reflectance from specific electromagnetic wave bands, but future satellites (i.e., Landsat 8) may not contain a thermal radiation band critical for crop stress and ET. Usually, the red band (0.63-0.69 μm or band 3 on Landsat TM or EM+) and the near infrared band (0.76-0.90 μm or band 4 on Landsat TM or EM+) are used to determine the Normalized Difference Vegetation Index (NDVI). Satellite and aircraft remote sensing platforms have not proven useful for irrigation scheduling due to issues of too coarse spatial and temporal resolutions and too long turn-around times for getting data processed and useful information to the field. Inexpensive infrared thermometers (IRTs) are being used as crop thermal temperature detectors ranging from hand-held to fixed units in the field to newer wireless IRTs using mesh networks to communicate with controllers. Near-surface remote sensing with sensors mounted on moving irrigation systems may provide critical spatial integration from point weather networks and useful feedback on crop ET and irrigation controls in advanced automated systems, particularly for SSI/PI.

INTRODUCTION

Many irrigation engineering advances in the past 20-30 years or longer have been focused on improving irrigation system performance (both efficiency and uniformity) and scientific irrigation scheduling using modeled soil water balance to predict irrigation dates or direct monitoring of soil or crop water status. Generally, these techniques or protocols are designed for an even irrigation application volume to a specific field area. These field areas are variable based on the farm scale and the particular situations. Most irrigation systems apply water with a predictable non-uniformity based on the irrigation method and usually the applied water depth (volume per unit area). Many other factors related to soils (nutrients, texture, and salinity) and biotic stress factors – disease or pests – or even environmental variables like rainfall or precipitation, air temperature and relative humidity, reference and/or actual crop evapotranspiration (ET) have a spatial non-uniformity. In many cases that results in uneven crop yields even when irrigation is applied efficiently and uniformly and even when scheduled properly. This paper reviews advances in precision irrigation and precise irrigation scheduling. The principle goals of these technologies are to: 1) improve crop yield and quality; 2) reduce percolation or runoff with the adverse environmental impacts from irrigated agriculture (nitrate leaching, sediment transport, and nutrient and agrochemical transport); and 3) mitigate larger scale impacts on regional sustainability and groundwater mining or surface water degradation. These goals must result in greater producer net profit or meeting regulatory goals or irrigation district rules.

PRECISION IRRIGATION

Precision irrigation is often discussed but seldom wholly quantified (Camp et al., 2006). In general, we use the term in the larger precision agriculture (PA) concept (Kitchen et al., 1996; Stafford, 1996; Pierce and Nowak, 1999). In this review we characterize precision irrigation (PI) as some version of site-specific irrigation management (SSI) (Sadler et al., 2005). SSI/PI can have various utility uses: 1) address soil texture differences; 2) address soil or crop development differences; or 3) avoid field areas (rock outcrops, physical obstructions, etc.). SSI/PI uses various engineering solutions to apply water at controlled, variable rates to specific management zones. If the irrigation has multiple purposes (fertigation, chemigation, etc.), these additional management zone layers require further definition. This SSI/PI has been characterized as prescription irrigation. Rawlins (1996) defined precision farming as having the ability to apply inputs precisely when and where they are needed. He further characterized prescription farming as utilizing real-time information regarding the processes that might be limiting production on a spatial scale in the field. He also suggested that variable seeding rates or variable fertility in PA had been successful for nutrients that don't readily leach or transport (phosphorous, potassium, lime, etc.), but he emphasized the need for real-time spatial management for water and nitrogen and biotic crop stress vectors (pest, disease, etc.). However, the "when needed" part of Rawlins' definition has rarely been applied to irrigation management, even in research. Hoffman and Martin (1993) utilized the term prescription irrigation, and they suggested that the design of PI should permit variable irrigation to individual parcels throughout the season. SSI/PI needs to be applied at a spatial agronomic scale appropriately matched to the ability to sense soil or crop data and the engineering constraints of particular application technology. They believed that prescription irrigation should be equally applicable to all irrigation methods even if the irrigation technology cannot apply irrigation in a variable rate. This seems rather academic in that prescription requires an ability to match applications with desired management zone requirements.

Prescription irrigation, or as we prefer SSI/PI, requires the sensing of the crop irrigation need and the ability to apply irrigations at rates applicable to the desired management zone. Implicit for

SSI/PI is the ability to define field management zone layers for the SSI/PI control (soil textural maps, soil fertility maps, soil salinity maps, etc.) and real-time management zone parameters (biotic stresses or water deficits). These will be discussed later in the precise irrigation section.

SSI/PI efforts have largely been focused on pressurized systems, although certain SSI/PI designs might be applied to surface irrigation. Typically, SSI/PI is focused on sprinkler irrigation machines (center pivot or lateral move) or solid-set sprinkler systems. Raine et al. (2007) estimated typical spatial scales for commonly used irrigation systems that varied from 0.1 m^2 to 10,000 m^2. SSI/PI is difficult to economically apply to microirrigation technology (drip emitters, micro-spray, drip tape, etc.). Most current applications use global positioning systems (GPS) and/or geographic information systems (GIS) to develop management zones within the field scale. SSI/PI applications for mechanical sprinkler machines require either individual nozzle/head controls or manifold control of a number of nozzles/heads. The management zone for SSI/PI on these systems will depend on the spatial scale coverage of the manifold and the distance coverage for the system (distance for a lateral-move system or radial path swath for a center pivot). These SSI/PI application zones can vary from ~50 m^2 for a lateral move to ~200 m^2 or more for a center pivot (larger zones are on the outer end). Sadler et al. (2005) reported a possible water savings and profits from near zero to 50% with averages in the range of 20-80%. They were principally addressing only soil texture effects for SSI/PI. A few SSI/PI efforts have involved drip irrigation and derived crop water stress (leaf water potential) and irrigation need from thermal imaging (Cohen et al., 2005; Sela et al., 2007).

Many engineering reports on center-pivot and lateral-move sprinkler systems described the spatial variable applications of water and nitrogen. Evans et al. (2006) provides a complete review of SSI/PI irrigation systems in Montana. Other examples are found in Camp and Sadler (1998); Camp et al. (1998); Evans et al. (1996); Duke et al. (1997); Heermann et al. (1997); King et al. (1996); King et al. (1998); and Sadler et al. (1997). The state of engineering, although somewhat diverse, demonstrates the options available. Most research efforts have focused on providing more relevant information to the irrigation manager, which is counterproductive since managers have limited time to process this information. It is more important to develop automated decision support systems (DSS) that process these data into real-time, automatic control of the irrigation system. Computer control is becoming more common with supervisory control and data acquisition (SCADA) systems or programmable logic controllers (PLC) systems. Most SCADA or PLC systems can be controlled remotely using radio links, wireless technologies, or even cellular phones. Spatial nitrogen sensing is also possible (Kim et al., 2007) to integrate fertility with SSI/PI.

Figure 1 shows a SSI/PI system valve arrangement on a lateral-move sprinkler system.

Precise Irrigation Scheduling

PI or SSI descriptions usually include irrigation scheduling information. Often soil water or crop water status sensors are included. However, precise irrigation scheduling (PIS) is at least as important as the correct spatial water placement, if not more important. Inherently, PIS needs to include aspects that affect the spatial aspects of crop water use for the field scale.

Recent reviews by Kim and Reid (2007) on crop chlorophyll remote sensing for estimating nitrogen deficiencies and by Evett et al. (2009) on crop water stress determination using remote sensing from both spectral and thermal indices indicate the potential of these technologies for PIS. Although remote sensing based on satellite or aircraft platforms has shown promise for irrigation scheduling since the 1970s, the technology has not been utilized mainly due to these factors:

a) turn around times of data processing for useful recommendations at the field level have been too long
b) pixel sizes are too coarse to apply to individual fields, and
c) data collection intervals are too infrequent for useful irrigation control.

Figure 1: PI system from the USDA-ARS, Northern Plains Agricultural Research Laboratory, Sidney, MT in 2005 illustrating the valve arrangement, control wires and pneumatic tubing on the Sidney system for both the spray heads and low-energy, precision application (LEPA) application methods. Source: R.G. Evans, USDA-ARS, Sidney, MT.

Aircraft imagery and satellite imagery allow the determination of spatial variability in crop visible and thermal spectrums useful for irrigation scheduling, but often with temporal and spatial resolutions that are inadequate for day-to-day irrigation management (Jackson, 1984; Moran, 1994; Moran et al., 1994). Current research is investigating the sharpening of coarse resolution thermal images with higher resolution images in the near infrared and visible spectrums that might provide improvements for the spatial resolution problem (Kustas et al., 2004). In conjunction with these efforts, progress has been made on the combination of these procedures to return daily images by combining daily satellite data with the less frequent (weekly or biweekly) imagery from other satellites with greater resolution (Anderson et al., 2007). Most crop water deficiency remote sensing useful for irrigation management requires thermal infrared radiance data, but these data are currently unavailable at an acceptable temporal or spatial resolution and may even be totally unavailable in new satellite platforms under development. The challenges of using remote thermal remote sensing are being addressed by several approaches using sensors that are mounted on moving irrigation systems (Evans and Sadler, 2008: Evett et al., 2006; Sadler et al., 2007) or on masts set in fields (Evett et al., 2000), and with some using aircraft platforms, including unmanned aerial vehicles (UAVs).

Several approaches have been used for irrigation management using remote sensing including:

a) Scheduling irrigation to replace evapotranspiration (ET) estimated from a reference ET (ETo), calculated from local weather data, which is multiplied by a crop coefficient (K_c) estimated with a crop coefficient function, Kc(NDVI), where NDVI is the normalized difference vegetative index (NDVI) or a similar index adjusted for reflectance from soil. The NDVI is based on canopy irradiance in the red and near infrared bands, which can be remotely sensed.
b) Scheduling irrigation with a fixed amount of water whenever a threshold criterion (trigger point) is generated by a crop water stress index (CWSI), which is estimated using remotely sensed crop canopy temperature (Ts) and local weather data.
c) Scheduling irrigation with a fixed amount whenever a threshold criterion is determined by the time-temperature threshold index (TTTI) reaching a crop and region-specific value. The TTTI is calculated using Ts.
d) Scheduling irrigation to replace ET estimated with the field surface energy balance (FSEB), which uses remotely sensed surface temperature, Ts, determined from thermal infrared data, and data on canopy cover and surface emissivity deduced from the near infrared (NIR) and visible bands.
e) Sensing of crop characteristics in order to guide timing, placement and amount of fertilizer and water through irrigation (or fertigation) systems of various orders of precision. The characteristics, including crop cover fraction, nitrogen status of leaves, disease and pest damage, all of which vary spatially and temporally, are inferred from various remotely sensed vegetative indices (VI).

Of the five approaches listed above, only the CWSI and the TTTI have been commercialized and used by irrigators, the latter recently under the name BIOTIC[15] (Upchurch et al., 1996) and the former since the 1980s. Practical use of both measurement procedures has been quite limited.

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[15] The mention of trade names of commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

Multispectral vegetation indices (VIs), such as the NDVI, are derived as ratios of signal strength in particular radiance bands. Multispectral VIs have been widely researched as means to quantify various biophysical aspects of vegetation canopies, such as leaf area index (Moran et al., 1995) and crop cover (Heilman et al., 1982). Remote sensing of VIs provides a means to synoptically and instantaneously determine crop conditions.

An approach that may improve the spatial representation of crop ET estimation is to incorporate remote sensing observations into irrigation scheduling protocols. Bausch and Neale (1987) proposed the utilization of multispectral VIs to estimate corn crop coefficients. Recent research has shown that observations of multispectral VIs can provide real-time surrogates of crop coefficients (K_c) for a variety of crops (Bausch, 1995; Neale et al., 2003; Hunsaker et al., 2005). Remote sensing that infers that the spatial distribution of K_c across the landscape can improve the ability of standard weather-based ET based irrigation scheduling methods to more accurately estimate the spatial crop water use within an irrigated-field (Hunsaker et al., 2007) or at the farm-scale level (Johnson and Scholasch, 2005). Although the VI-based K_c approach has strong practical appeal, this approach is hindered by its reliance on empirical relationships between VIs and K_c and the problems previously discussed on imagery availability and the transferability of K_c calibrations from one region to the next, and by timeliness and cost effectiveness of the necessary imagery (Gowda et al., 2008).

