GLOBAL CLIMATE CHANGE: EFFECT ON AGRICULTURE FOOD SECTOR IN SRI LANKA IN THE YEAR 2025.

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ABSTRACT

Global warming and resultant climatic change by the year 2025 has been predicted at various degrees and magnitudes world over. The predicted changes for Sri Lanka is the increase in ambient temperature, increased incidence of high intensity rainfall and sea water rise (approximately 1 meter) around the Island. Agriculture food sector in the country is still at subsistence level and is the most vulnerable area. Since it has no room for horizontal expansion and many other factors, the shrinkage possibilities are still more acute in the future. Further, this sector consumes most part (96%) of water withdrawals, which will be a scarce natural resource in years to come. A recent study on domestic water supply cautions that Colombo will be a ‘thirst city’ by the year 2025, if the present trend in base flow, (which is $21m^3/sec$ while the need for domestic water with the increase in population and industrial demand is $42.m^3/sec$) in Kelani river is continued.

However, with the population increase (domestic demand) and the industrialization by the year 2025, present water use for agriculture needs to be diverted to fulfil the demand by these sectors. Moreover the increase in ambient temperature also creates an additional demand by the crop sector itself for their increased metabolic activities. The sea level increase around the island will inundate sizable land area belongs to the agriculture food sector, largely paddy lands, reducing production and creating soil problems like salinity and alkalinity. Therefore the future rice plant should possess some degree of tolerance to salinity and alkalinity to sustain the production with shrinking land area. Over the last few decades the soil and water conservation was not paid enough emphasis as a result of which some of the 103 rivers and streams flowing in all directions of the country, some of which changed from perennial to seasonal water flow with much reduced base flow.

Therefore special programme need to be identified and implemented to conserve moisture in higher elevations which receives the islands highest rainfall and effective in recharging the ground water aquifers and increase the base flow of the major rivers in the country in order to counteract the unfavourable effects of global climatic change to the country.

INTRODUCTION

Global warming is the observed increase in the average temperature of the Earth's atmosphere and oceans in recent decades. The Earth's average near-surface atmospheric temperature rose 0.6 ± 0.2 °Celsius (1.1 ± 0.4 °Fahrenheit) in the 20th century. The prevailing scientific opinion on climate change is that "most of the warming observed over the last 50 years is attributable to human activities". It is a complex phenomenon, and its full-scale impacts are hard to predict far in advance. But each year scientists learn more about how global warming is affecting the globe, and many agree that certain consequences are likely to occur if current trends continue.

Ambient Temperature

Over the course of the last century, global temperatures increased by about 1 degree Fahrenheit and will likely rise even more rapidly in coming decades. An increase in global temperatures can in turn cause other changes, including a rising sea level and changes in the amount and pattern of precipitation which may increase the frequency and intensity of extreme weather events, such as floods, droughts, heat waves, hurricanes, and tornados.

Sea level rise

Global sea level has already risen by four to eight inches in the past century. Scientists' best estimate is that sea level will rise by an additional 19 inches by 2100, and perhaps by as much as 37 inches. The current pace of sea-level rise is three times the historical rate and appears to be accelerating. Sea-level rise is expected to increase as a result both of thermal expansion of the oceans and of partial melting of mountain glaciers and the Antarctic and Greenland ice caps. Consequences of this rise in sea level include shoreline erosion, and destruction of important ecosystems such as wetlands and mangroves and barrier islands, and a greater risk of flooding in coastal communities.

Green house gases

Global warming is also caused by the increase in emission of green house gases such as methane and other organic gases and majorly carbon dioxide. These are the primary causes of the human-induced component of global warming. They are released by the burning of fossil fuels, land clearing and agriculture, etc. and lead to an increase in the greenhouse effect. This will lead to other consequences, which include higher or lower agricultural yields, glacier retreat, reduced summer streamflows, species extinctions and increases in the ranges of disease vectors. Warming is expected to affect the number and magnitude of these events; however, it is difficult to connect particular event to global warming. Although most studies focus on the period up to 2100, warming (and sea level rise due to thermal expansion) is expected to continue past then, since CO_2 has a long average atmospheric lifetime.

Only a small minority of climate scientists discount the role that humanity's actions have played in recent warming. However, the uncertainty is more significant regarding how much climate change should be expected in the future, and how to deal with the predicted consequences.

In the Sri Lankan context too the scientists predict sea level rise to about a meter height, increase in Carbon Dioxide concentration resulting in the rise in ambient temperature and changes in the amount and pattern of precipitation by frequent high intensity erosive rainfall and extreme weather events, such as floods, droughts, heat waves, hurricanes, and tornados. These will have very great impact in Agriculture food sector in the country in the year 2025.

AGRICULTURE FOOD SECTOR IN SRI LANKA.

Sri Lanka is a developing country and its agriculture food sector is dominated by rice which is the major or staple diet of average Sri Lankan. Country is nearing self sufficiency in rice due to adoption of improved varieties and imporved production technologies. Agricultural land area during the last few decades has generally taken a decreasing trend due to many social reasons though the unit area yield and total production showing an increasing trend during the last decade over the period from 1981-2004 (Table 1). Further the natural resource, water, which is important for the agriculture food sector for food production has also taken a similar trend over the years. The other factors of production is either available unlimited ie. Solar radiation, or can be applied externally (nutrients).

Table 1. National Annual Extent, Average Yield and Production of Paddy by Cultivation year (Maha and Yala Seasons) 1981 - 2004

Year	Annual Extent 000'ha	Average Yield Kg/ha	Production mt
1981	837	2,982	106,845
1986	835	3,475	123,956
1990	825	3,452	121,674
1994	930	3,363	128,630
1995	915	3,536	134,678
1996	749	3,514	98,807
1997	730	3,619	107,333
1998	848	3,636	129,044
1999	892	3,665	136,942
2000	878	3,857	137,085
2001	798	3,953	129,134
2002	852	3,893	137,029
2003	983	3,761	146,983
2004	779	4,080	125,016

However, the increase in population in the year 2025 (Table 2) indicate that the country's population size will rise to about 23 million by the year 2031, even though the rate of growth would continue to decrease. Table also shows that increase in population size will be larger the older will be the age group. This differential growth by age results in rapid aging of the country's population whereby the relative share of the aged increases phenomenally. This process of aging has a multifaceted impact on the future socio-economic life of the people and more specifically the agriculture food sector, which needs a very efficient labour force to keep up the food production with the food demand. The parallel food demand, with no possibility of lateral expansion for production and the threats to reduce the acreage available for food production, due to shortage of land mass for housing and industry, shortage of labour and the shrinkage effect of global warming are crutial issues that need to be addressed in the future.

Labour in agriculture is perticularly important for a good and efficient production programme. The key factor for success of such programmes is a healthy and efficient labour force. Unfortunately the predicted labour force in Sri Lanka in the year 2025 will have ove-aged labour around 22%. Therefore one of the options country has is the incorporation of mechanization in to the agriculture production systems to sustain production.

Table 2. Age composition and growth of the population in Sri Lanka, 1946-2031

Year	Population (thousands)		Proportion aged 60+	Annual growth rate*	
	Total	Aged 60+		Total	Aged 60+
1946	6,657	360	5.4	—	—
1953	8,098	437	5.4	2.80	2.81
1963	10,582	621	5.9	2.63	3.41
1971	12,690	807	6.3	2.22	3.20
1981	14,847	986	6.6	1.67	2.10
1991[a]	17,259	1,399	8.1	1.46	3.44
2001[a]	19,015	1,907	10.0	0.97	3.10
2011[a]	20,873	2,742	13.1	0.93	3.63
2021[a]	22,324	3,980	17.8	0.67	3.72
2031[a]	23,129	5,062	21.9	0.35	2.40

Source: Data for 1946 to 1981 are from Census Reports of the Department of Census and Statistics. Data for 1991 to 2031 are from De Silva (1993).

Water Resource in Sri Lanka

Water is an important and essential factor for agriculture food production. Sri Lanka is richly endowed with water resources, which receives mainly from the rainfall. Based on rainfall, country is divided into Dry zone with rainfall less than 1750 mm, Intermediate zone with rainfall between 1750-2500 mm and Wet zone having rainfall above 2500 mm. More specifically based on rainfall and other important agricultural indexes 46 agro-ecological regions (2002 edition) were identified and therefore Sri Lanka has an array of micro- climatic areas. In Sri Lanka rainfall has a sharp and spatial variation from less than 1000mm to more than 5000mm. The average being 1937 mm, in the global perspective Sri Lanka is not considered as a water scarce country. However, this has masked the localized water scarcities, within the country.

The total rainfall in the country is received by monsoon and inter-monsoon activities and it has already shown a decreasing trend up to 1990 and the prediction for the year 2025 was also decreasing (Table 3).

The rainfall alone provides 13 million ha. m. per year of water to the country of which
40 % goes as runoff (5.2 million ha. m. per year)
20% will infiltrate replenish the ground water table and
20% is lost by evapo-transpiration and the rest is stored in soil as adsorbed soil moisture which is generally not available for crop growth or evaporation except under extreme conditions.

Of the runoff water, good part is used for irrigation purposes by storing water in a cascade system of surface reservoirs and finally 3.3 million ha. m. per year reaches the sea . The final run off water uses 103 watersheds and some highly seasonal water streams, flowing in all directions in the country, to dispose of this water to the sea. With the global warming the amount of run off water could be expected to rise and infiltration chances are reduced because of the incidence of high intensity erosive rains

Table 3. Change and Variability of mean rainfall during different rainfall seasons for periods 1931 to 1990. (Jayathilake *et al.* 2004)

Rainfall season	1931-1960		1961-1990		Change (mm)	Change %	Prediction 2025 mm
	Rain Fall (mm)	CV %	Rain Fall (mm)	CV %			
North East Monsoon (Dec-Feb)	591.5	31	478.5	42	-113.0	-19.1	
First Inter-monsoonal (Mar-Apr)	299.7	23	268.3	27	-31.5	-10.5	
South West Monsoon (May – Sept)	547.0	21	556.2	16	+9.2	+ 1.7	
Second Inter-monsoonal (Oct-Nov)	566.9	12	558.1	23	- 6.7	- 1.1	
Annual (Jan – Dec)	2005.1	12	1861	14	-144.1	-7.1	1837

Sri Lanka's total water withdrawals in 1991 was 9.77 km3, of which, 96 percent (9.38 km^3) was used for irrigated agriculture. Domestic and industrial sectors used, two percent each (ESCAP 1995). Domestic withdrawal rate for the country was only 31liters/person/day in 1991 but the estimates of variations between districts are substantial and ranges from a maximum of 65 in Colombo district to a minimum of 19 litres in the Moneragala district. Per capita withdrawal for industry is also 31liters/peson/day but the district wise distribution is not available and calculated based on Industrial output (Amarasinghe *et al*. 1999). Irrigated agriculture in Sri Lanka covers an extent of 642,000ha out of which 575,000ha are cultivated to staple food, rice, which crop however uses excessive amounts of water leading to heavy losses and waste. In the case of rice, which is the Sri Lanka's staple food, farmers consume about 3000 litres for producing 1 kilo of rice and per capita consumption is about 98 kilos of rice per year. However, with the future retrieval of this resource from agriculture to meet the demand in the industrial and domestic sector, one has to follow the concept of 'more crop per drop' to sustain production if not to satisfy the total demand for food in the future. Therefore the future crop varieties and the production technology should be developed to consume at least 50% less water than today's water use, assuming that human being uses 50 litres of water daily and shall remain unchanged in the future (Amarasinghe *et al*. 1999). More over these varieties should be infused with salt tolerance genes in their genome in order to sustain the yield potential and production level of the country.

It has been reported that if the current rate of irrigation water use continues in the future several districts with major irrigated rice areas will have severe water scarcities according to IWMI criteria by the year 2025. Some of them will be in serious water scarce conditions so that the available water resources may not be adequate to meet their projected demand. Therefore they have to, either reduce their irrigation demand by increasing efficiency, or importing food or transporting them from the wet zone districts. Several districts in Sri Lanka will face severe water scarcity by the year 2025. However by doubling the irrigation efficiency, the number of water scarce districts can be reduced by 50 percent (Amarasinghe, *et.al* 1999). The same study concludes that the savings of water in agricultural sector alone are quite adequate to meet the increased demand of water for other sectors. A recent study on domestic water supply (Dharmasena 2004) cautions that Colombo will be a 'thirst city' by the year 2025, if the present trend in base flow, (which is $21m^3$/sec while the need for domestic water with the increase in population and industrial demand is $42.m^3$/sec) in Kelani river is continued.

The ground water is another source of fresh water available in the country and amounts to 7250 million m^3 per year, which is about 15% of the surface available water. Best sources are in the areas covered by Miocene limestone in the Jaffna peninsula extending northeast coast as far as Puttalam. Rest of the area especially in the wet zone the precipitation is very high and water consequently infiltrate to replenish the water table. Most of these aquifers are present in low-lying land and with the increase in sea water level possibility of them getting saline is at high risk and their withdrawal for agriculture will be questionable, unless appropriate soil and water conservation programme is implemented in the central highland to create high pressure conditions in the ground water aquifers which can keep away the salty water intrusion, at least to some extent. Moreover the withdrawal should also be carried out very cautiously not to disturb the salt to fresh water balance in the aquifers.

Soil and water conservation

Ancient Sri Lanka according to the history with 80% of the land area covered with thick rainforests and the cascade of reservoirs built by ancient kings, had no water problem except for excess moisture. Lately, the clearing of slope lands of central highland for commercial agriculture left the soil exposed and subjected to soil erosion and the eroded soil filled up the surface reservoirs downstream. Further, the plantation agriculture in the central highland again without adequate soil conservation measures also enhance the soil erosion resulting in the loss of fertile top soil which further decreased the water conservation in the land.

Monitoring and research work on soil erosion during the last few decades were at very low ebb The policy makers still have not conceived the importance of these activities and the gravity of critical land loss to the future posterity. Soil erosion in the central highland is taking place at an alarming rate of 75mt/ha/year due to lack of appropriate conservation programmes. However, with the global warming the trend is such that these areas will receive erosive rains much more frequently as a result of which the soil erosion will also takes place at very much higher rate. This trend needs to be monitored and accounted for future benefit.

In order to mitigate this condition more appropriate and concrete soil and water conservation programme need to be implemented. More over the eroded soil can get deposited in the reservoirs downstream resulting in reduction of tank capacities which will have effect on cultivated extend of food commodities, if not creates water stress to them. Recent study conducted after the commissioning of accelerated Mahaweli Project the sedimentation has produced alarming statistics. Environment impact assessment done in 1980 shows that soil loss were estimated to be 400-900 mt/ha/yr from tobacco growing land in Maha Oya catchments (TAMS 1980). This study also revealed that 30 % of Mahaweli upper catchments area (92,000 ha) was subjected to severe soil erosion (Table 4).

Table 4. Erosion from Mahaweli upper catchments area and sedimentation recorded in some tanks in the Mahaweli System

Reservoir	Period of study	Rate of sedimentation (% per year)
Rantambe	1990-1992	4.30
Victoria	1985-1993	0.08
Polgolla	1983-1993	2.30

(Source: Hydraulic Research, Wellingford (1995) Sedimentation studies in the upper Mahaweli catchments in Sri Lanka, Report No. Ex 3201)

However, some documented soil movement by various scientists are

1. Joachim and Pandithasekera (1933): 132,000 -273000 tonnes/year movement of suspended material from Mahaweli Ganga and actual soil loss is estimated as 110/ha/year.
2. Hesselo and Sikurajapathi (1965): Soil loss of 250 tonnes/ha was recorded during the tea-replanting period of 4 years in upcountry tea estates.
3. Manipura (1972) 51.93 mt/ha/yr from a clean-weeded 1- year old tea plantation.
4. Manipura *et.al* (1969) High intensity Inter-monsoon rain fall the soil loss from exposed plots is around 40 mt/ha and when mulched reduced to 0.07mt/ha
5. De Silva and Dimantha (1981) estimated as much as 30 cm of top soil have been lost from upland tea lands over the last century; the annual loss thereby 40mt/ha.

These data suggest the importance of soil and water conservation in the future as the soil erosion hazards are more frequent and will be at a very high magnitude by the year 2025 due to global warming, more appropriately higher frequency of occurrence of extreme weather events.

Seawater rise

Sri Lanka being an island surrounded by sea has special consequence due to seawater rise. Sri Lanka was also endowed with 103 perennial watercourses and several other seasonal water streaks. With the commercialization of the central highland as above, water streaks died down completely whereas some of the perennial water courses (rivers and streams) became seasonal though almost all of them reduced their base flow. With the increase in sea level around the country could inundate some of the low lying land used for agriculture food sector, mainly rice cultivation, which will definitely be a sizeable part of the annual acreage. In the north central province it is anticipated nearly 40-50,000ha will go under water due to this reason (personal communication, Rajarata University). Sri Lanka already has 10-15000ha of land, which is below sea level, and salt water intrusion is observed during high tide. Moreover, the mouths of these rivers and streams will be the inlets for salt water intrusion, which through under water currents may travel several km upstream and deposits salts in the agricultural lands meant for rice cultivation making them saline or alkaline or even acid sulphate conditions. This is more serious than the inundation *per se*. A classic example is already in the country in the southern province where one of the biggest rivers in the country (Nilwala River) which flows and empty into the sea at Matara coastal town. Land Reclamation, Flood Protection and Drainage project was implemented in this watershed of Nilwala River in early 80's and developed acid sulphate conditions due to excessive drainage. The reason for this was investigated and found that over last several decades, during dry months of July and August, there was salt water intrusion travelling 6-8 km upstream of the river, and depositing salts, mainly iron pyrite, on adjacent paddy lands. With the implementation of the Project these paddy lands were drained too much and oxidation of pyrites caused acid sulphate conditions in nearly 8000 ha of land, which were abandoned today.

Increase in ambient temperature and GHG gases

These two effects are interrelated and will be discussed together. Over the last few decades the temperature rise was observed though not high but steady. Table 5 shows the mean ambient temperature during 1969-90 and projections for the future as predicted by different models. It shows that there will definitely be an increase in Minimum, Maximum and Mean temperatures in the year 2025 with a maximum of 0.3 – 0.4^{0}C. In the Philippines the minimum temperature has increased by 1^{O}C during the last decade and it has envisaged that it has resulted in rice yield decrease of 10-11 % in the country (Wang 2006)

Table 5. Mean Air temperature (^{o}C) predicted for year 2025 and above. (Jayathilake et al 2004)

Model/Observed	**1969-1990**			**2025**			**2050**		
	Min[a]	**Mean**	**Max[a]**	**Min[a]**	**Mean**	**Max[a]**	**Min[a]**	**Mean**	**Max[a]**
Observed	12.1	26.7	28.6						
Modeled-CGCM*				12.3	26.9	28.9	12.7	27.3	29.2
Modeled- CSIRO**				12.4	27.0	28.9	12.8	27.3	29.3
Modeled- HADCM3***				12.4	27.0	29.0	12.9	27.5	29.5

* = Canadian General Circulation Model
** = Commonwealth Scientific and Industrial Research Organization General Circulation Model
*** = Hadley Centre General Circulation Model – Version 3
a = Max and Min refers to the highest and lowest values within the country.

The creation of biomass by plants is influenced by the availability of water, nutrients, and carbon dioxide. Part of this biomass is used (directly or indirectly) as the energy source for nearly all other life forms, including feed-stock for domestic animals, and fruits and grains for human consumption. It also includes timber for construction purposes.

A rise in atmospheric carbon dioxide can increase the efficiency of the metabolism of most plants, potentially allowing them to create more biomass and increase harvestable yields. This effect can further be increased due to increase in ambient temperature with the global warming process. A rising temperature can also increase the growing season in colder regions too. It is sometimes argued that these effects can create a greener, richer planet, with more available biomass. However, there are many other factors involved, and it is currently unclear if plants benefiting from global warming is a realistic scenario. Plant growth can be limited by a number of factors, including soil fertility, water, temperature, and carbon dioxide concentration.

However, Sri Lanka's staple food production was at stand still for several decades and it has now taken an increasing trend during the last decade (Table 1). There are several reasons for this phenomenon like, better fertilizer use, technology improvement and new varieites, but, it may also argued that this increase in trend may have its contribution due to increase in ambient temperature and increased concentration of carbon dioxide in the atmosphere as there was no constraint of solar radiation limitations for biomass production in crops, being a tropical country.

FUTURE SCENARIO

The cost of environmental damage in Sri Lanka caused by deforestation, land degradation, coastal damage and damage from all forces approximates 2.4% of the gross national production and therefore development, without depleting natural resources to a point of no return, is highly essential (Ranasinghe 2002). Over the last few decades the soil and water conservation was not paid enough emphasis as a result of which some of the 103 watersheds flowing in all directions of the country, changed from perennial to seasonal water flows with much reduced base flow. At least, time is ripe now; the policy makers and agriculturists should treat it as an immediate timely requirement. It has been stated that land degradation can be countered by conservation farming technologies (FAO), which integrates soil, water, and water conservation in its technology. Furthermore. along with appropriate irrigation, crop management and erosion control conservation farming has with it, the right focus to the success of facing the future land degradation.

The levels of adaptation undertaken by a region may have significant effects on how climate change will affect agriculture in that area. In Rosenzweig and Parry (1994) levels of adaptation were grouped into two levels.

Level 1 adaptations include: shifts in planting date (±1 month) that do not imply major changes in crop calendar, additional application of irrigation water to crops already under irrigation, changes in crop variety to currently available varieties and more adapted to the altered climate. Level 2 adaptations imply more substantial change to agricultural systems, possibly requiring resources beyond the farmers' means, including: investment in regional and national agricultural infrastructure and policy changes at the regional and national level.
In conclusion, global warming may result in detrimental effects on food supply and security, through the effect on agriculture food sector in the country. Even if we adapt to climate change, we will not be able to completely avoid the problems associated with climate change. Furthermore, these harmful outcomes of climate change and potentially positive outcomes in developed countries will probably increase the gap in wealth, access to food, and health between us.

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CLIMATE AND VEGETATION IN THE MIDDLE EAST: INTER-ANNUAL VARIABILITY AND DROUGHT FEEDBACKS

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ABSTRACT
The climate of the Middle East is characterized by large inter-annual variability, particularly in semi-arid and arid areas. As vegetation in these areas is primarily limited by available soil moisture, annual vegetation cover is sensitive to variability in precipitation and evaporative demand. This sensitivity is greatest in areas of marginal rain-fed agriculture, including much of the Euphrates Plain, where crop yield and range productivity vary widely between years. In addition, satellite analyses indicate that peak vegetation cover is negatively correlated with surface albedo both during and after the growing season. For the Euphrates Plain, inter-annual variability in albedo produces an estimated forcing on the surface radiation balance that peaks at 16.0 W m^{-2} in May. A forcing of this magnitude has the potential to influence both air temperature and precipitation.

Simulations with a regional climate model indicate that surface energy fluxes during a drought year (1999) differed substantially from those during a year with normal precipitation (2003). These differences were geographically specific. The Euphrates Plain exhibited increased albedo and decreased sensible heat flux while the neighboring Zagros Plateau region showed no albedo effect, a large increase in sensible heat flux, and an offsetting reduction in latent heat flux. In both the Euphrates Plain and the Zagros there was a potential for positive feedbacks on temperature and drought in late spring, though the most likely feedback mechanisms differed between the two regions: in the Euphrates Plain surface brightening leads to cooling and reduced turbulent heat flux, while in the Zagros reduced latent heat flux leads to warming and a deepening of the planetary boundary layer.

The results of these studies clarify the role of land-atmosphere feedbacks in Middle Eastern climate. Improved understanding these processes in the modern climate makes it possible to evaluate their significance to past and future climate change in the region.

INTRODUCTION

Semi-arid regions are subject to regular seasonal dryness and large inter-annual variability in precipitation. This results in variable vegetation cover on annual and inter-annual timescales, as both natural ecosystems and non-irrigated crops rely on soil moisture derived from seasonal rains or springtime snow melt. Opportunistic annual species green up rapidly in response to wetting of the soil surface, and their vigor is primarily related to recent rainfall events. Winter crops and perennial vegetation have access to deeper reserves of soil moisture. Growth of these vegetation types depends on the precipitation pattern over weeks and months, on evaporative demand, and, for some regions, on temperature constraints.

Climate-induced variability in semi-arid vegetation is a matter of both ecological interest and economic concern, as strong sensitivity to climate can result in rapid land use change and vulnerability to human-induced degradation [1]. Over longer time scales, relatively small shifts in background climate may have a substantial influence on the distribution of ecosystems and, perhaps, the viability of agricultural and pastoral systems [2]. Interest in the climate sensitivities of semi-arid vegetation—particularly crops and rangelands—is evident in the large body of research devoted to characterizing the relationships between precipitation, soil type, land management, and vegetation growth in water stressed regions.