Sensors, especially infrared thermometers (IRTs) or multi-band spectral sensors, mounted on irrigation systems such as center-pivot or lateral-move systems offer an alternative to satellite or airborne platforms. In regions where center-pivot or lateral-move irrigation systems are popular, they appear to be a logical sensor platform for irrigation management since they pass over the field at regular intervals. These sensors can reduce turn-around time for imagery because they do not require extensive processing such as atmospheric or geometric correction. Phene et al. (1985) provided an early example of the deployment of IRTs aboard a mechanical-move irrigation system. However, thermal radiometric sensors are responsive to soil emittance in addition to reflection from vegetative canopy. Less than full canopy cover may cause false positive irrigation threshold triggers in the early growing season and thermal measurements from mixed pixels of sunlit soil and vegetation can provide unduly high temperature readings. Discrimination between thermal radiance from soil and vegetation in low cover or leaf area index situations is a problem still under active investigation, and the solution will probably require an imaginative combination of multi-spectral data, sensor view angles and understanding of canopy and soil characteristics.

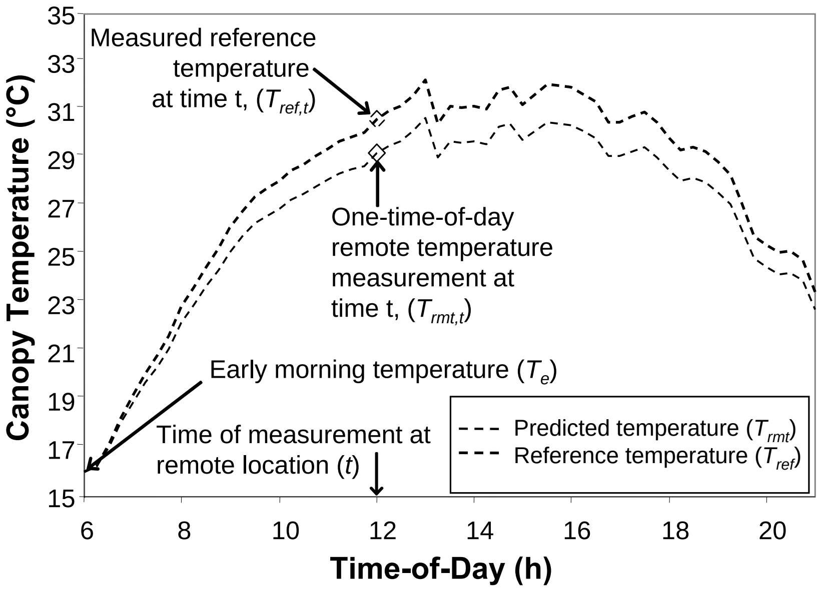

Figure 2: Example diagram of the scaled canopy temperature from one-time-of-day measurements by IRTs. Source: Adopted from Peters and Evett (2004).

Figure 2 illustrates a scaled canopy temperature procedure (Peters and Evett, 2004) to activate an irrigation event based on one-time-of-day measurements with IRTs.

Center-pivot and linear-move irrigation systems generally apply water quite uniformly; however, substantial variations in soil properties and water availability exist across most fields. In these cases, the SSI/PI ability to match spatially and temporally variable conditions can offer attractive opportunities for increased application efficiencies to reduce environmental impacts from leaching or runoff, more effective agrichemical use, and the potential to improve crop yields and quality. Additionally, these systems offer the ability to precisely manage deficit irrigation strategies. The development of in-field sensor-based control of SSI/PI applications of water and water soluble nutrients through the irrigation system offers an effective means to implement PA technologies. However, the seamless integration of sensors, irrigation control, data interface, software design, and communication at costs that are in balance with the profit advantages of site-specific applications is challenging, requiring novel engineering solutions and eventually parameterization standards.

Wireless sensing systems seem to offer the necessary control and versatility required to implement PIS with SSI/PI. Peters and Evett (2008) illustrated the potential to integrate TTTI with a SSI/PI center-pivot irrigation system. Evett et al. (2006) demonstrated the control of microirrigation systems using the TTTI concept with IRTs. Miranda et al. (2003) used a closed-loop irrigation system and determined irrigation amount based on distributed soil water measurements. Shock et al. (1999) used radio transmission for soil moisture data from data loggers to a central computer logging site. Wall and King (2004) explored designs for smart soil moisture sensors and sprinkler valve controllers to implement plug-and-play technology and proposed architectures of distributed sensor networks for site-specific irrigation automation (King et al., 2000). Kim et al. (2008, 2009) used distributed sensor networks and GPS with Bluetooth® wireless communications to control water applications with off-site computers. Software design for automated irrigation control has been studied by Abreu and Pereira (2002). They designed and simulated set sprinkler irrigation systems by using software that allowed the design of a simplified layout of the irrigation system.

The coordination of control with data from sensors is effectively managed using data networks and low-cost microcontrollers (Wall and King, 2004). A hard wired system from in-field sensing station to a base station takes extensive time and cost to install and maintain. It may not be feasible to hardwire the system for long distances, and it may not be acceptable to growers because it can interfere with normal farming operations and the maintenance costs may be unacceptable. A wireless data communication system can provide dynamic mobility and cost-free relocation. Radio frequency technology has been widely adopted in consumer wireless communication products and it provides numerous opportunities to use wireless signal communication in agricultural systems. Industrial wireless standards such as the ZigBee protocol are open standards that allow integration of sensors and equipment from different manufacturers into a SCADA system (O'Shaughnessy and Evett, 2007, 2008). Present challenges include meeting power requirements of remote sensors, radio interference, cost reduction, interfacing with existing irrigation control equipment, and development of rugged and inexpensive but accurate sensors (e.g., reflectance photodiodes and infrared thermometers).

OBJECTIVE FUNCTION

Critically important to SSI/PI with PIS is the definition of the objective function for the added technology and management. In the simplest case, the principle objective of the producer is usually to maximum net profit. Operations research theory has several potential variations that might be adopted depending on the risk the producer is willing to accept. These are to 'minimize' the maximum loss or to 'maximize' the minimum profit. Other objectives include 1) minimize labor costs; 2) maximize reliability; 3) maximize water use efficiency; 4) maximize 'irrigation' water use efficiency; 5) minimize off-site environmental impacts (water quality, etc.); or 6) minimize irrigation water use to avoid groundwater over exploitation or minimize any institutional regulation exceedence and/or sell or lease the remaining water. With SSI/PI the producer has added complex decisions regarding whether to increase productivity on the lower producing zones or to maximize production on the more productive zones. In the future, we expect environmental and institutional restrictions to have a greater dominance, limiting profit in most cases, but emphasizing the value of SSI/PI and PIS for sustainable productivity.

SUMMARY

Precision irrigation offers advanced technology to meet constraints imposed by spatially variable soil and crops. The use of site-specific application technology is feasible engineering wise; however, its acceptance depends strongly on a simple interface using technology with which the producer is already familiar (i.e., wireless communication, cellular telephones, internet, etc.). For precision irrigation to be effective, precise irrigation scheduling based on soil water status or crop water status seems to be a weak link currently, but research is improving the integration of crop water status and evapotranspiration feedback based on spectral and thermal remote sensing. Additionally, spectral sensing offers great potential with the spatial management of nutrients and biotic stresses from pests and diseases. The larger remaining obstacle appears to be in characterizing the objective function of this advanced technology and management so as to benefit the producers and the public.

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THERMAL REMOTE SENSING OF CROP WATER STATUS: PROS AND CONS OF TWO DIFFERENT APPROACHES

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ABSTRACT

Recent climate change has led, in many places around the world, to a decrease in the availability of fresh water resources. This limited water availability decreases the cost-effectiveness of irrigated agricultural crops, and increases the desirability of practices that reduce applied water without decreasing quantity and/or quality of yields. Routine monitoring of crop water status may provide useful information allowing growers to irrigate only when and where needed, thereby conserving water. Continuously growing availability of airborne and spaceborne data has led to development of various methods utilizing thermal remote sensing to detect and monitor water status in agricultural crops. In large, these methods can be divided into two main approaches.

The first approach, used since the 1960s, is based on the understanding that canopy temperature is indicative of crop water status. Generally, canopy temperature is normalized to upper and lower bounds, representing non-transpiring and fully transpiring leaves, respectively, to calculate a crop water stress index (CWSI). The normalization allows comparison between the CWSI under different environmental conditions. This approach is simple to apply and requires relatively few inputs, but necessitates thermal images at high spatial resolution, since the remotely sensed temperature must represent the canopy only, isolated from the surrounding soil. Such high resolution thermal images are not currently routinely available.

The second approach is based on more complex physical models, of which the prime input is thermal images. Numerous models have been developed, which can be further divided into two main categories. The first is based on the "big leaf" theory, according to which the land surface is assumed homogeneous and is treated as a whole. In the second category are the “two-source” models, which relate to the vegetation and the soil separately. The physical models in general,

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and the two-source models particularly, require more inputs than the CWSI approach, but can utilize thermal images at a coarser spatial resolution. Such imagery is regularly available from several satellite systems.

A discussion of the pros and cons of each of the two approaches follows a brief description of their principles and utility.

INTRODUCTION

Recent climate change has led, in many places around the world, to a decrease in the availability of fresh water resources. This limited water availability decreases the cost-effectiveness of irrigated agricultural crops, and increases the desirability of practices that reduce applied water without decreasing quantity and/or quality of yields. Routine monitoring of crop water status may provide useful information allowing growers to irrigate only when and where needed, thereby conserving water. Continuously growing availability of airborne and spaceborne data has led to development of various methods utilizing thermal remote sensing to detect and monitor water status in agricultural crops. In large, these methods can be divided into two main approaches.

The first approach, the "crop water stress index" (CWSI), is based on leaf temperature measurement, which is inversely correlated with transpiration and stomatal opening (Fuchs, 1990). Canopy temperature has been used as an indicator for crop water stress since the 1960s. The CWSI is based on the difference between canopy temperature and a "non water-stress baseline" referring to the temperature of a well watered crop (Jackson et al., 1981; Jackson et al., 1988). Despite robust results with the CWSI approach for arid and semi-arid regions, limitations of its use as a routine tool stem from its high sensitivity to climate factors, and from the need to establish crop-specific non-water-stressed baselines for different agroclimate zones (Jackson et al., 1988). Normalized CWSI uses thermal imagery for canopy temperature measurements combined with visible and near infrared images for exclusion of non-leaf material in temperature estimates. This technique have been demonstrated to successfully measure water stress in cotton (Cohen et al., 2005; Sela et al., 2007) and in grapevines (Möller et al., 2007).

The second approach is based on more complex physical models, of which the prime input is thermal images. The potential integration of remotely sensed data in modeling schemes for mapping ET has long been identified, and a suit of models, mostly based on observations of land surface temperature (LST) and vegetation indices (VIs) have been developed and evaluated over various parts of northern America. These models include, amongst others, the Two Source Model (TSM; Norman et al., 1995a), the Atmosphere-Land EXchange Inverse (ALEXI) model (Anderson et al., 1997; Mecikalski et al., 1999), the disaggregated ALEXI (disALEXI) model (Anderson et al., 2004; Norman et al., 2003), and the Dual Temperature Difference (DTD; Kustas et al., 2001; Norman et al., 2000). Each of these models estimates surface fluxes at different spatial scales (from local/field scale to regional/continental scale), and represents the land-atmosphere system with varying levels of complexity. The core of these energy balance models is the TSM, a two-source land-surface representation, coupling conditions inside the canopy to fluxes from the soil, plants, and atmosphere. The TSM partitions the surface fluxes and composites thermal signature of a heterogeneous scene into soil and canopy contributions, given an estimate of fractional vegetation cover.

The following sections provide a brief description of the principles and utility of the CWSI and the TSM and a discussion of the pros and cons of each of these two approaches.