There is also a substantial literature concerned with vegetation feedbacks on climate in semi-arid regions. In an effort to understand the role of land-atmosphere interactions during the extended Sahel drought of the early 1970's, Charney hypothesized a negative albedo-precipitation feedback in which dry conditions lead to surface brightening, a decrease in available energy, and reduced convection [3]. This, in turn, leads to vegetation die-back and increased albedo. Charney's hypothesis has informed numerous studies on albedo-precipitation feedbacks, including detailed field campaigns, satellite analyses, and global-scale modeling exercises. This line of investigation has revealed important interactions between vegetation, albedo, and climate. The nature of these interactions depends on scale and regional context, and the forcing mechanisms are not always obvious.

In addition to albedo effects, vegetation is thought to influence the atmosphere through a number of structural and physiological mechanisms. Most notably, vegetation exerts direct control on latent heat flux from the surface. An active vegetation cover tends to increase latent heat flux, due to increased soil infiltration and subsequent transpiration of otherwise unavailable moisture. Increased latent heat flux both humidifies the planetary boundary layer (PBL) and increases moist static energy (MSE) of near-surface air, increasing the potential for precipitation [4]. Such coupling between surface conditions and atmospheric processes is thought to be particularly strong in semi-arid regions [5].

This study takes advantage of recent inter-annual climatic variability to characterize the climatic sensitivities of vegetation in the Middle East and to investigate the potential for land-atmosphere feedbacks in the region. First, timeseries data from the Advanced Very High Resolution Radiometer (AVHRR) are used to describe seasonal and inter-annual patterns in vegetation and albedo. Second, these data are analyzed in conjunction with climate data to characterize drought sensitivity and to quantify the impact of vegetation variability on the surface radiation balance. Third, a regional climate model is employed to study the impacts of drought on surface energy fluxes and land-atmosphere feedbacks in two sub-regions: the Euphrates Plain (EP) of Syria/Iraq and the Northern Zagros Plateau (NZ) of Iran.

VEGETATION TYPES AND VARIABILITY

The Middle East is a predominantly semi-arid region that contains a strong north to south precipitation gradient (Figure 1). Humid regions of Turkey and Transcaucasia receive more than 1000 mm precipitation per year, while the deserts south of the Euphrates River receive 100 mm yr^{-1} or less. Inter-annual variability exceeds mean annual precipitation throughout the southern portion of the region. This variability is of particular interest because it coincides with the southern limit of the historical Fertile Crescent agricultural zone and important rangelands of the Euphrates Plain. Present day variability has a significant impact on crop yields and range productivity, and variability on longer time scales appears to be associated with the rise and fall of early civilizations [2].

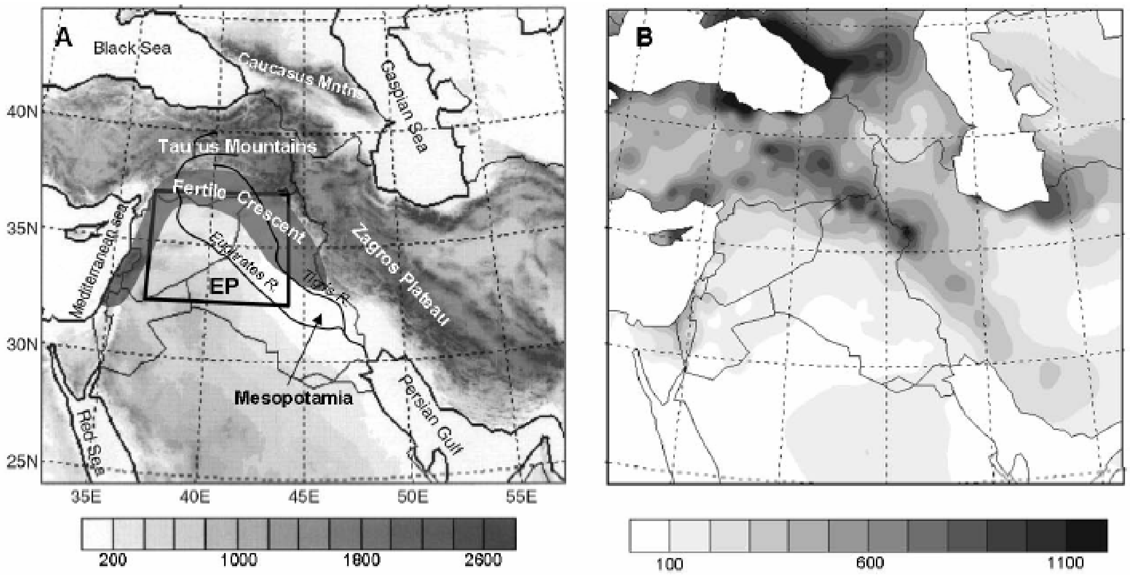

Figure 1. The Middle East. (A) Major geographic features and topography (m). (B) Mean annual precipitation from FAO reporting weather stations, (1940-1973), interpolated using Cressman distance weighting (mm).

The north to south precipitation gradient is accompanied by an ecological gradient, ranging from temperate forests and warm season agriculture in the north to winter crops, grasslands, and eventually shrublands and desert in the south. These land cover types differ in vegetation density and phenology (Figure 2A). Forests in the highlands of Turkey are characterized by seasonally high *NDVI*, with vegetation intensity peaking in early summer and fading gradually in late summer and autumn (Figure 2B). Rain fed agriculture in the northern portion of the domain follows a similar pattern, returning negative *NDVI* values in the winter (indicative of snow cover), a rapid green-up in late spring, and relatively high *NDVI* throughout the long summer growing season. Agricultural phenologies in the Fertile Crescent are quite different. Here agriculture is limited by summertime dryness rather than wintertime frost, and the *NDVI* of rain fed crops peaks in late spring (Figure 2B). Harvest of field crops in this region takes place in May and June. Orchard crops such as olive also have their phenologic peak in springtime, but the active growth period is both longer and more moderate (Figure 2B). Along the river valleys and in regions of intense canal or groundwater irrigation a third field crop phenology is found, indicative of double cropping practices (Figure 2C). In these situations the winter crop may receive supplementary irrigation and the summer crop is entirely dependent on irrigation water. It should be noted that in AVHRR-based analysis many agricultural fields are contained within a single pixel, so a “double crop” phenology actually represents a composite of winter cropping, summer cropping, and some fields with active double cropping. Outside of irrigated areas, land cover south of the Fertile Crescent, east of the Caspian Sea, and in much of Iran is limited to sparse grasslands and shrubs. These lands are utilized seasonally for grazing, but they have extremely limited vegetation cover for much of the year. Phenologically, grasses and shrubs both green up in response to winter rains, peaking in March or April (Figure 2C). Senescence comes rapidly in late spring, though this pattern varies with grazing pressure and the density of shrub cover, as shrubs have access to deeper moisture reserves and can stay green well into the dry season [6]. Finally, much of the region is essentially barren, with no distinct *NDVI* phenology (Figure 2C).

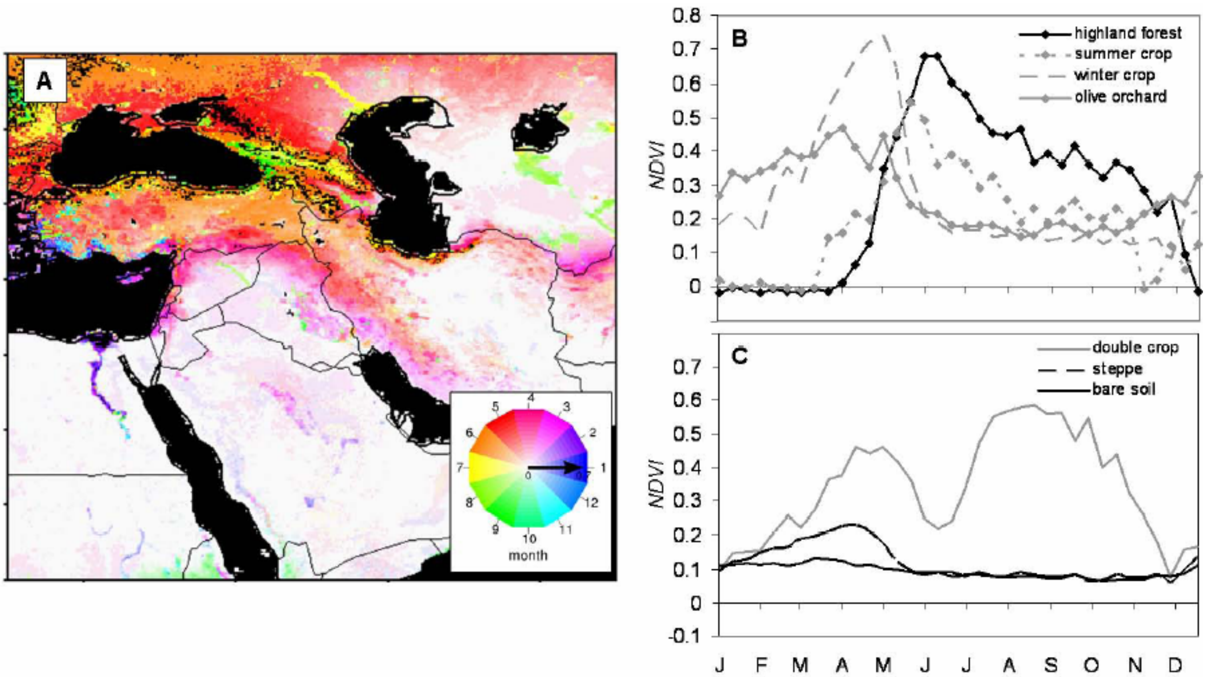

Figure 2. Vegetation intensity in the Middle East. (A) Map of mean annual NDVI maximum, based on monthly averaged AVHRR data, 1981-2001. Color hue indicates the month of peak NDVI and color saturation indicates the magnitude of the NDVI peak. (B,C) Phenology of representative pixels for major land cover types, based on SPOT 10-day NDVI composites for 2003.

For the Tigris-Euphrates watershed, inter-annual variability in vegetation is greatest along the southern margin of the Fertile Crescent, an area which includes both rain-fed agriculture and semi-arid rangelands. The nature of this climate-driven variability can be explored by analyzing AVHRR data in conjunction with meteorological data. For each pixel in the study region, independent linear correlations were calculated between the annual maximum *NDVI* in AVHRR data (n=20 years) and six variables that describe weather conditions in each hydrologic year: total precipitation in early winter (Nov-Dec), late winter (Jan-Feb) and spring (Mar-Apr) and average air temperature for the same three periods. Figure 4 maps the results of this analysis for all pixels with reasonably substantial vegetation coverage (mean annual $NDVI_{max} > 0.12$) and significant climate sensitivity (linear correlation between $NDVI_{max}$ and at least one of the six climate variables significant at $\alpha = 0.1$). Colors on the map indicate the climate variable for which the coefficient of linear correlation was largest for a given pixel. In highland regions of northern Iran, for example, we find that variability in *NDVI* correlates most strongly with wintertime temperatures (Figure 3, Area A)—low wintertime temperatures in this area are associated with strong vegetation growth in spring. The negative correlation between wintertime temperature and $NDVI_{max}$ can be attributed to the importance of sub-zero temperatures for the development of a winter snow pack, which is the primary source of springtime soil moisture.

Moving down slope and southward along the precipitation gradient, vegetation growth in the Fertile Crescent and rangelands of the EP correlates more strongly with precipitation than with temperature (Figure 3, Area B). The mediating factor is, again, soil moisture, but in this area snow is not a significant factor in the water balance of non-irrigated lands. Instead soil moisture is replenished by winter and spring rains. In areas where soil moisture storage is sufficient, deep rooted woody plants or winter crops are able to access moisture that infiltrated during winter rain events well into the spring, leading to a strong correlation between Jan-Feb precipitation and $NDVI_{max}$. In areas with shallow soils, or those dominated by opportunistic annual grass ecosystems, $NDVI_{max}$ correlates most strongly with Mar-Apr precipitation, the period coinciding with the annual vegetation maximum. Sensitivity to precipitation is also dominant in the southern Zagros Plateau (Area C), where vegetation includes hillslope grasses and several large agricultural areas. Somewhat surprisingly, a portion of arid north-central Saudi Arabia also exhibits sensitivity to precipitation (Area D). The most striking vegetation features in this area are large cropped fields that are supported almost exclusively by groundwater irrigation [7]. The area also includes several large wadis, however, and it is possible that the detected climate sensitivity results from the response of natural vegetation to rare wadi floods.