THE CROP WATER STRESS INDEX (CWSI)

Canopy temperature is indicative of water status in the leaves; however it is influenced by other environmental conditions, mainly radiative flux, air temperature, wind speed, and relative humidity. Therefore, canopy temperature derived from a thermal image must be normalized relative to a reference in order to be applicable to varying conditions. The CWSI is defined by upper- and lower- boundary temperatures, T_{dry} and T_{wet}, representing a non-transpiring leaf and a fully transpiring leaf, respectively (Jones, 1992):

$$\mathrm{CWSI} = \frac{T_{\mathrm{canopy}} - T_{\mathrm{wet}}}{T_{\mathrm{dry}} - T_{\mathrm{wet}}} \qquad \textbf{(1)}$$

with T_{canopy} the canopy temperature. The CWSI ranges from 0 to 1, indicating well-watered and stressed conditions, respectively. T_{dry} and T_{wet} can be derived either empirically or analytically.

CWSI empirical (CSWI$_E$)

In the empirical approach, T_{dry} is set to 5°C greater than air temperature (Irmak *et al.*, 2000) and T_{wet} is determined based on reference measurements of artificial wet cloth (Meron *et al.*, 2003), with a typical size of 30 × 40 cm. Two main drawbacks limit the applicability of the CWSI for high spatiotemporal monitoring of stress. The first is the somewhat arbitrary value of 5°C. While it had indeed been proven to represent the maximum leaf temperature under several conditions (Cohen et al., 2005; Irmak et al., 2000; Möller et al., 2007), the CWSI is quite sensitive to the value assigned to T_{dry}, and a significant uncertainty is introduced to the index's value. The second drawback lies in the need for a wet reference to exist in every analyzed image. This limits the frequency at which data can be acquired, and requires high spatial resolution (to detect a significant number of pixels within the reference, while avoiding mixed pixels), thus limiting the usefulness of the method for routine measurements.

CWSI analytical ($CSWI_A$)

To overcome the drawbacks of the empirical method, analytical expressions have been developed to compute T_{dry} and T_{wet}, based on the canopy energy balance (Jones, 1999):

$$T_{\mathrm{dry}} = T_{\mathrm{air}} + \frac{Rn_{\mathrm{i}} r_{\mathrm{HR}}}{\rho C_{\mathrm{P}}} \quad \textbf{(2)}$$

$$T_{\mathrm{wet}} = T_{\mathrm{air}} - \frac{r_{\mathrm{RH}} r_{\mathrm{V}} \gamma}{\rho C_{\mathrm{P}} \left(\Delta r_{\mathrm{HR}} + \gamma r_{\mathrm{V}} \right)} Rn_{\mathrm{i}} + \frac{r_{\mathrm{HR}}}{\Delta r_{\mathrm{HR}} + \gamma r_{\mathrm{V}}} VPD \quad \textbf{(3)}$$

in which T_{air} is air temperature; *Rn* is net-radiation; r_{HR} is a combined resistance to sensible heat transport; r_{V} is aerodynamic resistance to latent heat transport; ρ is dry air density; C_P is the specific heat of dry air at constant pressure; VPD – vapor pressure deficit; Δ is the slope of saturated water vapor pressure versus temperature curve; and γ is psychrometric constant.

Utilization of the analytical approach requires measurement of incoming solar radiation, air temperature, relative humidity, and wind speed. These measurements are available from any meteorological station, and can be representative for an entire field or orchard. Note that there is some uncertainty in the estimation of the resistances, which induces a level of uncertainty to this approach as well.

THE TWO-SOURCE MODEL (TSM)

The Two-Source Model (TSM) of Norman et al. (1995b) is a land-surface parameterization of the radiative and turbulent energy exchanges between the soil, vegetation and lower atmosphere in which radiometric land-surface temperature, derived from remote sensing images collected in the thermal waveband, serves as the key boundary condition. The TSM formulation is based on a two-source energy balance equation:

$$Rn_C + Rn_S + G + H_C + H_S + \lambda E_C + \lambda E_S = 0 \quad \textbf{(4)}$$

where the subscripts ‘c’ and ‘s’ denote the canopy and soil components, respectively; Rn is net-radiation; *G* is soil heat flux; and *H* and *λE* are sensible and latent heat fluxes, respectively. This modeling framework follows earlier development of two-source schemes based on the Penman-Monteith big leaf model (Monteith, 1981) to deal with sparse canopy cover conditions (Shuttleworth and Gurney, 1990; Shuttleworth and Wallace, 1985). Given an estimate of fractional vegetation cover, the TSM partitions the observed surface temperature into soil and canopy contributions (illustrated in Figure 1):

$$T_{RAD}(\theta) = \left(f(\theta) T_C^4 + \left(1 - f(\theta)\right) T_S^4 \right)^{1/4} \quad \textbf{(5)}$$

in which $T_{RAD}(\theta)$ is the surface radiometric temperature at look angle θ, $f(\theta)$ is fractional vegetation cover seen by the sensor, and T_C and T_S are the derived canopy and soil temperatures. The component (soil and vegetation) sensible heat fluxes (H_S and H_C) are then computed along the gradients in temperature, regulated by transport resistances (see Figure 1). Extinction of net radiation within the canopy (Rn_C) is approximated with an analytical formalism described by Campbell and Norman (1998) based primarily on leaf absorptivity and leaf area index (LAI), while G is parameterized as a fraction (0.31) of the net radiation above the soil surface (Rn_S), following Choudhury et al. (1994). The canopy transpiration component of the latent heat flux (λE_c) is approximated using the Priestley-Taylor (PT) approach:

$$\lambda E_c = \alpha_c \frac{\Delta}{\Delta + \gamma} Rn_c \quad \textbf{(6)}$$

in which α_c is the PT parameter applied to the canopy (see below for more details), Δ is the slope of saturation vapor pressure vs. temperature, and γ is the psychrometric constant. Finally, the soil evaporation term is computed as the residual of the overall energy balance equation (Eq.**Error! Reference source not found.**).

The two-source representation is a major improvement over previous single-layer thermal models, which required site-specific adjustments to compensate for differences in aerodynamic coupling between the soil, canopy, and atmosphere (Hall et al., 1992; Kubota and Sugita, 1994; Kustas et al., 1989; Stewart et al., 1994).

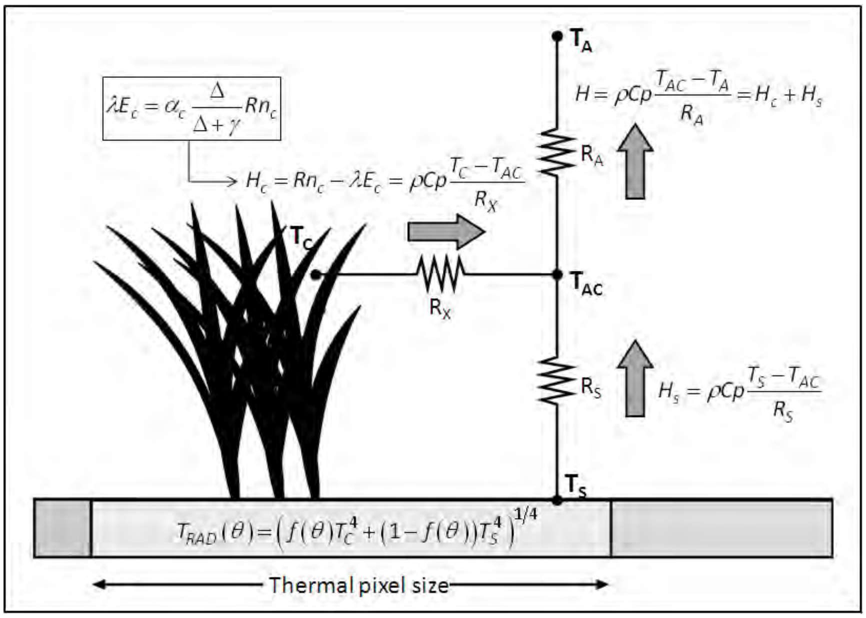

Figure 1: Schematic diagram representing the TSM resistance formulation used in computing sensible heat flux. The model computes fluxes of sensible heat (H) from the soil and canopy (subscripts s and c) along gradients in temperature (T), derived from the directional surface radiometric temperature (T_{RAD}(θ)), at look angle θ, given vegetation cover f(θ)). **The fluxes are regulated by transport resistances R_A (aerodynamic), R_X (bulk leaf boundary layer), and R_S (soil surface boundary layer). Canopy transpiration (λE_C) is computed by the PT approach (Eq. 3), and by residual, $H_C=Rn_C- \lambda E_C$, which is used to obtain initial estimates of component temperatures (T_C and T_S), heat fluxes (H_C and H_S) and the temperature in the canopy air space (T_{AC}). The value of λE_S is solved by residual in the energy balance for the soil (see Eq.(4).**

Table 1. A summary of the requirements and outputs of each of the Crop Water Stress Index (CWSI) and the Two-Source Model (TSM) approaches to assessing canopy water status.

	CWSI	TSM
Required inputs	• *Canopy temperature* – i.e., *high* spatial resolution thermal imagery that enables separation of canopy and soil pixels • Meteorological data (incoming solar radiation, air temperature, relative humidity, wind speed)	• *Surface temperature* – i.e., *any* spatial resolution thermal imagery (the model separates the two component temperatures) • Meteorological data (incoming solar radiation, air temperature, relative humidity, wind speed) • NDVI (to estimate fraction vegetation cover) • Land use maps (canopy height and type for estimating parameters of radiation transfer and momentum resistances) • Soil characteristics (mainly soil albedo and emissivity)
Processing	Non-iterative computation Requires *less* resources	Iterative model Requires *more* computation resources
Output	Estimation of plant water status on *a relative scale* (0-1) compared to non- and fully- transpiring leaves	*Quantitative maps* of the energy-balance components Crop water status map

COMPARISON BETWEEN THE CWSI AND THE TSM

The CWSI and the TSM were developed with different objectives. The CWSI is very specific and focuses on deriving a relative index indicating crop water status by applying few inputs in a relatively simple processing procedure. The TSM, in contrast, was developed as a full energy balance model requiring more inputs and having a more intensive processing procedure. As such, the TSM provides quantitative information of the entire energy balance, including the transpiration flux which can be related to plant water status. Table 1 summarizes the requirements and outputs of each of these two approaches.

While the CWSI requires less inputs compared to the TSM, the thermal imagery used to compute CWSI must be at a very high spatial resolution (a few centimeters at the most) in order to allow non-mixed pixels, representing either canopy or soil. In the process of computing the CWSI, only the canopy pixels are used. To date, such high spatial resolution imagery is achievable only by *in-situ* or airborne acquisition, and are, thus, either expensive or limited in spatial/temporal distribution. Therefore, mapping large areas with the CWSI technique is currently impractical. On the other hand, the extra inputs needed to run the TSM (namely, NDVI, land use, and soil characteristics) are mostly readily available, and the thermal imagery can be much coarser (up to 100 m for agricultural purposes and 1000 m for regional mapping).

Being less intensive in computation time, the CWSI may have a small advantage over the TSM. However, the ever improving technology and computer power makes this consideration increasingly less critical.

Lastly, perhaps the most significant difference between the CWSI and the TSM is their output. While the CWSI only provides a relative estimate of a crop's water status, the TSM produces quantitative maps of the energy balance, and especially of actual evapotranspiration. If necessary, a relative map representing plant water status may be derived from the evapotranspiration map, similar to the CWSI.

CONCLUSIONS

Both the CWSI and the TSM provide important information regarding crop water status. The simplicity of the CWSI makes it appealing and easy to use, provided high spatial resolution thermal imagery is available. The TSM, although more complex, has the advantage of utilizing available satellite imagery and yielding quantitative flux estimates. The choice of method should be made according to the available data and the required output.