Finally, some areas show a significant positive correlation between air temperature and $NDVI_{max}$. These areas fall in two regions. First, along the Mediterranean coast and in south-central Turkey (Area E) the correlation with temperature reflects the fact that cold winters limit the growth of winter crops and orchards, which normally peak early in the year (Figure 2A). The area is humid relative to the interior of the Middle East (Mean annual precipitation 350 – 700 mm yr^{-1}), so the correlation between vegetation and precipitation is less important. The second region of positive temperature sensitivity is Mesopotamia (Area F). Land use in this region includes vast areas of irrigated agriculture, so vegetation growth is decoupled from local precipitation. Instead, warm winters allow for healthy growth of the cold season crop and a higher peak *NDVI*.

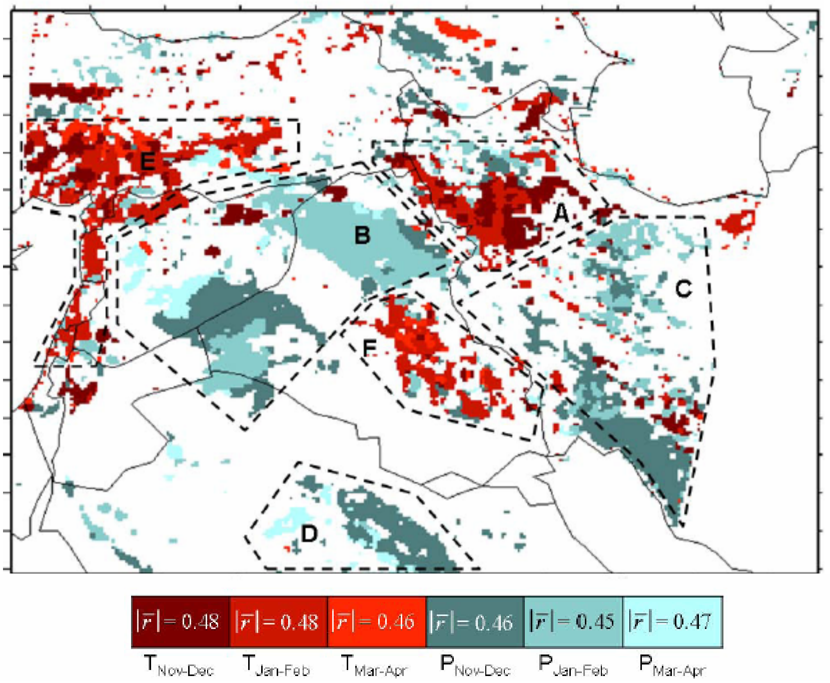

Figure 3. Linear correlation between annual maximum *NDVI* and variables of winter/spring climate. Climate parameters are average air temperature and accumulated precipitation for Nov-Dec, Jan-Feb, and Mar-Apr in the hydrologic year of the *NDVI* maximum. Colors indicate the climate variable of greatest correlation for all pixels with mean annual *NDVImax* > 0.12 and linear correlation is significant at $\alpha = 0.1$. Mean correlation coefficient for each class is indicated on the label bar. Dashed lines indicate regions of coherent correlation type discussed in the text.

ALBEDO AND THE SURFACE ENERGY BALANCE

Vegetation is known to impact surface albedo in several ways. The most direct effect is that photosynthetically active vegetation is dark in the visible range of the electromagnetic spectrum, where incoming solar radiation is greatest. This means that live plant material reflects less solar radiation than most semi-arid soils [8]. Senescent or dormant vegetation also influences surface albedo. Dry herbaceous material is relatively bright, so the presence of leaf litter over a wet or dark soil can cause an increase in albedo. Woody material, on the other hand, tends to be darker than dry leaves. Dormant trees and shrubs also cast shadow, reducing the total solar radiation incident on the soil surface. If the background soil is brighter than the woody material itself then this effect will lead to a decrease in effective albedo and an increase in absorbed radiation.

Over 20 years of AVHRR data, there was a consistent negative correlation between spring *NDVI* in the EP and albedo in both spring and summer; that is, strong springtime vegetation made for a darker surface throughout the summer months. This negative correlation is strongest between March *NDVI* and June albedo (EP average statistics: r = -0.44, p=0.13). There are three reasons for this negative correlation. First, at the resolution of an AVHRR pixel, the *NDVI* signal can be dominated by wadis and depressions that remain green throughout the summer in years with plentiful runoff. These concentrated areas of dark vegetation reduce the reflectance values recorded for the entire pixel. Second, certain succulent shrubs that are unpalatable to livestock can retain green vegetation well into the dry season, and these shrubs are most green in years with good precipitation. Third, summer albedo is negatively correlated with summer *NDVI* due to the structural effects of woody vegetation described above. Thus the albedo effect can persist even after all green vegetation has senesced. This third phenomenon was confirmed in a field experiment in the Aleppo Steppe: regular measurements with a portable spectrometer indicated that high spring *NDVI* was associated with low summer albedo across a variety of rangeland environments, even after differences in *NDVI* had dropped to near zero [6].

To carry the analysis a step further, it is possible to calculate the influence of inter-annual variability in surface albedo on the absorption of shortwave radiation, using AVHRR estimates of albedo and NCEP/NCAR Reanalysis Project estimates of surface-incident shortwave radiation. According to this calculation, the inter-annual standard deviation in surface albedo is associated with a forcing on the surface radiation balance that exceeds 10.0 W m^{-2} in every month from March through August, averaged monthly for the EP. This forcing peaks at 16.0 W m^{-2} for the month of May (Figure 4). The effect is strongest in areas with large inter-annual variability in albedo.

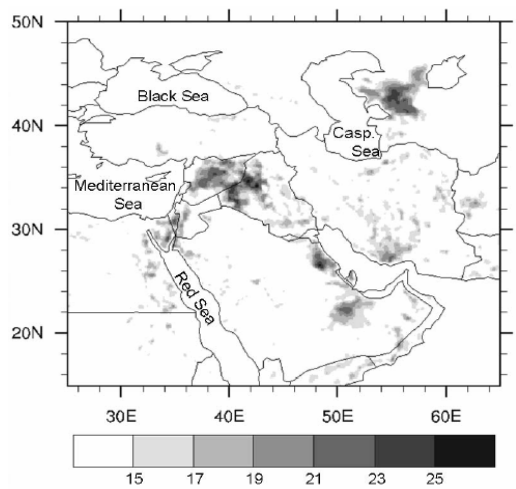

Figure 4. Inter-annual standard deviation in May absorbed shortwave radiation (W m^{-2}).

To put this forcing in context, the radiative forcing associated with a doubling of atmospheric CO_2 is on the order of 3.7 W m^{-2} [9]. In a regional climate modeling study, Schar et al. [10] found that a 17.1 W m^{-2} increase in net surface radiation was sufficient to produce feedbacks on precipitation in sensitive regions. Clearly, inter-annual variability in albedo in the EP has the potential to have a considerable impact on local temperatures and, potentially, hydrometeorology on the regional scale.

CLIMATE MODEL EXPERIMENTS

Four 14 month simulations were performed with an advanced regional climate model, MM5-Noah. First, control simulations were run for a drought period, 1 November 1998 – 31

December 1999, and a non-drought period, 1 November 2002 – 31 December 2003. In each case the first two months were treated as spin-up and results were recorded for the calendar year. For these simulations surface albedo and vegetation fraction were drawn from SPOT-Vegetation data for the corresponding time period. It was necessary to prescribe albedo as well as vegetation fraction because vegetation fields do not inform the predicted surface albedo field in MM5-Noah. All simulations were performed at a horizontal resolution of 27 km, and with 23 levels in the vertical.

Detailed results of these model experiments are presented elsewhere [11]. For the purposes of this conference, we focus on one key result of an intra-regional comparison between the EP and the NZ: the influence of albedo on the surface energy balance, and its implications for land-atmosphere feedbacks on precipitation.

First, it is important to note that the 1999 drought led to an increase in albedo only in the semi-arid lowland areas of the EP and, in the northeast of the study region, the Caspian steppe. In the Zagros foothills and plateau—where soil moisture is greater, soils are darker, and vegetation is less sensitive to precipitation drought—there was no detectable difference in May surface albedo between 1999 and 2003 (Figure 5A).

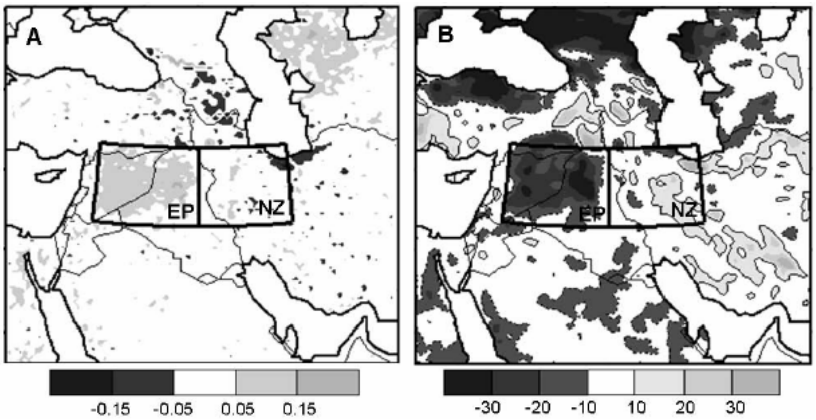

Figure 5. Average difference for the month of May, 1999 – 2003, in (A) surface albedo and (B) net surface radiation, according to MM5 simulations. Boxes **EP** and **NZ** indicate the Euphrates Plain and Northern Zagros sub-regions.

This spatial variability in albedo is important because of its implications for the surface radiation balance. Model simulations indicate that the 1999 drought was associated with a significant reduction in net radiation available at the surface (R_{net}) in the EP ($p<0.0001$) but not in the NZ (Figure 5B), relative to the non-drought year 2003. In fact, R_{net} was slightly greater in 1999 for the Zagros ($p=0.359$), due to clear sky conditions and an increase in solar radiation incident on the ground surface. The difference in drought impact on R_{net} in the EP versus the NZ has an impact on turbulent heat flux via the surface energy balance: $R_{net} = H + \square E + G$, where H is net surface sensible heat flux, $\square E$ is surface latent heat flux, and G is conductive heat flux from surface to sub-surface. The drought-related reduction in R_{net} in the EP for 1999 was associated with a decrease in H of 6.1 W m^{-2} relative to 2003 ($p<0.0001$), averaged over the month of May, while the clear-sky associated increase in R_{net} for the NZ was associated with an increase in *H* of 32.4 W m^{-2} ($p<0.0001$). Latent heat flux (□*E*), meanwhile, was reduced in 1999 for both the EP (by 9.6 W m^{-2}; $p=0.0007$) and the NZ (by 29.7 W m^{-2}; $p<0.0001$) due to reduced soil moisture. The effect was considerably larger in the NZ area because soil moisture in the EP was quite low in May even in the relatively wet year of 2003.

This intra-regional difference in energy and moisture fluxes is relevant to land-atmosphere feedbacks on precipitation. According to one hypothesized feedback mechanism, precipitation is inhibited during drought in part because reduced Rnet is associated with reductions in turbulent heat flux (*H* and *λE*), such that the local land surface contributes less to the moist static energy density (<MSE>) of the planetary boundary layer (PBL). The density of MSE in the PBL is directly associated with conditional instability, so a reduction in the local contribution to MSE leads to reduced potential for convective precipitation {Eltahir, 1998 #46}. Under this hypothesis, early dryness in 1999 may have triggered a drought-enhancing feedback in the EP, but there is no evidence for such a feedback in the NZ.

A second hypothesized feedback mechanism, however, posits that a drought forcing on precipitation is possible even when there is no change in R_{net}. Under this proposed mechanism, it is a shift in the partitioning of turbulent energy fluxes that matters: a decrease in *λE* in favor of *H* makes for more vigorous mixing in the local atmosphere and a deepening of the planetary boundary layer (PBL) via entrainment of dry air from above. This deep, dry PBL has low <MSE>, and the potential for precipitation is limited [12]. According to MM5-Noah simulations, the NZ did, indeed, exhibit enhanced *H* and a deepened PBL in 1999 versus 2003, suggesting that this type of feedback might have operated.

The proposed feedback mechanisms for the EP and NZ are summarized in Figure 6. Sensitivity studies performed with MM5-Noah further demonstrated that vegetation changes were primarily responsible for the feedback in the EP, while inter-annual variability in soil moisture was of greater importance in the NZ [11]. This is consistent with expectation, as the dry, sparsely vegetated EP fits the profile of a region prone to vegetation-atmosphere feedbacks, while the less arid, more densely vegetated NZ bears a resemblance to other regions where soil moisture variability has been found to impact seasonal climate.

CONCLUSIONS

In this study it was found that inter-annual fluctuations in climate lead to considerable variability in vegetation for much of the Middle East. The greatest variability was found in a sensitive transitional climate zone that includes much of the Fertile Crescent and its neighboring rangelands. In this area vegetation intensity is strongly correlated with surface albedo both during and after the prime growing season. An externally-imposed drought, then, leads to reduced vegetation, increased albedo, and the potential for feedbacks associated with changed land surface conditions.

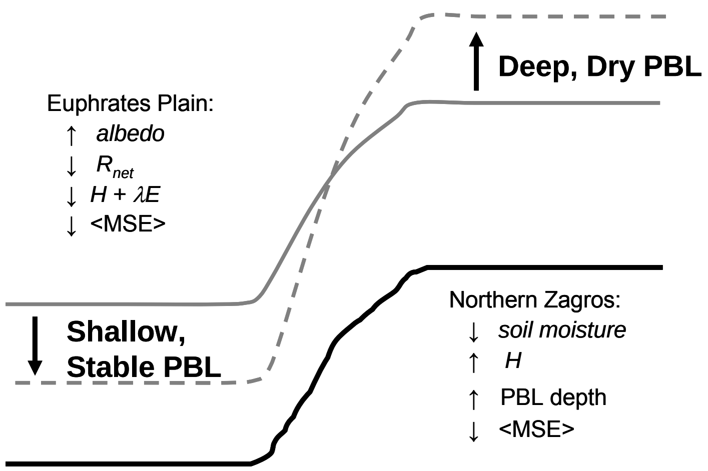

Figure 6. Surface processes relevant to drought precipitation forcings in the EP and NZ (schematic). Solid grey line represents the height of the planetary boundary layer (PBL) under non-drought conditions and the dashed line represents the height of the PBL during drought. The black line is the land surface.

During the drought of 1999, the impact of drought on vegetation, albedo, and soil moisture led to conditions that are consistent with surface feedbacks on precipitation. In the Euphrates Plain (EP), increased albedo led to reduced local heat flux, producing a shallow, stable planetary boundary layer (PBL) with low conditional instability (Figure 6). In the neighboring northern Zagros region (NZ), drought led to reduced soil moisture and increased sensible heat flux, causing a deep, dry PBL to develop. This condition is associated with enhanced entrainment of dry air at the top of the PBL and a reduction in conditional instability.

The EP is substantially more arid than the NZ. Differences in drought impacts and feedbacks between the two sub-regions are analogous to differences observed during drought in predominantly arid zones versus more humid regions. In dry areas, vegetation cover is sparse and soils are typically bright. Vegetation drought therefore causes an increase in albedo and a reduced energy environment. In more humid regions, drought is not necessarily associated with an increase in albedo—senescent vegetation tends to be brighter than live vegetation, and dry soils are brighter than wet soils, but these effects can be mitigated by resilient vegetation and offset by increased exposure of soils that are relatively dark even when dry [13]. Under these circumstances feedbacks related to evapotranspiration are expected to dominate, as drought transforms a normally moisture-rich landscape into a moisture-limited environment [14].

In the Middle East, climate variability is largely a product of external factors, and drought is a common occurrence for both the Euphrates Plain and the more humid—but still drought-prone—Zagros Plateau. In a region that contains steep precipitation gradients and large areas of marginal rain-fed agriculture, any local processes that enhance or mitigate drought are of interest. These processes can include local forcings on air temperature, feedbacks on vapor pressure and cloudiness, and modification of precipitation events. The present study revealed strong evidence for a local influence on temperature, water vapor, and cloudiness during moderate drought, with inconclusive results on precipitation. Further studies of Middle East drought, including analysis of historically extreme or persistent droughts, will further our understanding of land-atmosphere interactions in this environmentally sensitive region.

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EFFECTS OF ENVIRONMENTAL CONDITIONS ON WATER STATUS AND PHOTOSYNTHETIC ACTIVITY IN OLIVETREES (*Olea europaea* L. cv "Chemlali") UNDER NON IRRIGATED FIELD CONDITIONS

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ABSTRACT

How does the olive tree respond to environmental stress in the Mediterranean climate under non irrigated field conditions with respect to photosynthetic activity and water status? To answer this question, we determined net photosynthesis, stomatal conductance and transpiration rate in olive tree (*Olea europaea* L. cv "Chemlali") during the summer (June – July – August) and the autumn periods (September – October – November) and related them to environmental parameters. The experiment was carried out at the experimental field of the Olive Tree Institute in Sfax (Tunisia). The environmental parameters we followed were: air temperature, monthly rainfall and solar radiations. Similar patterns of net photosynthesis (Pn), stomatal conductance (Gs) and transpiration rate (E) were observed during both the plant rest (summer period) and the partial plant growth (autumn) phases. Low levels of all these parameters were observed and high relationships were determined between them. The maximum of photosynthesis (3.7 μmol m^{-2} s^{-1}) was reached in June in coincidence with the intense plant activity of the Chemlali olive cultivar. The minimum was detected in August (0.57μmol m^{-2} s^{-1}). The Chemlali olive tree tends to acclimatize to prolonged hot – dry seasons. As the olive tree perceived water deficit, it adjusted rapidly its water flux by closing its stomata, to maintain plant hydration, and therefore reducing its photosynthetic activity. High relationship was determined between Pn, Gs and E and leaf water status. It appears that heat and drought are the most important environmental stress factors that disrupt the plant's activity. Our results showed that the olive tree developed different mechanisms to cope with harsh climatic conditions. Its activity was slowed under severe climatic conditions and was immediately established when conditions become favourable.

Key words: Environmental conditions, *Olea europaea*, photosynthetic activity, water deficit

INTRODUCTION

Plants grown under Mediterranean climate are often exposed to a long period of drought and harsh environmental conditions which affect plant growth and agriculture development.

Olive tree, which characterizes the Mediterranean landscape subjected to regular dry seasons, is well known for its resistance to severe and prolonged water stress [1, 2, 3 and 4]. Indeed, its cultivation is highly encouraged in such areas [5]. Several researches have studied the relationship between photosynthesis activity and environmental conditions; they have shown that drought and heat are the most important environmental stress factors that disrupt the plant activity [6 and 3].

[7] showed that some olive tree cultivars cultivated in Mediterranean areas exhibit low photosynthetic activity and transpiration rates during dry seasons. [8] reported that series of adaptation mechanisms are triggered in such plants to resist to severe conditions. These adjustments led to changes in leaf water status, stomatal closure and therefore a reduction in photosynthetic rate. [3] also reported that Stomatal control is the major physiological factor to optimize water use in drought conditions. Moreover, [9] reported that stomatal closure is the earliest response to drought which may result in cell dehydration. On the other hand, [2] showed that olive leaves often experience a diurnal water stress during the dry season because the high hydraulic resistance of their stem causes the development of water deficit in leaves. The same authors showed that the olive tree tolerates lower water potential than the peach tree. On the other hand, [10] have also reported that water deficit applied at the final phase of growth of the peach tree affects photosynthetic performances.

[11] essentially explained the decrease of net photosynthesis in olive trees under water deficit by stomatal limitations. [12] reported that olive photosynthetic apparatus is resistant to mild water stress reinforced when it is accompanied by other environmental stress factors such as high light conditions.

In semi arid areas like Tunisia, in addition to the scarcity of rain water, difficult climatic conditions increase water stress in olive trees.

The main purpose of this paper is to investigate the responses of the Chemlali olive cultivar (*Olea europaea* L.), characterizing the arid climate in the south of Tunisia, to harsh environmental conditions under non irrigated field conditions.

MATERIALS & METHODS

Experimental Site and plant material

Trials were carried out in 2003 at the Tunisian Olive Tree Institute plantation (Sfax, 34°43N, 10°41E). Twelve -year- old non irrigated olive trees (*Olea europaea* L.) cv Chemlali were used. Plants were subjected to water deficit from March 2003 (T0). The sandy soil had an organic matter content of 1.3%; 12.3% $CaCO_3$; 1.2% N and a pH of 7.8.
Climatic conditions of the experimental site were obtained from a meteorological station installed within the Institute. Average of rainfall, air temperature and global solar radiations were recorded.

Water status measurements

Concomitant measurements of leaf water content (LWC) were calculated using the equation:

$$\text{LWC (\%)} = \frac{FW - DW}{FW} \; x \; 100 \qquad (1)$$

where *FW* is the fresh weight and *DW* the dry weight of leaf samples. They were respectively determined before and after oven drying at 80 °C for 48 hours. Soil moisture (SM) was measured monthly on a depth of 80 cm using the same equation. The values are the mean of four replications per treatment.

Gas exchange measurements

Leaf gas exchange measurements were taken four days per week from 7:00 am to 13:00 am, on well exposed six leaves (which developed after the imposition of the water stress) from each treatment using a portable gas exchange system (Li-Cor Inc-6200). It measures net photosynthesis (Pn), stomatal conductance (Gs), transpiration (E), air humidity, air and leaf temperature, air CO_2 and intercellular CO_2 concentrations.

Note: Local Time (Tunisia) = GMT + 1.

Statistical analysis

Statistical analyses were performed using analysis of variance (SPSS.10 Windows). Significant differences between values of all parameters were determined at $P \leq 0.05$ according to Duncan's multiple range tests.

RESULTS

Environmental parameters of the experimental site

The rainfall pattern in the trial year was characterized by a scant rain in spring (from March to May) and in autumn (93 and 111 mm of rain, respectively) and a dry summer (from June to August). The most important quantity (132 mm) was recorded at the beginning of winter (December). The experimental period was characterized by a moderate temperature during spring time (28°C), a high temperature average from June to October (34.5 °C) and an average of 24° C during November - December period. Indeed, in semi arid areas like Tunisia, the summer period does not last only three months (from June to August). It practically continued to mid- October with high temperature and less precipitation. The maximum of photosynthetic active radiations was marked during the summer season in coincidence with high temperature. Table 1 summarizes the most important environmental parameters recorded during the experimental period.

Table 1. Environmental parameters of the experimental site during the trial period.

Date	Mar	Apr	May	June	July	Augst	Sept	Oct	Nov	Dec
Precipitation (mm)	0.5	79	13.8	0.4	0.8	0.6	79	38.8	14.1	132
Temperature (°C)	27	28.5	29	34.5	37	39	31	31	26.5	21.5
PAR (µmol m^{-2} s^{-1})	950	1080	1150	1250	1450	1420	980	872	760	640

Time course of changes in water status

Soil moisture (SM) value was 5.6% at the start of measurements (5th of June), becoming significantly lower ($p = 0.007$) in August when it dropped to 3.5%.

During the period between June and August (summer), the severe climatic and soil conditions induced noticeable water deficit as shown by the decrease of leaf water content (LWC). In September, a slight re-increase of LWC was observed (Figure 1).

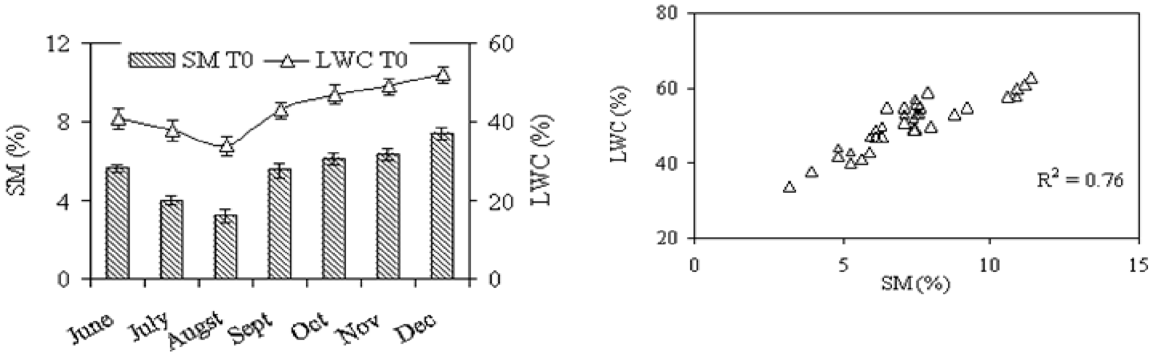

Figure 1. Time course of soil moisture (SM) and leaf water content (%) from June to December (on the left) and relationship between SM and LWC (on the right).