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HIGH RESOLUTION MONITORING OF ROOT ZONE AND VADOSE ZONE PROCESSES

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ABSTRACT

Advanced agricultural irrigation practices require precise application of water and nutrients to the plants to maximize efficiency and minimize losses. This approach led to the development of drip and mini sprinkler irrigation techniques, as well as fertigation practices. Traditionally, the root zone and the vadose zone were treated as pseudo homogeneous domains. However, these modern practices clearly create and require more detailed spatial treatment. We present here two different applications of geophysical tools for monitoring water distribution in the root zone and the vadose zone. Both make use of electrical resistivity tomography and supporting tools. The first aims at mapping the root zone of a single plant for water content at relatively high resolution, for a detailed understanding of water content dynamics, flow patterns, and root water uptake and its dependence on environmental conditions. The second aims at mapping the water regime and flow patterns under drip irrigated orchards.

Preliminary results for the single root investigation clearly indicate that different environmental conditions create significantly different plant behaviour that is expressed, among other indices, in different uptake rates and therefore different water distribution schemes. The outcome is that for modern irrigation techniques, simplistic assumptions regarding root distribution and root uptake are insufficient. For the vadose zone monitoring, results show significant heterogeneity in water flow patterns, which is season dependent. By spatially monitoring water content distribution throughout the year we identify water that is not used by the plant and therefore leads to lower irrigation and fertigation efficiency.

INTRODUCTION

It is long understood that the subsurface is far from being homogeneous at any scale and that this heterogeneity affects all the physical, chemical, and biological processes that occur in it. For example, *Wierenga* et al. (1989) and *Hills* et al. (1991) studied the heterogeneity using tracer tests and intensive coring in a heavily instrumented 4 by 9 m trench in New Mexico. They found that the hydraulic conductivity varied in over 3 orders of magnitude in that space. *Kung* (1993) and *Ju and Kung* (1997) described and demonstrated in laboratory conditions a mechanism of funnels created by soil layers and abrupt changes in texture that can trigger preferential flow. *Wallach and Jortzick* (2008) described the fingering created by repellent soil. Heterogeneity is not limited to a physical process. *Trapeznikov* et al. (2003) as well as *George* et al. (1997) and *Hodge* (2004) studied the effect of heterogeneous nutrient availability on root morphology and found that roots at nutrient-rich regions were shorter and shallower than those in nutrient-poor regions. *Kleb and Wilson* (1997) studied the effect of soil heterogeneity, created by forest, on the invasion of grass species. *Zhou* et al. (2002) studied the spatial distribution of microbes in soil and found that it is correlated with the availability of resources. Similar conclusions regarding the role of physical, chemical, and biological heterogeneity were obtained by many others.

Prediction of flow and transport phenomena requires understanding of the subsurface heterogeneity (e.g. *Kowalsky* et al., 2004). However, the effort required in mapping the heterogeneity, and its invasive and destructive nature, caused the adaptation of one of two general solutions: homogenization, or stochastic treatment. Homogenization means that the heterogeneity is ignored and the treatment is as an equivalent domain, typically requiring induced testing (e.g. a simple pumping test). A stochastic approach means that the subsurface properties are taken into account in details, but without specifically assigning specific values at accurate locations (e.g. *Russo*, 1991; *Russo* et al., 1994). The result in both cases is that the solution to a process modeling effort will be "averaged". That is, the model result will not necessarily be accurate at a point (or in specific time). A more detailed discussion of deterministic and stochastic approaches can be found in *Gee* et al. (1991). While for general investigations and studies these approached may be sufficient, clearly they are not for addressing site specific problems. Furthermore, in many cases subsurface parameters are "forced", based on available data from nearby regions (for example, *Russo* et al., 2006 adopted statistical variation of soil properties from a site (*Russo and Bouton*, 1992) about 25 km away; this is far from being an exception). Clearly stochastic and homogenization approaches, while both are important, do not provide a comprehensive solution to the need to understand subsurface heterogeneity.

An alternative may be found in the use of geophysical instrumentation to visualize the subsurface. The advantages of geophysical methods are mostly clear and include their non-invasive and non-destructive nature, and their relatively low cost (systems are relatively expensive, but typically can be used at many locations). The limitations of geophysical methods are primarily associated with the ill-posed nature of the geophysical inverse problem, and the weak relations that sometimes exist between the geophysical signature and the agronomic/hydrologic signal of interest. Geophysical methods penetrated the field of environmental research in the last few decades primarily due to significant modernization of the equipment and developments in the mathematical aspects of the inverse problem. Examples of applications of geophysics in environmental studies are already numerous, and include e.g. *Singha and Gorelick* (2005) for tracer tests in groundwater using electrical resistivity tomography, *Binley* et al. (1996) for flow pathways in unsaturated soil, *French and Binley* (2004) for snowmelt infiltration, *Michot* et al. (2003) for infiltration in corn field, and many more. A comprehensive review of the use of geophysics in soil science is given by *Samouelian* et al. (2005). The purpose of this paper is to demonstrate several applications of geophysical instrumentation, and specifically electrical resistivity tomography (ERT) to the study of the root zone and the vadose zone.

METHODS

We follow here with examples from three different sites, each with a slightly different objective. In the first site the vadose zone beneath an orchard is monitored to several meters. In the second site the root zone of a tree is under the spotlight, and in the third the root system of a single bell-pepper plant is investigated. In all three cases ERT (SYSCAL PRO96 by Iris Instruments, France) was used.

Vadose Zone Beneath an Orchard

Two ERT lines were placed in a grapefruit orchard near Nir Galim, Israel. The soil type at the site is sandy clay to about 5 m depth, and sand/sandstone below it. The orchard is irrigated during the spring, summer and fall by drippers along the tree rows. Annual rainfall at this region is about 480 mm and occurs only during the winter. We focus here on the line that runs perpendicular to the tree rows. A total of 96 electrodes were placed about 20 cm below the soil surface (to prevent mechanical damage), at 0.5 m intervals. ERT surveys, composed of about 2,300 individual measurements (mixture of array types) were taken at irregular temporal intervals, about every 2 months. Interpretation of the results was performed using RES2DINV (Geotomo, Inc.). Conversion of inverted resistivity to water content was performed using Archie's law (*Archie*, 1942) calibrated using laboratory experiments, field measurements, and comparison to a FlexTDR system (*Rimon* et al., 2007) that was installed at the site.

Tree Root Zone

A single ERT survey was performed at an orange orchard near Safaria, Israel. This mature orchard is irrigated with reclaimed wastewater by mini-sprinklers. The annual rainfall at this site is around 500 mm. A total of 60 electrodes were placed along the tree row at 15 cm intervals. A survey composed of over 7,000 measurements (double dipole and Schlumberger) was taken. ERT inversion was performed using RES2DINV (Geotomo, Inc.). No conversion of the data to water content was performed.

Bell-Pepper Root System

Bell peppers were planted in cylindrical chambers of 44 cm in diameter, 55 cm height filled with coarse sand. Three different irrigation schemes were used, where all plants received the same daily amount of water and nutrients by drippers starting at 8:00 AM: 2 l/h in a single pulse; 0.25

l/h in a single pulse; and 2 l/h in 8 pulses. Six chambers were equipped with 96 ERT electrodes in 6 rings at different depths and 12 electrodes at the soil surface. ERT surveys were performed weekly for the 8 weeks of the experiment, and continuously for 24 hours towards the end of the experiment. Six other chambers were equipped with 5 TDR electrodes each, at different depths, measured (with some breaks) every 15 minutes. Three of these chambers were placed on digital scales, where the bulk weight and the drainage weight are recorded at high resolution. In addition, 36 chambers of similar shape made of geo-textile were used for destructive mapping of the root system and its development (3 sacks of each treatment every two weeks).

RESULTS AND DISCUSSION

All three examples shown in this paper are ongoing research projects at various stages of progress. We present here partial results from the three cases under discussion.

Vadose Zone Beneath an Orchard

We present (Figure 1) a single cross section obtained in September 2008. For clarity we added a sketch of the location of the trees. One can clearly note the different wetting patterns below the tree trunks (and the irrigation lines), and the space between the tree rows. The region beneath the trees is characterized by higher water content to a depth of roughly 2 m, while the space between the rows is characterized by lower water content, but plumes stretch to depths of about 5 m (the plumes stretch further down, but this is difficult to see because the soil type changes to sand/sandstone, meaning lower water contents). It is important to note that the patterns are repeated for many tree lines, indicating high reliability for the results.

As noted above, ERT measurements were repeated throughout the year (not shown here). The first measurement, performed in mid March 2008 (see Figure 2), showed a more uniform wetting pattern, while all later measurements looked similar to Figure 1. It can be seen that most of the wetting pockets, shallow (below trees) and deeper (between tree rows), are almost washed out. The water content below trees is clearly lower than observed only two weeks later, after the beginning of irrigation.

We believe that the March image indicates the effect of the rainfall that is more uniform spatially (and occurs at time of minimal root uptake). The increased root uptake that occurs in the spring, combined with the beginning of irrigation, creates the spatial patterns that are characteristic for all later images, evidenced as early as the beginning of April (time span of 2 weeks only). This is yet to be verified (the first significant rain of winter 2008-9 occurred only in mid February 2009).

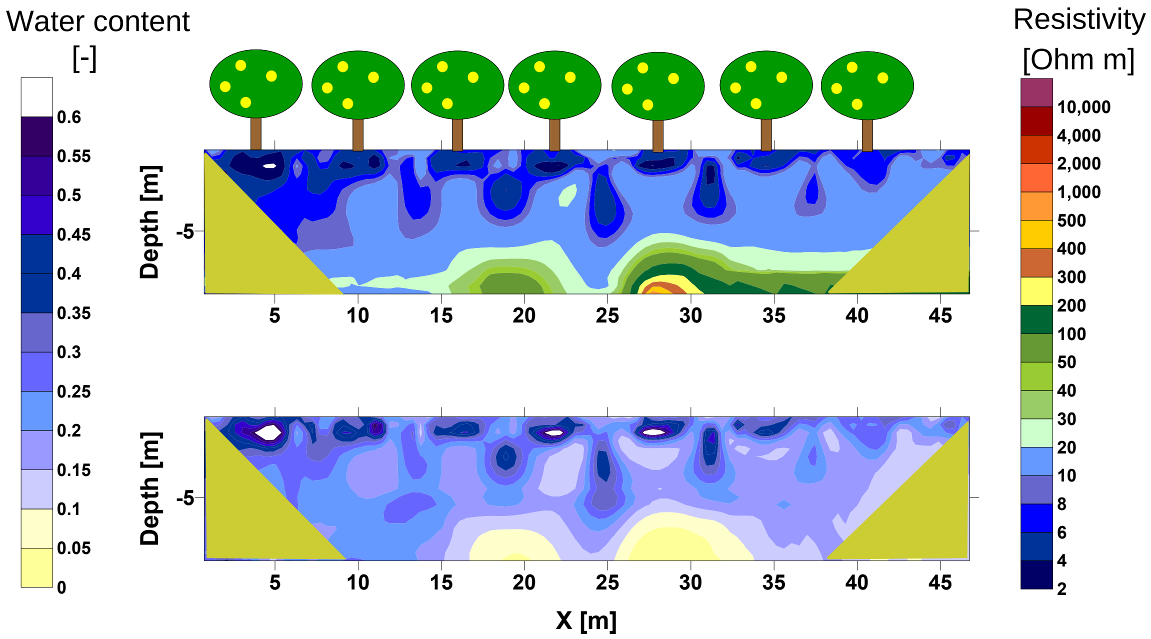

Figure 1: Resistivity (top) and water content (bottom) cross sections (perpendicular to tree rows) from Nir Galim, obtained in September 2008. Trees were sketched for clarity at their approximate locations.

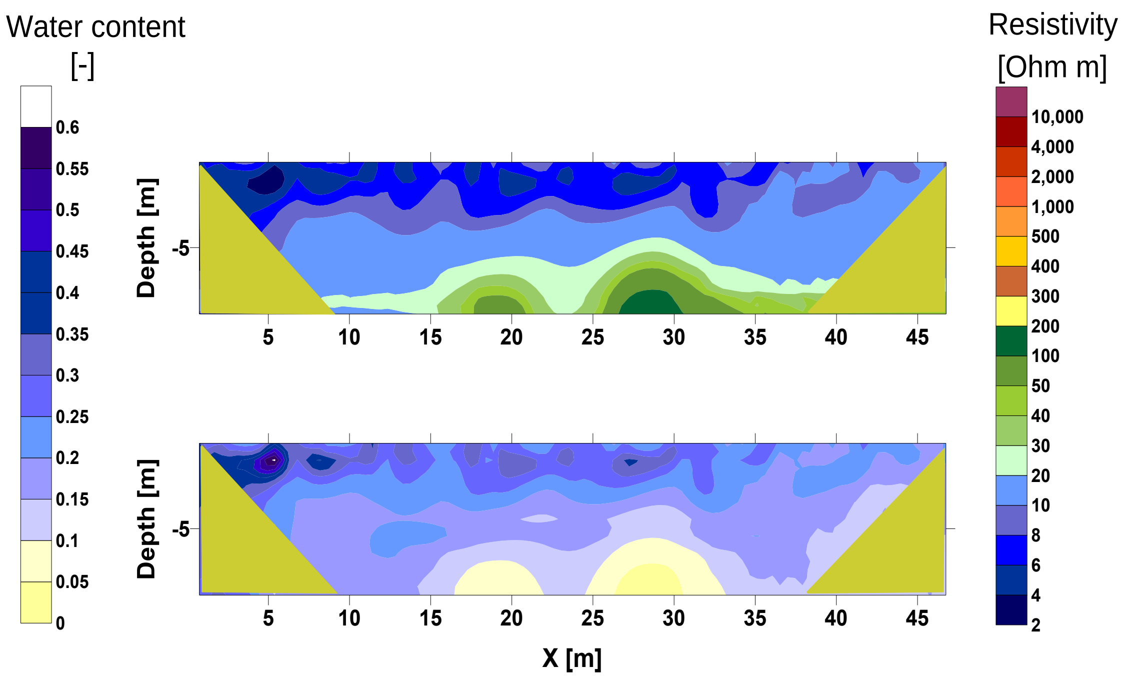

Figure 2: resistivity (top) and water content (bottom) cross sections (perpendicular to tree rows) from Nir Galim, obtained in mid-March 2008.

As suggested above, the profiles are practically stagnant during the summer and fall. This does not indicate that no percolation exists but that the percolation rate is constant. In other words, pseudo steady state flow conditions occur during the irrigation seasons. The consequence is that water flows, primarily between the trees, towards groundwater.

Tree Root Zone

The purpose of this ERT survey was to examine the possibility to use ERT for high resolution mapping of water content. The cross section (Figure 3) stretches along the tree row over three trees, where the tree trunks are located roughly at x = 0, 4, and 8 m. The image presents soil bulk resistivity, where resistive regions generally indicate dry soil, and conductive regions indicate wet zones (assuming no extreme salinity at the site). A wet layer at about 1 m depth can be clearly seen. The region above it is indicated by very high heterogeneity in water content, presumably related to heterogeneity in properties, some effect of major roots, the outcome of surface repellency (*Wallach and Jortzick*, 2008), and non uniformity of the irrigation. We believe that the reddish surface zones at roughly x = 3 and x = 7 m indicate either a section that was not irrigated due to trunk shadow, or not wetted due to repellence.

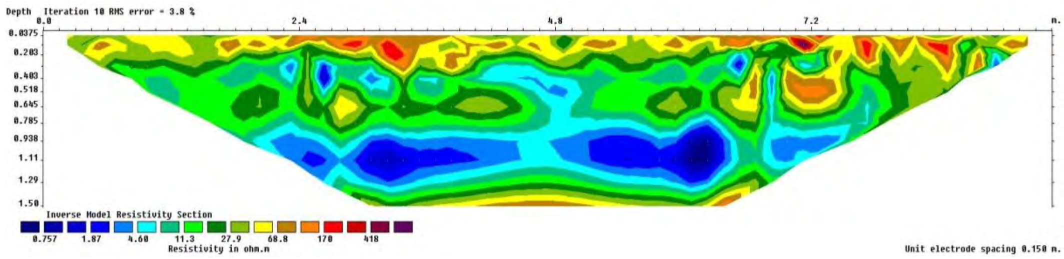

Figure 3: Electrical resistivity profile along tree row from Safaria.

Bell-Pepper Root System

We present here several indicators for water content distribution in the root zone of bell peppers. Reliable ERT images are not available at this time. First, we look at the TDR water content at 5 different depths (Figure 4). The TDR probes are placed horizontally pointing towards the chamber center. The probes are 15 cm long (net) and, including the probe head, almost reach the center (total radius is 22 cm), and therefore indicate a radial averaging of the water content.

The impact of the different irrigation schemes is clearly seen close to the irrigation time (starting at 8:00 AM in each case). The wetness increase for the 2 l/h pulse is very sharp and increases the water content at the 5 cm level by about 5% almost instantaneously. Similar impact is seen also at 15 cm depth, and a more restrained signal at deeper probes. For the lower discharge schemes (both the 0.25 l/h and the pulses) the increase in water content is of the same order for the shallow probe, but it lasts much longer. The increase in water content for the deeper probes is seen at all depths other than the 45 cm probes.

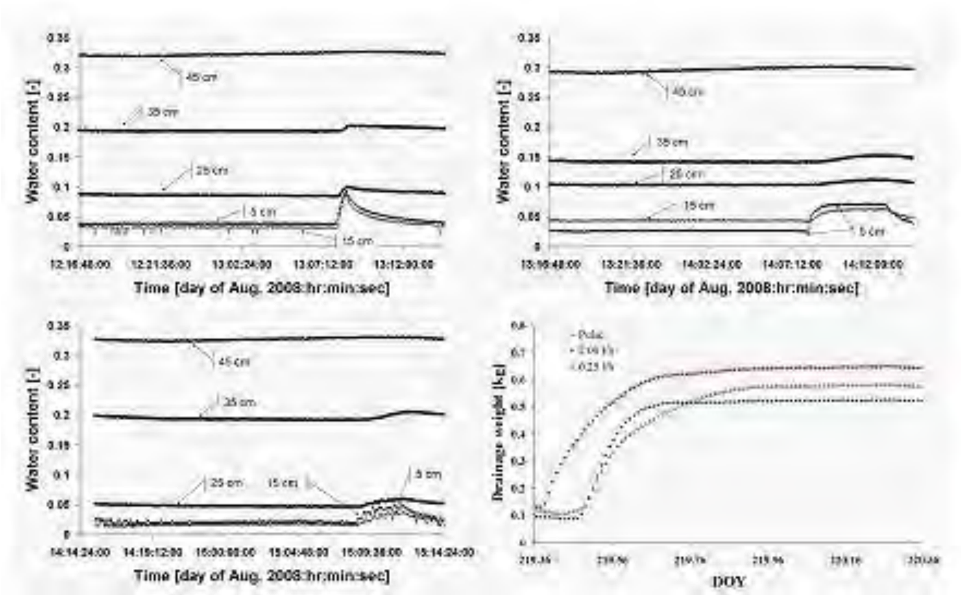

Figure 4: Water content variations for single 2 l/h pulse (top-left), single 0.25 l/h pulse (top-right), 8 2 l/h pulses (bottom-left), and corresponding drainage (bottom-right)

Drainage from the 2 l/h chamber starts almost instantaneously with the irrigation, while drainage from the other two chambers is delayed by over an hour. The total drainage for the 2 l/h chamber is higher by about 20% than that of the 0.25 l/h (and about 10% of that for the pulses). Note however that while the drainage from the 2 l/h was consistently higher, the other two schemes generally exhibited more similar behaviour.

SUMMARY

We have seen through three examples the importance of considering heterogeneity in investigation of the root zone and the vadose zone. Three levels of heterogeneity were presented. First, we considered heterogeneity in boundary conditions and in root uptake at coarse resolution (about 1 m). Our evidence suggests that large volume of water exists at the region between the tree rows. This water can be the result of surplus irrigation combined with lateral flow, and can be the remains of winter rainfall that did not percolate downwards. Regardless of the source, these waters can be considered waste of valuable resources in semi-arid regions, or a threat to groundwater.

The second level of heterogeneity was that observed in higher resolution within the root zone of a plant. Regardless of the question of the trigger for this heterogeneity (soil, induced repellence, etc.), it is clear that the ability to identify this heterogeneity at a per-site basis may allow proper planning of irrigation systems and their operation. It is also clear that geophysical methods, with limitation of depth, can infer this level of heterogeneity.

The last level is related to timing of boundary conditions. Here also it is clear that the timing of the application of boundary conditions led to very different environmental conditions within the root zone, leading to significant difference in the system behaviour/response.

Altogether, we have demonstrated the effect of heterogeneity at various scales and levels on agricultural and hydrological processes. We have also shown that geophysical methods, and specifically ERT, are decent tools for inferring this heterogeneity. This opens the way for site specific deterministic level of system modeling that takes into account the system's heterogeneity.

ACKNOWLEDGMENTS

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Symposium Summary

The summary below refers to the most important issues, findings, conclusions and subjects worthy of follow up, which were raised in the various presentations. These are grouped according to the nine sessions and the most import messages are italicized and underlined. This is done to allow scientists and technologists from the many disciplines concerned with "Crop and Food Production in a World of Global Changes, Environmental Problems, and Water Scarcity" to easily identify high priority topics that should be dealt with in the future in order to ensure the safety and security of food and crop production.

GLOBAL CLIMATE CHANGE - WATER ISSUES, AGRICULTURE AND GLOBAL CHALLENGES (SESSIONS 1 AND 2)

Presenters in the first two sessions addressed general, global aspects of climate change and their relations to water problems and agricultural production. A very clear understanding that emerged from these presentations was that *worldwide food production will have to double by the year 2050*. This increase must –by all means– be sustainable (i.e., environmentally friendly, resource conserving, oriented to societal needs). At the same time *more water shortage problems are foreseen in many regions, accompanied by additional constraints such as increasing temperatures; precipitation variability; intensification of extreme events (droughts, storms)* and many more unforeseen problems like emerging infectious diseases. *Changes in environmental conditions such as air or soil temperatures, humidity, soil moisture, salinity and nutrient loads are also likely to affect soil-water-plant inter-relations and thus affect food production on one hand while on the other increasing emissions of undesired constituents into the troposphere and atmosphere.*

Predictions attained by complex meteorological models, presented by **Pinhas Alpert** ("Moisture Budget over the Eastern Mediterranean Based on a Super-High Resolution Global Model") suggest that a drier scenario is inevitable at the end of this century for the water body area and most of the coastline countries. Consequently, *a water crisis is an inevitable challenge for the drier countries of the eastern Mediterranean and part of the Middle East region in the near future.* This implies that *both better prediction tools and models with higher resolutions are required, particularly for the eastern Mediterranean region*. Considering water shortage problems already being faced in these regions, the situation predicted for the following years will find scientists, technologists and specialists all the more challenged to provide sustainable solutions for food production and conservation of resources (water, soil).

Using two different Global Climate Models (GCM's), in conjunction with a recently developed hydrosalinity model, for a 1,400 km^2 irrigated area in the San Joaquin valley, **Jan Hopmans** and co-workers indicate that climate change in the western USA is predicted to produce significant changes in temperature, precipitation and their spatial/temporal distributions. These changes will have profound affects on California's water resources and on both natural and agricultural ecosystems. The *greatest threat to agricultural sustainability in California appears to be the continued salinization of downslope areas, jeopardizing crop production and requiring future land retirement.* Technological adaptations, such as *increasing irrigation efficiency, may mitigate these effects*. Their analysis does not only apply to California, but can *be extended to other irrigated regions in the world, as many have similar constraints regarding water supply and land degradation*.