The increase of LWC and SM values observed in November-December was due to abundant rainfall that restored better soil moisture added to clement climatic conditions. There was a high correlation between LWC and SM (Figure 1).

Time course of changes in net photosynthesis

The maximum of photosynthetic activity was observed in June coinciding with the intense vegetative growth phase of the olive tree occurring under climate environmental conditions. After that, a significant decrease was recorded until the end of August (summer period). It decreased from 4.7 µmol m^{-2} s^{-1} in June to 1.8 µmol m^{-2} s^{-1} at the end of August. This was in coincidence with the lowest values of LWC (Figure 2A). During dry seasons, the Chemlali olive tree may have a special survival mechanism which reduces photosynthetic activity to prevent damaging plant survival chances.

In autumn, the recovery of leaf water status was accompanied with a better photosynthetic activity. However, Pn remained significantly lower than the average habitually noticed in this cultivar during this period. During this season, coinciding with the partial vegetative growth phase, the overall average of net photosynthesis was 2.5µmol m^{-2} s^{-1}.

Time course of transpiration rate

The patterns of transpiration rate were in some ways similar to those of Pn. The maximum of transpiration rate was observed in June, too. Therefore, it decreased steadily until the end of August when it marked the lowest values which were statistically lower than those recorded at the start of measurements ($P = 0.0003$). This was in parallel with the increase in air temperature and the decrease in SM and LWC.

At the beginning of autumn (September), an appreciable recovery of E rate was observed. However, it remained lower than that signaled during the intense vegetative growth phase (June). During this season, the transpiration rates were 2 mmol m^{-2} s^{-1} and the recovery did not permit to these plants to reach high values. Besides, E rate recovery depended on the level of water status previously reached. In December, E rate showed a slight decrease in comparison with values registered in November (Figure 2A).

Time course of stomatal conductance

The highest value of Gs (83mmol m^{-2} s^{-1}) was observed in June and the lowest values at the end of August (40 mmol m^{-2} s^{-1}). In autumn, Gs re-increased to 65mmol m^{-2} s^{-1} (Figure. 2B). They were significantly higher than those recorded at the end of summer (August). However, the time taken for recovery varied with the plant's water status. The more severe the water deficit was (T0), the slower the stomatal recovery was. The autumn rainfall allowed rain-fed plants to restore better stomatal conductance values under appreciable soil and leaf water status.

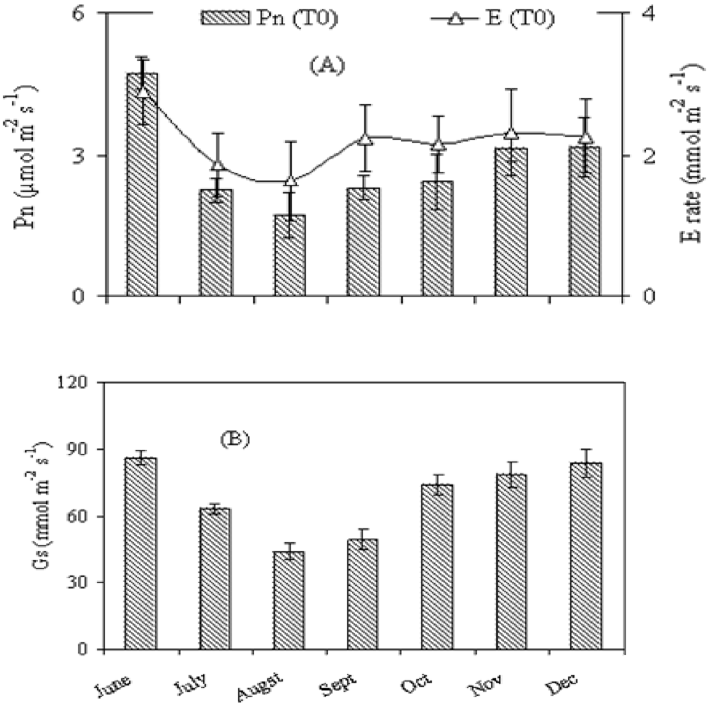

Figure 2. Time course of net photosynthesis, transpiration rate (A) and stomatal conductance (B) from June to December. Bars indicate S.E. (n = 12).

Daily course of net photosynthesis during June and August

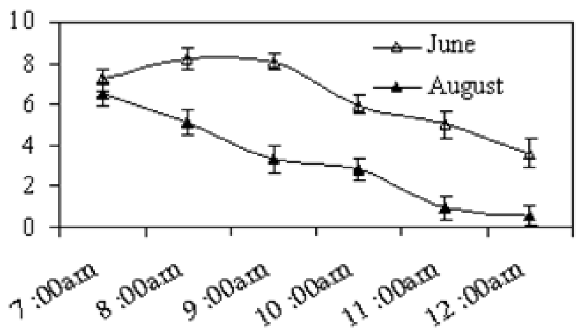

Figure 3. Daily course of net photosynthesis (Pn) at the morning in June (A) and in August (B). Bars indicate S.E. (n = 12).

In June, Pn showed a value of 7.2 µmol m^{-2} s^{-1} at 7:00 am, and increased progressively until a maximum of 8.25 µmol m^{-2} s^{-1} between 8:00 and 9:00 am. After that, a reduction was observed until the midday depression when Pn values reached 3.61 µmol m^{-2} s^{-1}.

In August, the patterns of Pn were different from those observed during June. The maximum was noticed at 7:00 am. A rapid decrease was observed and Pn reached a minimum (almost zero) at midday depression (Figure 3).

DISCUSSION

During summer, the occurrence of water deficit coincides with the increase in air temperature. The water deficit (T0) induced a large decrease in SM and therefore in LWC. Under severe climatic conditions (high temperature and low atmospheric humidity), LWC decreased markedly. During autumn, the re-increase of LWC was related to the second growth phase which caused the development of well hydrated young leaves. In addition, at this period of the year, the climatic conditions became more clement with lower temperatures, more precipitations and higher air humidity. This is consistent with earlier findings suggesting that more clement climatic conditions cause an increase in leaf water content [13, 8 and 3].

Accompanying these changes in LWC were large variations in leaf gas exchange parameters (Pn, Gs and E rates). Indeed, the maximum of Pn was reached in June during the intense growth phase of the olive tree occurring under favorable climatic conditions. However, these values remained lower than those recorded in irrigated plants under the same climatic conditions (data not show). On the other hand, these values were lower than those signaled in the same olive tree cultivar under non irrigated field conditions by [14]. This gives further evidence that high temperature occurring in 2003 has enormously affected plant activity.

Furthermore, it appears that water deficit applied during vegetative growth phase of the olive tree affects enormously gas exchange parameters. Furthermore, it confirmed previous findings by [9] who showed that water deficit affects water relations and consequently leaf photosynthetic activity.

The large depression of Pn occurring in summer (July – August) can be clearly linked to the climatic conditions. Indeed, Pn was controlled by temperature and photosynthetic active radiations intensity (PAR). Thus, rain-fed plants had the maximum of photosynthetic activity at a temperature of 28°C and a PAR of 950 µmol m^{-2} s^{-1} (Figure 4). It seems that a direct relation exist between air temperature and photosynthetic activity. Indeed, at high temperature, net photosynthesis decreased to almost zero.

The reduction of Pn under water stress may result from lower diffusion of CO_2 across leaf membranes [15]. The same idea has been developed by [16] who concluded that water stress induces a decrease in leaf conductance to CO_2 diffusion. In this work, this was shown by the decline in stomatal conductance during the summer period. It confirms results obtained by [17] who noticed that the prime role of stomata might be to avoid damaging the plant survival under water deficit.

During the plant rest phase (summer period), the decrease of transpiration rates suggests that under severe conditions, stomatal closure seems to be the earliest response to prevent cell dehydration and damaging plant survival. Indeed, olive trees gradually close their stomata to avoid water loss by transpiration as was shown by [2, 18 and 19]. This is consistent with findings of [20], who noticed that stomata did close in response to drying soil. Besides, high positive relationships were obtained between Pn, Gs and E and LWC (Figure 5). This kind of relation suggests that a hydraulic feedback mechanism exists between LWC and physiological activities of olive tree.

The decrease of Pn and Gs values during July and August resulted from a set of physiological regulations. As soon as olive tree perceived water deficit, it adjusted rapidly its water flux by stomatal closure to avoid water loss [9 and 21]. A positive relationship was also found between stomatal conductance and vapour pression in peach tree by [22]. They have reported that this relation can be expected for the hydraulic feedback mechanism and could indicate that a direct effect of soil / leaf water status on stomatal conductance should not be excluded.

It seems that during this season, this cultivar has a special survival mechanism which permits to the plant to reduce its activity and to enter in a plant rest phase. This behavior may be adopted to avoid damaging plant survival which can be justified by the display of some aspects of these activities even when irrigation was maintained during summer period (data not shown).

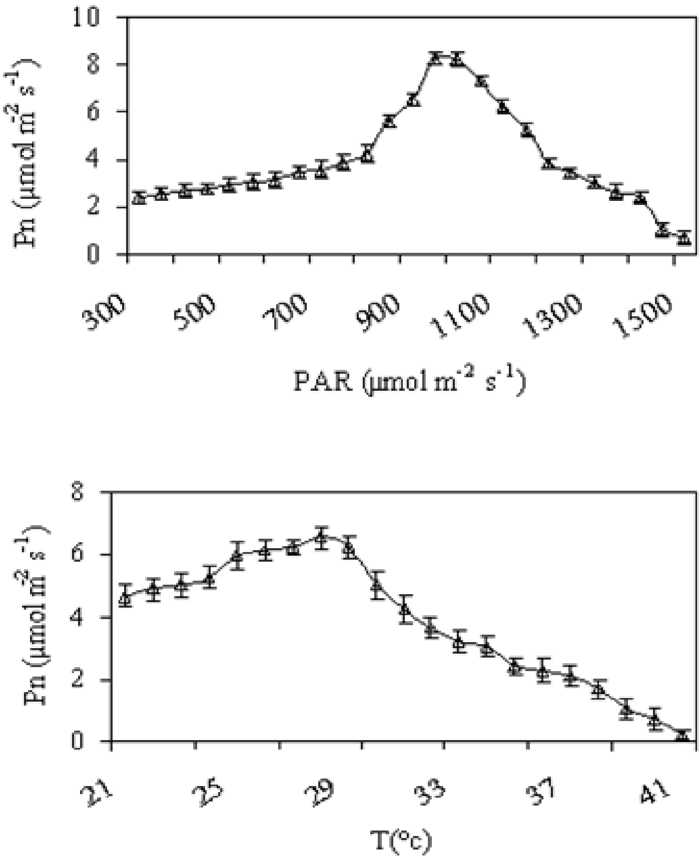

Figure 4. Changes of net photosynthesis with temperature (A) and photosynthetic active radiations (B) for all treatments.

Furthermore, in comparison with three forest species (*Quercus suber*, *Quercus ilex* and *Eucalyptus globulus*), [23] reported that *Olea europaea* showed the lowest values of net photosynthesis, stomatal conductance and transpiration rate from July to September. This suggests that some physiological mechanisms are not only related to environmental parameters but also to the species genetic characteristics. On the other hand, in their work on the banana tree, [24] reported that water deficit, applied during growth phase of this species, affects enormously the banana's development and that it required uniformly warm and moist conditions for optimum growth and yield. The same effects of water deficit have been shown on the pistachio tree by [25].

During autumn, the olive tree cv Chemlali restored its photosynthetic activity in conjunction with better LWC and SM status. However, these values remained lower than the average habitually recorded in this cultivar. In spite of rainfall occurring in autumn (176 mm), net photosynthesis of rain-fed plants was still low. It seems that precipitations were insufficient for these plants to establish their physiological activities during the vegetative growth phase. These results can also be explained by assuming that plant need for water increases when the plant is not at rest.

Furthermore, during this season, the olive tree seems to be invested in vegetative growth, fruit expansion and oil accumulation. Indeed, fruit growth constitutes a metabolic source in which were absorbed photosynthetic products and leaf reserves; a phenomenon that can affect photosynthetic performances. This is consistent with findings of [26] who suggested that fruit growth reduces water relations and photosynthetic activity. On the other hand, the autumn 2003 in Sfax was marked by a high temperature average (34°C) which could have slowed down net photosynthesis and affected enormously fruit maturation, average weight and oil accumulation (Ben Rouina, person. comm.).

In December, photosynthetic activity was low. Indeed, cold occurring during winter (T < 12 °C) affected Pn. During this season, the partial plant rest can be another tolerance strategy developed in olive tree cv Chemlali to resist to such climatic conditions.

Comparing the patterns of Pn between the two most important periods (June and August corresponding respectively, to the active growth phase and the partial plant rest); we could conclude that during June, Pn was active for a long period of day even in low rates.

In August, harsh environmental conditions triggered the mechanism that limits photosynthetic activity and reduced it to almost zero under water deficit. Indeed, under water deficit, high air temperatures induced a decrease of atmospheric humidity and an increase of transpiration which diminished leaf water content. This confirms previous findings by Rashke and Resemann, 1996 who stated that when subjected to severe conditions, the plant's most rapid response is stomata closure followed by a decrease in stomatal conductance affecting enormously photosynthetic activity. The effects of severe climatic conditions occurring the experimental period were reinforced by the water deficit. The reduction of photosynthetic performances under severe conditions helps the olive tree to avoid water loss, to maintain its hydration and to survive.

CONCLUSIONS

Scarcity of water available for irrigation in addition to severe environmental conditions is the most serious problems for agriculture in arid and semi arid regions. We can conclude with certainty that effects of water deficit are clearly expressed through an overall decline in gas exchange parameters (Pn, Gs, E). Besides, CO2 assimilation performances showed that they do not depend only on water availability for the plant. They seemed to be determined by some environmental factors such as light intensity, atmospheric humidity and air temperature. Indeed, the olive tree is known to rest in summer and in winter in order to survive. Its most intensive activity is in spring and to a lower extent in autumn.

On the other hand, another characteristic of the olive tree is its long lived leaves which let the photosynthetic activity to be accomplished during a long period of the year (even in low rate). Furthermore, the Chemlali olive tree is an active arid species which can survive severe environmental conditions and its activity is established when conditions become favorable. Under harsh environmental conditions, which are reinforced by water deficit, the olive tree developed many physiological and tolerance strategies in order to resist and avoid damaging plant activity.

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EFFECTS OF ENVIRONMENTAL CONDITIONS ON OLIVE TREE (*Olea europaea* L. cv Chemlali) UNDER IRRIGATED FIELD CONDITIONS

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ABSTRACT

Are the effects of environmental conditions in the Mediterranean climate on the olive tree softened by supplementary irrigation? To answer this question, we determined photosynthetic activity, stomatal conductance, transpiration rate and fruit growth of olive tree (*Olea europaea* L. cv "Chemlali") under irrigated field conditions during summer and autumn seasons. The summer period was characterized by high temperature and high light intensity. During autumn, climatic conditions were more clement and coincide with the partial plant growth phase. The experiment was carried out at the experimental orchard of the Olive Tree Institute in Sfax (Tunisia). Twelve year- old- drip irrigated olive trees were used. Trees were subjected to two treatments, T1 and T2 corresponding respectively to 33 and 66% of crop evapotranspiration (ETc). During summer, for both treatments, net CO2 assimilation, stomatal conductance and transpiration rate were markedly reduced by environmental conditions. Net photosynthesis was reduced by 72 and 66%, respectively in T1 and T2 in comparison with maximums (10.8 and 12.7 µmol m^{-2} s^{-1}, respectively in T1 and T2) reached in June coinciding with the intense plant's activity. In autumn, when climatic conditions became more clement, a significant increase in all parameters was observed for both of these treatments. Fruit growth was almost similar for both of these treatments. It reached 0.66 and 0.71g at the harvest, respectively in T1 and T2. For all parameters, differences between the two treatments were not statistically significant. Ours results demonstrated that heat is between the main important environmental factors that disrupt the plant's activity in Mediterranean climate and that supplementary irrigation would not be beneficial under harsh climatic conditions. Water supply will be of a great benefit if applied during vegetative growth phase occurring under climate conditions.

Key words: Environmental conditions, fruit growth, *Olea europaea*, photosynthetic activity, stomatal conductance, transpiration.

INTRODUCTION

The limited water availability in Mediterranean ecosystems and the current decrease of water resources are leading to the urgent need to better manage water use for irrigation in arid and semi arid areas. Several researches have studied the relationship between photosynthesis activity and environmental conditions; they have shown that heat is between the most important environmental stress factors that disrupt the plant activity [1, 2]. [3] showed that some olive tree cultivars cultivated in Mediterranean areas exhibit low photosynthetic activity and transpiration rates during dry seasons. [4] reported that series of adaptation mechanisms are triggered in such plants to resist to severe conditions. These adjustments led to changes in leaf water status, stomatal closure and therefore a reduction in photosynthetic rate. [2] also reported that Stomatal control is the major physiological factor to optimize water use in drought conditions. The same idea has been developed by [5] and [6] who noticed that under conditions of high temperature, olive plants can reduce an excessive water loss by closing their stomata. [7] reported that olive photosynthetic apparatus is resistant to mild water stress reinforced when it is accompanied by other environmental stress factors such as high light conditions.

The main purposes of this paper are (1) to investigate if the effects of harsh environmental conditions on the Chemlali olive tree are softened by supplementary irrigation and (2) to assess the needed quantity of water for this cultivar.

MATERIAL & METHODS

Experimental Site and plant material

Trials were carried out in 2003 at the Tunisian Olive Tree Institute plantation (Sfax, 34°43N, 10°41E). Twelve -year- old olive trees (*Olea europaea* L.) cv Chemlali were used. Trees were spaced 4 x 6 m and subjected to the same fertilization and common olive cultivation practices. The sandy soil had an organic matter content of 1.3%; 12.3% $CaCO_3$; 1.2% N and a pH of 7.8.

Climatic conditions of the experimental site were obtained from a meteorological station installed within the Institute. Average of rainfall, air temperature and global solar radiations were recorded.

Irrigated treatments

The ground water used for irrigation had a pH of 7.65 and an electrical conductivity of 2.5 dS m^{-1}. The concentration of the main ions was: 2.1 mM Na^+, 0.38 mM K^+, 4.3 mM Ca^{++} and 0.43 mM Mg^{++}. At the beginning of March 2003, two drip irrigated treatments, applied on the basis of crop evapotranspiration (ET_c, mm) were used. T1 and T2 were irrigated respectively with 33 and 66% of ET_c taking rainfall into account. The water use of olive tree (ET_c) was calculated as:

$$ET_c = ET_o * K_c * K_r \text{ [8]} \qquad (1)$$

$$ETo = 0.0023 * Ra * (T_{average} + 17.8) * (T_{max} - T_{min})^{0.5} \text{ [9];} \qquad (2)$$

where ET_o was the reference evapotranspiration; Ra: Solar radiation (MJ m^{-2} j^{-1}); $T_{average}$: the average of temperature; Tmax: maximum temperature; Tmin: minimum temperature

To estimate ET_c, the reference evapotranspiration was corrected by a crop coefficient K_c of 0.6 [8] and a reduction coefficient K_r of 0.9 [10]. The K_r applies to orchards more than 50 % ground cover and is described as:

$$K_r = 2 * C / 100; \qquad (3)$$

where C is the percent canopy cover.

Water status measurements and fruit weight control
Concomitant measurements of leaf water content (LWC) were calculated using the equation:

$$\text{LWC}\ (\%) = \frac{FW - DW}{FW}\ x\ 100; \quad (4)$$

where *FW* is the fresh weight and *DW* the dry weight of leaf samples. They were respectively determined before and after oven drying at 80 °C for 48 hours. Soil moisture (SM) was measured monthly on a depth of 80 cm using the same equation. The values are the mean of four replications per treatment.

Control of fruit average weight was made four times per month. In every control, 20 olives from each treatment were collected and weighed.

Gas exchange measurements
Leaf gas exchange measurements were taken four days per week from 7:00 am to 13:00 am, on well exposed six one-year-old leaves from each treatment using a portable gas exchange system (Li-Cor Inc-6200). It measures net photosynthesis (Pn), stomatal conductance (Gs), transpiration (E), air humidity, air and leaf temperature, air CO_2 and intercellular CO_2 concentrations.

Note: Local Time (Tunisia) = GMT + 1.

Statistical analysis
Statistical analyses were performed using analysis of variance (SPSS.10 Windows). Significant differences between values of all parameters were determined at $P \leq 0.05$ according to Duncan's multiple range tests.

RESULTS

Environmental parameters of the experimental site
The rainfall pattern in the trial year was characterized by a scant rain in spring (from March to May) and in autumn (93 and 111 mm of rain, respectively) and a dry summer (from June to August). The most important quantity (132 mm) was recorded at the beginning of winter (December). The experimental period was characterized by a moderate temperature during spring time (28°C), a high temperature average from June to October (34.5°C) and an average of 24°C during November - December period. Indeed, in semi arid areas like Tunisia, the summer period does not last only three months (from June to August). It practically continued to mid- October with high temperature and less precipitation. The maximum of photosynthetic active radiations was marked during the summer season in coincidence with high temperature. Table 1 summarizes the most important environmental parameters recorded during the experimental period.

Table 1. Environmental parameters of the experimental site during the trial period.

Date	Mar	Apr	May	June	July	Augst	Sept	Oct	Nov	Dec
Precipitation (mm)	0.5	79	13.8	0.4	0.8	0.6	79	38.8	14.1	132
Temperature (°C)	27	28.5	29	34.5	37	39	31	31	26.5	21.5
PAR (µmol m^{-2} s^{-1})	950	1080	1150	1250	1450	1420	980	872	760	640

Time course of changes in water status

During the summer period, SM values in T1 and T2, which were very similar and were not statistically different between them (P = 0.325), remained almost constant at 5 and 6%, respectively (Figure 1).

During the period between June and August (summer), the severe climatic and soil conditions induced a noticeable decrease of leaf water content (LWC) which showed a clear decrease. In August, for both treatments, LWC reached values statistically lower than those signaled at the start of measurements (P = 0.0002). In September, there was a re-increase of LWC. (Figure 1). The re-increase of LWC values was almost similar in both irrigated plants. These values were 48 and 50% respectively, in T1 and T2. There was a high correlation between LWC and SM (Figure 1).

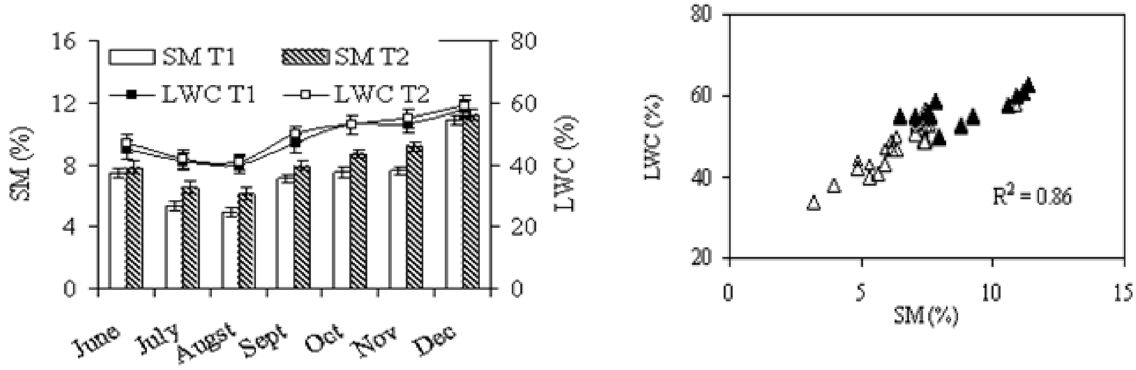

Figure 1. Time course of soil moisture (SM) and leaf water content (%) from June to December (on the left) and relationship between SM and LWC.