An economic analysis of climate-change impacts on agricultural profitability and land use in Israel was presented by **Mordechai Shechter** (**Kan Iddo** et al). Model results indicate a reduction of about 20% in statewide annual agricultural net-revenues by the year 2100 in comparison to those of 2002. Land allocated to field crops is expected to increase at the expense of forages and vegetables, whereas the shares of field crops and forages in the agricultural irrigation-water allotment are predicted to increase while those of vegetables decline. An advanced model is being developed by the presenters, which, among other improvements *will apply a multi-regional analysis where inter-regional water transfers are considered endogenous*. Such a model may constitute an *efficient tool for analyzing the impact of changes in various exogenous parameters on the agricultural sector in terms of agricultural water and land uses.* It will *be able to simulate optimal managements scenarios with respect to climate conditions, agricultural terms of trade, water economy policies,* etc. The results, or the model itself, may be incorporated into an integrated assessment model to provide a better understanding of the mutual relationships between agriculture and other factors in the economy.

According to **Arnon Karnieli, Nurit Agam** and co-workers, a large number of water- and climate-related applications, such as drought monitoring, are based on spaceborne-derived relationships between land surface temperature (LST) and the Normalized Difference Vegetation Index (NDVI). The majority of these applications rely on the existence of a negative slope between the two variables found from site- and time-specific studies. The authors discussed the *importance of using such tools and stressed the need to use the LST - NDVI relationship with caution and restrict its applications as a drought index to areas and periods where negative correlations are observed, since these relationships change during the growing season and whenever water or energy are limiting factors.*

Nicole Wrage in her presentation "Using Diversity in Times of Global Changes - Productivity, Nutrients and Water Use" suggests that *plant diversity can be used to improve productivity, resilience and sustainability of grasslands*. Co-existing plant species can preferentially use distinct nutrient pools. *Different species root in different depths leading to a better use of available nutrients and water*. This may also increase the resilience to climatic changes, since an increased use of nutrients may reduce losses of nitrogenous species such as nitrous oxide (N_2O). *There is evidence for an uptake and further reduction of N_2O from the atmosphere into the soil, so that soils may even act as a sink for N_2O. The influencing factors for this net N_2O consumption are not yet fully understood , but lower soil N content due to increased plant uptake may stimulate the soil's sink strength for N_2O.*

Sharon Avrahami presented a study where the response of nitrous oxide (N_2O) emission rates and β-Proteobacterial ammonia-oxidizing (AOB) communities to changes of temperature, soil moisture and nitrogenous fertilizer concentration were investigated. Path analysis revealed that at high concentrations of fertilizer treatment, the major path by which ammonia influenced the rate of N_2O formation was indirect, through an influence on the abundance of one particular phylogenetic group (AOB "cluster 10"). In contrast, at low and moderate fertilizer treatment concentrations, soil moisture influenced the rate of N_2O formation both directly (the major path) and indirectly through AOB community structure. The study thus demonstrates *the potential effect that change in environmental factors may have via AOB community shifts on N_2O emission rate variability. The ecological consequences of such findings are that community shifts may play an important role in N-transformations and gaseous losses under changing environmental conditions*. Furthermore, *community structure may play a role in determining important feedbacks related to global change.*

AGRICULTURAL PRODUCTION AND ENVIRONMENTAL CONCERNS (SESSION 3)

Ramesh S. Kanwar addressed water quality concerns related to the highly intensive agricultural and animal production systems in the USA having negative impacts on surface and groundwater quality. This interest and concern triggered intensive tillage and nutrient management studies at Iowa State University (1990 to 2007) to develop best agricultural practices (cropping, tillage and nutrient management systems) and to reduce nitrate and phosphorus transport leaching to surface and groundwater systems. Some of the best agricultural practices developed have the potential to significantly reduce NO_3-N concentrations in shallow groundwater and surface water systems in Iowa and other simlar regions in the world (e.g., non-traditional cropping systems of strip cropping and alfalfa rotation with corn, soybean and oats; corn-soybean production system with no-till and chisel plow systems). *Agricultural practices developed in Iowa studies can be adopted* *by farmers to reduce hypoxia problems in the Gulf of Mexico with appropriate combination of tillage, crop rotation, and rate and method of N-application*.

Luc Maene, director general, International Fertilizer Industry Association (IFA), stressed that the big challenge for agriculture is to adapt to the changing climate and shift production practices to reduce and mitigate the effects of climate and other environmental changes, while meeting the food, feed, fiber and energy demands of the growing population. The following Good Management Practices (GMP's) were emphasized: i. Maximizing on-farm recycling of nutrients; ii. Matching fertilizer applications to crop needs; iii. Planting varieties that absorb nutrients efficiently; iv. Creating physical or vegetative barriers to prevent the movement of nutrients out of the field; and v. Applying *efficient plant nutrient products at the right place and time and in the right amounts.* The complexity of defining GMP's involves answering the question: *Best for what target? For maximizing and stabilizing yields, reducing greenhouse gas emissions, limiting nutrient leaching, enhancing nutrition balance and quality of food products,* or something else? *Ideally, enhanced practices should accomplish all of the above mentioned targets. In reality, there are trade-offs between several goals.* The *challenge is, therefore, to determine top priorities and achieve the greatest net and sustainable benefit possible*.

CARBON SEQUESTRATION AND SOIL PRODUCTIVITY (SESSION 4)

Research conducted by The USDA Agricultural Research Service's Southeast Watershed Research Laboratory and reported by **Tim Strickland** has demonstrated the many benefits of conservation tillage and cover crops (including reduced runoff and increased infiltration, decreased soil erosion and reduction of soil carbon loss) at the small plot, farm, and watershed scales. *Of special significance are the efforts to move from plot oriented work to examinations of larger scales* (farm and watershed). Preliminary assessments at the larger scales indicate higher yields and a reduction in crop canopy temperatures in areas that have maximized winter cover crop returns and minimized tillage. Data suggest that many of the conservation tillage benefits observed at the small plot scale are manifested at the landscape level as well. As a direct result, ongoing research efforts have been dedicated to the development of remote sensing tools to map levels of winter cover biomass, associated patterns in soil moisture and plant heat stress. *Development of maps based on remote sensing tools offers the option to streamline spatial irrigation, nutrient and pesticide application strategies*.

In a presentation dealing with the "Relationships Between Soil Carbon Sequestration and Climate Change and Elevated Atmospheric CO_2," **Renduo Zhang** (see Session 7) demonstrated that the concentration of soil organic carbon (SOC) was found to be negatively correlated with the annual average temperature and positively correlated with the elevated CO_2 for the vegetation covers and with precipitation changes for soybean and corn. *Such relationships offer a tool for defining a "cutoff surface" for each of the vegetation covers, which quantifies conditions for soil carbon sequestration or release under climate change and elevated CO_2*.

Eyal Rotenberg and **Dan Yakir** presented a quantitative examination of pine forest functioning in semi-arid conditions based on measurements of carbon, water and energy fluxes in a 40-year-old Aleppo Pine forest in southern Israel. The main conclusion of this analysis was that *afforestation activities in the semi-arid region have the potential to capture a relatively large amount of carbon and play a significant role in mitigating the CO_2 effect on climate*, because semi-arid regions cover almost 20% of the land surface. The presenters suggested that *the results may become increasingly relevant also to currently wetter regions, due to observed and predicted drying trends*.

Biochar, produced by pyrolysis of biomass in the absence of oxygen, was presented by **Ellen Graber** as a product that can be used as carbon sink, soil ameliorant and energy source. Biochar produces 3-9 times more energy than is invested, and is carbon-negative (withdraws CO_2 from the atmosphere). Modest *additions of Biochar to soil have been found to reduce NO_x emissions* by up to 80% and *to completely suppress methane emissions*, thus directly reducing agricultural greenhouse gas emissions. Understanding and optimizing its production and application modes requires an organized research effort, focusing on the following issues: i. Production factors affecting its efficiency in soil; ii. Possible occurrence of phytotoxic compounds or leachable metals in the Biochar, their availability to plants and their potential for leaching to the environment; iii. Optimizing the ability of carbon-based materials to serve as excellent sorbents for many organic and inorganic pollutants, and thus help reduce pollutant leaching out of the soil zone; and iv. Development of suitable methods and agro-techniques for effective application.

ADVANCES IN PLANT SCIENCES (SESSION 5)

Thomas Sinclair addressed the subject of "Hydraulic Conductance Trait to Improve Crop Yield in Water-deficit Environment". He reviewed the factors that influence the relationship between yield and water use, and then examined a solution that might contribute to a modest yield increase on a fixed amount of water. While *the delayed-wilt trait for sensitivity to vapor pressure deficit, VPD, is a result of the apparent low leaf hydraulic conductivity and is especially useful in some regions*, results indicate that it might be acceptable for use in all regions of the U.S. Even in those years when the trait was simulated to result in yield loss, the yield decrease was usually quite small. Using this indicator, soybean producers will have the information to make risk decisions about the possibility of yield increase in most years, at the price of small yield decreases in the wettest years. The enthusiasm of incorporation of the delayed-wilting trait in commercial breeding programs makes it seem *likely that soybean cultivars across the U.S. will be producing modest yield increases as a result of what appears to be decreased hydraulic conductance in their leaves*.

Addressing the issue of "Improving Plant Stress Tolerance and Yield Production: Is the Tonoplast Aquaporin a Key to Isohydric to Anisohydric Conversion," **Menachem Moshelion** showed that their results support the hypothesis that *"isohydric and anisohydric water potential regulation may partition species between survival and mortality."* The benefit of maintaining a certain level of transpiration during stress, as opposed to a complete shutdown of transpiration, ensures not only continuous CO_2 uptake, but also a continued supply of nutrients and a reduction in leaf temperature, promoting plant growth. This offers *a new approach for biotechnological application in various agricultural crops exposed to different environmental stresses*. The findings, in addition to the fact that TOM-SlTIP2;2 (a tonoplast-localized aquaporin gene isoform) plants showed significant increases in fruit yield, support the hypothesis that the constitutive expression of SlTIP2;2 might convert tomato from isohydric growth behavior to the drought tolerant anisohydric growth manner.

Rony Wallach examined "Patterns of Synchronized Physiologically Induced Oscillations in Whole-Plant Transpiration and Their Role under Drought Conditions." He showed that as the soil progressively dried, the gradual decrease in transpiration rate of tomato plants was accompanied by an increase in self-regulated oscillations and changes in pattern. The switch from ambient condition-regulated to self-regulated oscillations in whole-plant transpiration rate as water stress increases indicates that the oscillations either prevent xylem water tension from reaching levels at which cavitation can form or they maintain xylem tension below a threshold value to impede runaway cavitation. Practically, this indicates the importance *of maintaining the xylem-tension thresholds within a range in which cavitation occurs but is repaired quickly enough to maintain the xylem water conductance at a value which does not induce further tension increases*.

While addressing "The Isohydric Response to Shading: Predicting Orchard Water Use under Screens," **Shabtai Cohen** emphasized that quantifying isohydric behavior is important for realistic predictions of crop water use and requirements and photosynthetic productivity under screens and in screen-houses. Leaf specific hydraulic conductance, leaf area index, critical LWP and climate variables (via the Penman-Monteith equation) can be used to predict canopy conductance and water use in shaded isohydric crops. He stressed that *the "isohydric" principle is applicable to shading studies and if we are to properly anticipate water use of crops in the shade, it is important to understand and quantify their hydraulic parameters and ascertain to what extent they are isohydric.*

"Assessment of the Effect of Climate Change on the Interactions of Plant, Pathogen and Microorganisms" was presented by **Yigal Elad**. The effects of climate change may be different in different plant-pathogen systems. Many early impacts of climate change can be effectively addressed through adaptation. The array of potential adaptive responses is very large, ranging from purely technological (e.g., pesticides application), through behavioral (e.g., crop change) to managerial (e.g., altered farm practices), to policy (e.g., planning regulations). Sustainable development is generally recognized as a key factor for the future of humankind. At present, however, few plans for promoting sustainability have explicitly included either adapting to climate change impacts, or promoting adaptive capacity. Even the *most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, which makes fast adaptation essential. This suggests the value of a portfolio or a mix of strategies that includes mitigation, adaptation, technological development and research*. A project, ENVIROCHANGE, was established to *accomplish the following goals: i.* Assess the *short-term impact (up to 25 years) of climatic change on agriculture at the regional level focusing on quality and pest management that are more likely to be influenced by climate change in the short term;* ii. Assess the *biophysical and socio-economic impacts of climate change on the region with special attention devoted to evaluating the economic impact on farmer profitability and on community welfare*; iii. Evaluate *autonomous adjustments and adaptation strategies made by farmers to global change*; and iv. Evaluate the *economic, environmental and social sustainability of selected adaptation strategies*.

WATER RESOURCES MANAGEMENT (SESSION 6)

Daniel Loucks discussed the topic of "Allocating Water When and Where There Is Not Enough." He referred to the important question of how we decide how much less water to allocate to all of us who want it to sustain and enhance our quality of life? He addressed some of the complexities of answering such a question, especially since society increasingly recognizes the need to provide flow regimes that will maintain healthy aquatic and floodplain ecosystems that also impact the physical and even the spiritual quality of our lives. His main conclusion is that *conflicting uses, as critical or desired as they are, which have negative impacts on the environment cannot be sustained*. Especially in times of water scarcity, the environment may have to suffer some because of higher priority uses, but it cannot suffer for long. By satisfying the need for naturally varying flow regimes and reduced pollutant and nutrient inputs, natural aquatic ecosystems can be maintained or restored to a sustainable state that will continue to provide the amenities and services society requires and has come to expect. Managers are challenged, especially in times of water stress, to meet both humans and ecosystem needs, now and in the future. Furthermore, *with increasing population pressures and climate change impacts, periods of water stress are likely to* *increase in duration and intensity.* It is *time to focus our best and brightest scientists and policy makers on how best to allocate our increasingly variable and uncertain water supplies to meet increasing demands in a way that optimizes water for life.*

The special water management problems of the Neretva River Valley located in the southern part of the Croatian Adriatic coast were analyzed by **Davor Romic,** as an example of estuaries and river deltas that are one of the coastal areas most at risk from human activities worldwide. Many of them are intensively-farmed arable lands. Most of the catchment areas of the examined valley spread into the neighboring country, thus introducing also transboundary problems. He emphasized that inappropriate management of a coastal aquifer, highly sensitive to disturbance, may lead to its destruction as a source of fresh water much earlier than other aquifers that are not connected to the sea. In addition to the impact of agricultural activity, large hydrotechnical interventions such as construction of dams, hydroelectric power plants and other structures can also change the water regime within a catchment area, and lower the quality of water for different purposes. Water management that focuses on issues such as water allocation and water quality almost always has a cross-border component, as is the case of this Valley. The Delta of the Neretva River is a hydro-ameliorated area that is being intensively used as a fertile agricultural land. Irrigation, which has become a common agrotechnique, has led to a significant increase in water abstraction, inducing water quality and pollution problems. Yet, it was emphasized that agriculture was not the only player disrupting the water cycle and quality in this region. One of the main conclusions for dealing with the farming related problems of this region was that "*appropriate technologies for the management of saline soils should be developed and adopted, as well as recommendations for the improvement of irrigation schemes.Additionally, networking between countries and research centers dealing with soil and water management is inevitable for preventing problems especially transboundary pollution."*

Friedler and Becker presented a paper dealing with the hydro-economic modeling efforts concerning the Alexander-Zeimar River basin. This is a transboundary river, originating in the Palestinian Authority (PA) and flowing through Israel (IL) to the Mediterranean Sea. Unfortunately, it has become a sewage outlet, used by Israelis and Palestinians alike. The major purpose of the study was to estimate the costs and benefits derived from the restoration plan, which has been conducted in the river since the mid 1990s. Another goal was to examine further cleanup efforts. To achieve these goals, the net benefits of different cleanup strategies both with and without cooperation between IL and PA were compared. The authors analysis showed that *restoration of contaminated rivers for public recreation can be economically sustainable* and the *best alternative was to treat both of the river's main focal points: the "turtle bridge" (Israeli part) and the "Peace Park" (Palestinian part).*

ADVANCES IN SOIL-WATER-PLANT MODELING (SESSION 7)

"Modeling for Risk Management and Adaptation Science in Agricultural Ecosystems and Environmental Policy" was presented by **Holger Meinke**. The water debate was brought as a typical example of an issue of high importance and considerable social relevance that needs to draw science out of its disciplinary comfort zones: the issue crosses many levels of temporal, spatial and disciplinary scale and requires scientific approaches that facilitate such scale transition. In maintaining a viable agricultural sector, science must contribute, to provide effective and socially acceptable solutions for overcoming issues such as water shortages. Engineering-based water saving techniques, biotechnology and adaptive farm business management strategies all offer a range of potential adaptation options that should be assessed in terms of their broader environmental, economic and social consequences and in terms of their locations. *Such assessments require "systems thinking" – the ability to quantitatively consider the consequences of proposed systems changes, across a wide range of temporal, spatial and disciplinary scales*. A *holistic approach to risk management thus requires:* i. A *good understanding of the* temporal sequences of the *different environments that define a region*, including their frequency of occurrence and how they may change with climate change, return intervals of extreme events and their predictability; ii. *Access to the technologies that are likely perform best in each environment type;* and iii. *Modeling frameworks that help integrate and make sense of the myriad of potential options and scenarios*.

Renduo Zhang presented results of a modeling study that proposes a simple and comprehensive relationship, relating Soil Organic Carbon (SOC) to the increasing annual average temperatures (warming), annual precipitation changes, elevated atmospheric CO_2 concentrations, and vegetation covers (land use). The parameters for the relationship were calculated via the CENTURY model, which can be used to simulate soil carbon dynamics in the top 20 cm of soils related to processes of fertilization, irrigation, cultivation, grazing, and fire, and simulate labeled carbon, enriched CO_2 effects and more. The effect of climate change on the SOC can be simulated using the model through input weather information. Using the relationship, *soil carbon sequestration was quantified under different conditions of the climate change, elevated CO_2, and vegetation covers*. The relationship was also *applied to predict the future SOC amount under climate change and elevated CO_2 with weather uncertainties*.

Matthias Langensiepen addressed the "Efforts to Standardize the Practical Application of the Penman-Monteith Equation to Manage Irrigation," which led to formulations compromising between scientific accuracy and practical convenience. The empirical parameterization of the transpiration model does not account for short-term perturbations within the plant system, which are caused by different responses of the canopy and root fractions to dynamic changes in their respective environments. Advancements *in structural-functional plant modeling will contribute* *to a better understanding of the underlying complexity, but the practical application of such models is not feasible, due to their inherent complexity and high data demands*. They provide a useful basis, however, for simpler multi-layer canopy models, which can be applied in practice for quantifying the effects of soil moisture variability on crop water use. *Better mathematical characterizations of causal relations between leaf and root processes controlling transpiration behavior will likely improve the performance of the Penman-Monteith equation under practical conditions.*

Moshe Silberbush described a method developed to measure uptake kinetics of nitrate by selected sections of corn (*Zea mays* L.) root systems, to be used in a plant uptake model that accounts for the root system architecture**.** This should be consistent with recent models that involve the genuine root distribution in the soil, considering plant genotype and soil characteristics. Based on the results the authors of this study suggest that, since all plants in the study were fully induced, the differences in *Km* (Michaelis-Menten coefficients) values of the different root classes are due to the expression of different genes that control the "high affinity nitrate transport systems." *Components of the corn root system do vary in their expression of genes that control their growth*. It is suggested that *such variations, together with differences in nitrate uptake, could be used to manipulate the corn root system, to meet differences in nitrate abundance and distribution in the soil profile.*

Addressing the topic "Detailed Modeling as an Essential Step in Developing New Analysis Techniques," **Uri Shavit** used the example of "The Isotope Pairing Technique (IPT)." This is a tracer method that was developed originally for measuring denitrification rates in sediments and was further modified by the presenters also as a tool to quantify nitrous-oxide emissions from sediments affected by agricultural inputs. In a detailed mechanistic numerical transport and reactions model of the nitrogen processes in sediments, large discrepancies were observed between denitrification rates computed in the simulation and those calculated by the IPT equations. Investigation of the sedimentary nitrogen processes *utilizing a comprehensive mechanistic numerical model showed that the error introduced by the IPT could be minimized with careful experimental design and by identifying misrepresentations done when applying the model to various scenarios*. The research identified the range of applicability of the IPT method to measure sedimentary denitrification rates and serves as a caution for the incorrect implementation of the IPT calculations caused by a misunderstanding of the original design.

IRRIGATION WITH RECLAIMED WASTEWATER –RWW (SESSION 8)

A summary of the state-of-knowledge related to the understanding of RWW interactions with soil-plant-water and their health and environmental implications was presented by **Avi Shaviv**.

The need to ensure that the overall increase in RWW use occurs while sustaining high agricultural production and concomitantly preserving the water, soil and environmental quality in the region was stressed. The following *special issues were mentioned as still requiring further investigation*. i. Better understanding and quantification of the contribution of hydrophobic compounds to the water repellence effects observed under irrigation with RWW; ii. *Elaboration of mechanisms and factors that facilitate transport of organic pollutants in soils irrigated with RWW*; iii. Corroboration of the findings that show depletion of OM in upper layers of soils irrigated with RWW due to stimulated microbial activity ("*Priming effect*"). Such an *effect, in the long run, may cause increased mineralization of soil OM and thus raise CO2 emission from RWW irrigated soils*; iv. *Investigation of risks associated with endocrine disrupting chemicals (EDCs), polycyclic aromatic hydrocarbons (PAHs)* and other organic compounds that may prevail in RWW, and the concern that the conventional technologies for WW treatment may not be effective enough in removal of such pollutants.

Special concern over the risk *of direct contamination of crops by human pathogens from the treated effluents used for irrigation*, and the risk of indirect contamination of the crops from contaminated soil at the agricultural site was addressed by **Nirit Berenstein**. Recent studies have demonstrated that *human pathogens can, to a limited extent, enter the plants through their roots, translocate and survive in edible, aerial plant tissues*. Yet, the practical implications of these new findings for food safety are still not clear, since they rely on many factors. Accordingly, several topics were outlined that need to be further investigated to facilitate evaluation of the health risks associated with irrigation with treated effluents. These include i. Survival of different pathogenic microorganisms present in the treated effluents in the agricultural soils; ii. *Factors affecting the internalization of human pathogens into plant roots*; iii. *Short and long-distance translocation of the pathogens in the plant*; iv. *Adherence of human pathogens to aboveground plant parts and the survival* and possible reproduction *of pathogenic bacteria* on and in the plant tissues.

Yael Laor addressed the problems associated with the increase in olive mill wastewater (OMW) production in Israel, given the growth of the olive oil industry, in which a three-phase extraction process yields oil, olive mill solid waste and olive mill wastewater. As of yet, there is no common or widely acceptable solution for OMW in Israel and it happens that some of the OMW is released to the environment in an uncontrolled manner. It was emphasized that multiple economical, environmental and practical aspects need to be considered in the search for viable solutions to this problem. Among the discussed options are: i. Choosing between engineered technology and environmental/agricultural recycling approaches; ii. Adopting agricultural recycling approaches, including controlled land spreading and co-composting of olive mill solid waste and olive mill wastewater; iii. Advantages of moving large mills into the two-phase extraction process. Based on the presented analysis, *cautious agricultural recycling approaches* *to OMW are viable and sustainable but are not necessarily cheaper than wastewater treatment technologies.*

Gurbachan Singh presented the *Indian Perspective of Reusing Treated Wastewater for Food Production* and stressed concerns over the potential transmission of infectious diseases by pathogenic agents and particularly so due to the use of poorly treated wastewaters. Considering the special situation and problems of wastewater treatment and re-use in India, several issues that must be addressed imminently were mentioned: i. There is an urgent need to segregate domestic and industrial wastewaters in each town/city; ii. Guidelines and mechanisms must be developed, to decrease health risks involved in the irrigation with reuse of wastewater; iii. There is a need for testing and standardizing the use of aquatic microphytes for removal of toxins. Identification, testing and culturing of microbes with bioremediation potential should be another priority research agenda; iv. To develop best management practices for reuse of wastewater, devised by multidisciplinary research teams comprising agricultural scientists, health engineers, medical doctors and animal scientists.

ADVANCES IN IRRIGATION (SESSION 9)

Terry Howell discussed *Advances in Precision Irrigation (PI) or Site Specific Irrigation (SSI)* and stressed that while precision irrigation advances have been considerable in research, commercialization lags. Precision irrigation is of limited utility without precise irrigation scheduling (temporally and spatially). Irrigation scheduling has advanced considerably in the past 20-30 years, with improved technology to measure soil or plant water status and, especially, within the past 10-15 years, with the utilization of remote sensing tools. The use of site-specific application technology is feasible engineering-wise; however, its acceptance depends strongly on a simple interface, using technology with which the producer is already familiar (i.e., wireless communication, cellular telephones, internet, etc.). *For precision irrigation to be effective, precise irrigation scheduling based on soil water status or crop water status seems to be a weak link currently, but research is improving the integration of crop water status and evapotranspiration feedback based on spectral and thermal remote sensing*. Additionally, spectral sensing offers great potential with the spatial management of nutrients and biotic stresses from pests and diseases. The *larger remaining obstacle appears to be characterizing the objective function for this advanced technology and management for the benefit of producers and the public.*

The importance of *High Resolution Monitoring of Root Zone and Vadose Zone Processes* was demonstrated by **Alex Furman**. He stressed the important contribution of precise application of water and nutrients to the plants to maximize efficiency of irrigation and minimize losses, which led to the development of drip and mini sprinkler irrigation techniques, and fertigation practices. These modern practices clearly create and require more detailed spatial treatment. He presented two different applications of geophysical tools for monitoring water distribution in the root zone and the vadose zone. Both make use of electrical resistivity tomography, ERT, and supporting tools. Work with the tools demonstrated the effect of heterogeneity at various scales and levels on agricultural and hydrological processes. It has been shown that *geophysical methods, and specifically ERT, are decent tools for inferring soil heterogeneity at various scales*. *These findings open the way for site specific deterministic level of system modeling that takes into account the system's heterogeneity.* By *spatially monitoring water content distribution throughout the year, they identified water that is not used by the plant and therefore leads to lower irrigation and fertigation efficiency.*

According to **Nurit Agam,** continuously growing availability of airborne and spaceborne data has led to the *development of various methods utilizing thermal remote sensing to detect and monitor water status in agricultural crops*. These in turn may *provide useful information allowing growers to irrigate only when and where needed, thereby conserving water*. Two methods, the Crop Water Stress Index (CWSI) and the Two Source Model (TSM), which differ in their output, were compared. While the CWSI only provides a relative estimate of a crop's water status, the TSM produces quantitative maps of the energy balance, and especially of actual evapotranspiration.

Both methods provide important information regarding crop water status. The simplicity of the CWSI makes it appealing and easy to use, provided high spatial resolution thermal imagery is available. The TSM, although more complex, has the advantage of utilizing available satellite imagery and yielding quantitative flux estimates. The choice of method should be made according to the available data and the required output.

Summary of Panel Discussion

In the last session, a panel of experts participating in the symposium (**Cohen, Hopmans, Meinke, Neumann, Wallach and Walters**) was asked to refer to the three key questions stemming from the different sessions held during the symposium. All of the symposium participants were asked to join the discussion led by this panel, either by directing questions to specific panel members or by adding their own comments to this discussion.

Highlights of this panel discussion follow.

QUESTION 1: WHAT CAN/SHOULD PLANT SCIENTISTS CONTRIBUTE TO THE DEVELOPMENT OF CROP VARIETIES (DROUGHT TOLERANCE, SALT TOLERANCE, AND WHAT OTHER PROPERTIES SHOULD THEY SEEK TO AFFECT)?

Peter Neumann:

The tools for developing new plant varieties are basically the same as they were for the past100 plus years. Selection of a crop is the key to finding a useful product. Biotech is just a new tool contributing to plant breeding techniques. Selection of a crop and breeding technique will produce new crop varieties that may or may not give us what we are looking for…increased yields with use of inputs such as water, nutrients etc.

Drought tolerance: Survival. We may engineer plants that can survive, but the price of a given crop variety will increase during drought times…not optimistic on this subject.

Salt tolerance: A lot of progress has been made in this area. You can put genes that keep toxicity of salts at bay, but if you keep salts outside the roots and in the soil, it creates an osmotic problem. Therefore, there is still a long way to go before adopting salt tolerant crop varieties from the lab to the field.

Root growth: This is a most promising area. We should be able to engineer plants to have longer roots. Undoubtedly, target production of roots when needed would be beneficial, but many plants already know how to do this in the natural field environment to seek either nutrients or water from the soil-water-air environment.

Practically: Better water distribution systems (irrigation) are needed and can contribute significantly to water use efficiency. Desalination of salty water needs more emphasis all over the world to provide greater quantity of high quality water, for irrigation to meet the food security needs of growing world population.

Controlling the increasing world population requires the use of birth control practices in water scarcity areas, to help develop a sustainable food system, but this is already beyond the scope of this forum.

Rony Wallach:

The problems related to food production will always be there and we need to develop holistic solutions to solve them.

A holistic solution: 1. Engineer plants, conventionally or using GMO techniques, to make them more tolerant to plant stressors; 2. Shift our traditional concepts of irrigation; this shift should demonstrate greater consideration of heat-water inter-relations. If we have to resort to deficit irrigation, then the key is not merely cutting a certain percentage, but cutting irrigation amounts according to the stage of the plant, so as to achieve overall less heat per unit of water and thus increase water use efficiency. This will result in increased crop production. The issue, then, is not only how to reduce the amount of water needed per unit of land to keep crop production, but also how to decrease the amount of water used by plants during drought periods of a growing season.

Menachem Moshelion:

There is a huge gap between biotechnology and plant performance in the field. We can find the genes that target certain processes, and usually this is successful in model crops, but it does not give you the answer on how this will affect processes in crop plants. It is not as easy as we may think to introduce these genes directly into the cropping plants. We should find a method for developing a high performing system, to be able to screen the plants prior to having to plant them in the field and see the effect on crop yields. if we are to succeed in creating the new high yielding crops of the future, we have to find a faster way than the 10-15 years it takes to develop a system nowadays.

Gurbachan Singh:

Looking for genes that confer resistance to plant stressors will help increase crop production. We can then take plants into the field and screen them for particular genes helping increase production.

Nirit Bernstein:

GMOs: The problem is that the world is not ready to accept GMOs. The newly developed science on GMOs needs to be accumulated and disseminated to the public for solving global food security problems. Otherwise we will be left with libraries full of scientific material and no one to use this important science to benefit humanity.

Moshe Silberbush:

Salinity: Consider a plant which can respond to different levels of salinity at different stages of plant growth. No one is doing this type of research in any part of the world.

<u>Nirit Bernstein:</u>

I have one question: Is there any research going on trying to find crops that can switch back and forth between fresh water and saline water or a mixture of both?.

<u>Jan Hopmans:</u>

There is need to work on increased productivity to develop low water consuming plants.

Yet, if water is scarce globally, we don't necessarily have to double the food production, but focus on changing the diet regime from meat protein to plant protein to meet global food demands.

<u>Dan Zaslavsky:</u>

In the first 20 years of Israel, we increased the agricultural productivity by a factor of 6 per m^3. We knew where to invest in high thrust research areas to increase productivity by a factor of 6 and we achieved this as a goal. Yet many places in the world are not even close to achieving this goal even today. This means that we need to push those areas of the world to improve production using modern agro-techniques.

<u>QUESTION 2</u>: WHAT CAN/SHOULD BE DONE IN TERMS OF IMPROVED MANAGEMENT AND/OR ADVANCED TECHNOLOGY DEVELOPMENTS TO IMPROVE CROP PRODUCTION UNDER: I) DROUGHT CONDITIONS AND II) TEMPERATURE RISE AND CLIMATE CHANGE/VARIABILITY?

<u>Mike Walters:</u>

First, let's try to not create problems, let's solve the problems at hand such as water etc.

Second, let us not abuse chief resources. We view them as infinitely available.

Third, we need to take a holistic-systematic approach to things; we need to look broadly at things and finding solutions. Use of biology as an engineering tool, i.e., bioinformatics …how did evolution solve this problem and how can we use this information? Use the knowledge gained in other fields (e.g., medical) to solve some of the world's problems. "Think young" to solve the problem.

Jan Hopmans:

Water Use Efficiency: Considering water use efficiency, about 70-80% of the agriculture in California is gravity irrigation. Water use efficiency is not considered as seriously in California as it is has been in Israel. There is much that can be learnt from what has been done in Israel.

Water Quantity Problems: Using reclaimed wastewater and desalinated salt water for irrigation could solve water quantity problems in water scarce areas. Then there is the energy problem which needs close examination when you look at desalination.

Holger Meinke:

We all have a duty to be optimistic. Unless we believe we can solve these problems, we just wind up doing more damage than has already been done. We have a responsibility to be optimistic. Holistic is a good idea, but it is difficult for most of us who are "experts" in our own specialized areas, and it is difficult to put our reputations on the line if we step out and look outside our areas of specialization. Holistic also means being problem focused in research and coming up with the best possible mix of solutions without disciplinary dominance (or arrogance). It is the key to a holistic solution. Back to the question at hand: we can package our knowledge in such a way that it is targeted to solving specific problems: GXEXM (Genetics X Environment X Management). The combo of the three gives you a plethora of options. This holistic systems approach allows you to look at the solutions as a package rather than a single solution. Adaptation science is an active process where you adopt new technologies and knowledge and are ready to use these in your own research. For example-Australia could learn a lot from Israel; however, Israel could learn too from Australia…there are no rainwater tanks in Israel, why doesn't every house have one?

QUESTION 3: HOW DO WE ENSURE CROP PRODUCTION THAT IS SUSTAINABLE IN TERMS OF ENVIRONMENT, RESOURCE CONSERVATION (ESPECIALLY WATER QUANTITY AND QUALITY) AND SOCIETAL NEEDS?

DO WE EMPHASIZE SAVING/CONSERVATION, DEVELOP SUSTAINING (AND SUSTAINABLE) TECHNOLOGIES, CHANGE HABITS/TRADITIONS, MAINTAIN A CLEANER ENVIRONMENT?

Peter Neumann:

Fewer humans: less livestock needed, less food needed…problem may be solved or easier to solve! Key is to control population growth rate.

Holger Meinke:

There will always be different interest groups when it comes to sustainability, but if they are well informed, the end solution of compromise will be easier to find.

Shabtai Cohen:

Was agriculture EVER sustainable? We are monitoring and finding out things that we didn't know before and that will lead to action to deal with these kinds of things. Sustainability is a good objective, but maybe reducing our footprint might be a better option and that will give us a chance to react.

QUESTION 4: WHAT CAN BE THE ROLE OF MODELING IN PROMOTING SUSTAINABLE CROP PRODUCTION?

Holger Meinke:

Modeling can help us understand the behavior of a given system and give us insight into a system. Beware that there is a lot of bad modelng. Systems analysis (the science behind the modeling) requires a broad understanding of all systems involved: 1. Modeling helps us identify R&D needs and prioritizes those by seeing where the needs are; 2. It contributes to "discussion support," by informing decision makers about likely consequences of alternative actions (alternative futures); and 3. It provides an analytical tool to look at non-linear and stochastic situations.

Mike Walters:

Even for monitoring you need to perform a good systems analysis, by using proper models, to be able to know where to collect the data.

Jan Hopmans:

Use models for scenario development and sensitivity meters not as predictors.

Holger Meinke:

The outcome from a model might not be wrong, but your perception might be. Alternatively, the model might be wrong. Either way, counterintuitive model results help to better understand systems behavior and dynamics.

Rony Wallach:

Modeling is dangerous. People get results; without knowing the assumptions and constraints, they then use these outputs as a sort of “bible.” We need to be careful and particularly when models are being used to create policies.

Alex Furman:

Models are used for very specific purposes. When you look into the details, you see that the assumptions that produced a given set of results may not be true for your scenario.