Time course of changes in net photosynthesis

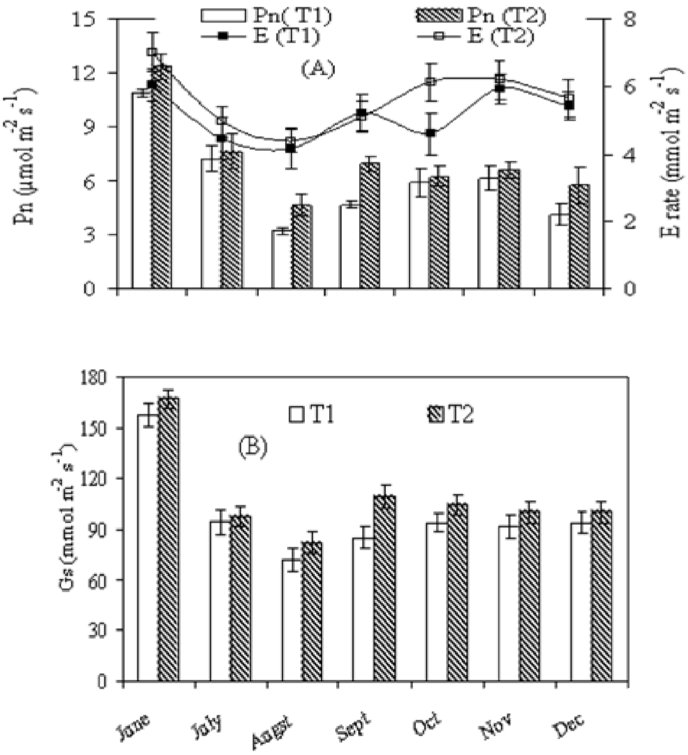

Figure 2. Time course of net photosynthesis, transpiration rate (A) and stomatal conductance (B) from June to December. Bars indicate S.E. (n = 12).

For both treatments, the maximum of photosynthetic activity was observed in June coinciding with the intense vegetative growth phase of the olive tree. It was 10.8 and 12.7 µmol m^{-2} s^{-1} respectively, in T1 and T2. After that, a significant decrease was recorded for both treatments until the end of August (summer period). This was in coincidence with the lowest values of LWC (Figure 2A).

During the same period, net photosynthesis decreased by 50% in T1 and 45% in T2 in comparison with values observed during June. In well irrigated plants (T2), Pn was almost similar to that subjected to milder water irrigation (T1) and differences between them were not statistically significant ($P = 0.325$). During dry seasons, the Chemlali olive tree may have a special survival mechanism which reduces photosynthetic activity to prevent damaging plant survival chances.

In autumn, coinciding with the partial vegetative growth phase of the olive tree, the overall averages of net photosynthesis were 4.5 and 6 µmol m^{-2} s^{-1} respectively, T1 and T2. This is an indicator that irrigation of the olive tree will be beneficial if applied during vegetative growth phase.

Time course of transpiration rate

The patterns of transpiration rate were in some ways similar to those of Pn. For both treatments, the maximum of transpiration rate was observed in June, too. Therefore, it decreased steadily until the end of August when it marked the lowest values which were statistically lower than those recorded at the start of measurements (P = 0.0003). This was in parallel with the increase in air temperature and the decrease in SM and LWC. The slight difference between values of E rates of irrigated treatments in terms of Pn was not significant (P = 0.453).

At the beginning of autumn (September), an appreciable recovery of E rate was observed as well in T1 as in T2. However, it remained lower than that signaled during the intense vegetative growth phase (June). During this season, the transpiration rates were 5 and 5.6 mmol m^{-2} s^{-1} respectively, in T1 and T2. In December, E rate showed a slight decrease in comparison with values registered in November (Figure 2A).

Time course of stomatal conductance

The patterns of stomatal conductance were in some ways similar to those of Pn and E rate. The highest values of Gs (161 and 166 mmol m^{-2} s^{-1} respectively, in T1 and T2) were observed in June. However the lowest values were recorded at the end of August. In autumn, Gs re-increased to 95 and 110 mmol m^{-2} s^{-1} respectively, in T1 and T2 (Figure 2B). They were significantly higher than those recorded at the end of summer (August) but they did not reached values recorded in June.

Daily course of net photosynthesis during June

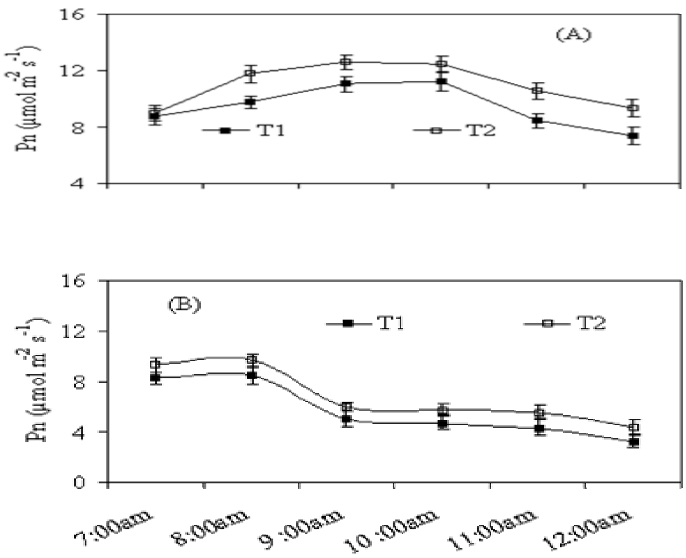

Figure 3. Daily course of net photosynthesis (Pn) at the morning in June (A) and in August (B). Bars indicate S.E. (n = 12).

At 7:00 am, the Pn showed a value of 9 µmol m^{-2} s^{-1} and increased progressively until a maximum of 11.2 and 12.6 µmol m^{-2} s^{-1} at 11:00 am, respectively in T1 and T2. After that, a decrease was observed until the midday depression (Figure 3A). However, differences between both treatments were not statistically significant (P = 0.653).

Daily course of net photosynthesis during August

The patterns of Pn were different from those observed during June. At the morning, values were almost similar for both treatments. The maximum was observed at 9:00 am. A more rapid and larger decrease was observed than that in June. The lowest values of Pn in T1 and T2 reached 3.2 and 4.3 µmol m^{-2} s^{-1}, respectively (Figure 3B).

Time course of fruit weight

Fruit weight averages increased markedly with time. In October, their values were 0.68 and 0.71g and reached 1.29 and 1.32g, respectively in T1 and T2 in January. The two irrigated treatments presented almost similar values of which differences were not statistically significant.

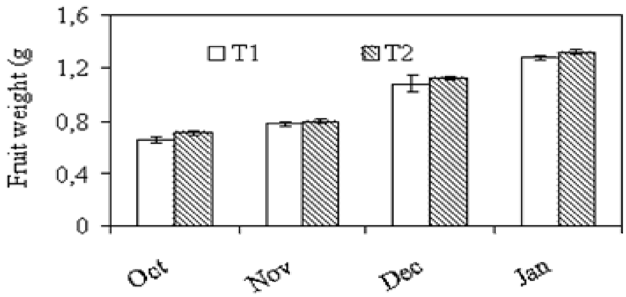

Figure 4. Time course of fruit weight from October to January. Bars Indicate S.E. (n = 4).

DISCUSSION

Under severe climatic conditions (high temperature and low atmospheric humidity), LWC decreased markedly for both irrigated treatments. During autumn, the re-increase of LWC was related to the second growth phase which caused the development of well hydrated young leaves. In addition, at this period of the year, the climatic conditions became more clement with lower temperatures, more precipitations and higher air humidity. This is consistent with earlier findings suggesting that more clement climatic conditions cause an increase in leaf water content [11, 4, 2].

Accompanying these changes in LWC were large variations in leaf gas exchange parameters (Pn, Gs and E rates). Indeed, the maximum of Pn was reached in June during the intense growth phase of the olive tree occurring under favorable climatic conditions. However, the recorded values remained lower than the averages signaled in this cultivar by [12], [13] and [14] who reported values of Pn of 20 µmol m^{-2} s^{-1} in irrigated plants. These differences can be explained by the particularly high temperatures characterizing the period of this study.

The large depression of Pn occurring in summer (July – August) can be clearly linked to the climatic conditions. Indeed, Pn was controlled by temperature and photosynthetic active radiations intensity (PAR). Thus, these plants had the maximum of photosynthetic activity at a temperature of 30°C and a PAR of 1250 µmol m^{-2} s^{-1} (Figure 6). Furthermore, at high temperature, net photosynthesis decreased to almost zero for both treatments. This is a clear evidence that water supply will be without benefits for plants if applied under harsh environmental conditions such as high air temperature and light intensity.

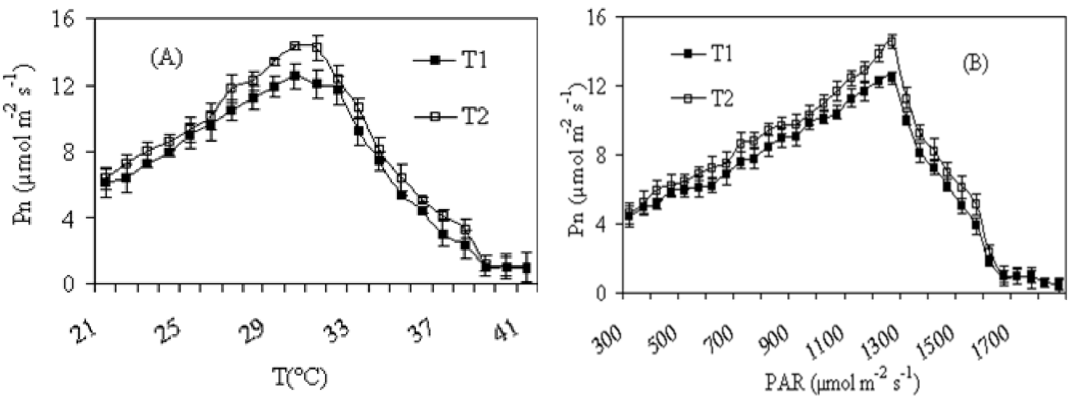

Figure 5. Changes of net photosynthesis with temperature (A) and photosynthetic active radiations (B) for all treatments.

Besides, it is a clear evidence that water supply would not be the only survival factor for these plants. Indeed, the availability of water is insufficient to induce maximum photosynthetic assimilation if other environmental factors (temperature, radiation intensity, air humidity) are not favorable [2].

During the plant rest phase (summer period), the decrease of transpiration rates for both treatments suggests that under severe conditions, stomatal closure seems to be the earliest response to prevent cell dehydration and damaging plant survival. Indeed, olive trees gradually close their stomata to avoid water loss by transpiration as was shown by [15], [5] and [6]. This is consistent with findings of [16], who noticed that stomata did close in response to drying soil.

Besides, it is possible that the Chemlali olive tree did not need water supply under described climatic conditions during the summer period. It seems that during this season, this cultivar has a special survival mechanism which permits to the plant to reduce its activity and to enter in a plant rest phase. This behavior may be adopted to avoid damaging plant survival which can be justified by the display of some aspects of these activities even when irrigation was maintained during summer period. Furthermore, in comparison with three forest species (*Quercus suber*, *Quercus ilex* and *Eucalyptus globulus*), [17] reported that *Olea europaea* showed the lowest values of net photosynthesis, stomatal conductance and transpiration rate from July to September. This suggests that some physiological mechanisms are not only related to environmental parameters but also to the species genetic characteristics. During autumn, the olive tree cv Chemlali restored its photosynthetic activity in conjunction with climate environmental conditions. These results can also be explained by assuming that plant need for water increases when the plant is not at rest; the Chemlali olive tree benefits from water supply only in spring (March - June) and in autumn (September - November).

However, values of Pn recorded in autumn remained lower than the average habitually recorded in this cultivar [12, 13 and 14]. Indeed, during this season, the olive tree seems to be invested in vegetative growth, fruit expansion and oil accumulation. In fact, fruit growth constitutes a metabolic source in which were absorbed photosynthetic products and leaf reserves; a phenomenon that can affect photosynthetic performances. This is consistent with findings of [18] who suggested that fruit growth reduces water relations and photosynthetic activity. On the other hand, the autumn 2003 in Sfax was marked by a high temperature average (34°C) which could have slowed down net photosynthesis and affected enormously fruit maturation, average weight and oil accumulation (Ben Rouina, person. comm.).

In December, photosynthetic activity was low. Indeed, cold occurring during winter (T < 12 °C) affected Pn even under well water availability. The partial plant rest during winter can be another tolerance strategy developed in olive tree cv Chemlali to resist to such climatic conditions.

Differences in Pn, Gs and E rates between the two irrigated treatments were not statistically significant. It appears that the Chemlali olive tree does not need more than 600 mm per year and that excess of water will not be valorized. In contrast, it will be lost by evaporation and percolation in soil. Our results confirm those of [12] and [19] who estimated that water needs for this cultivar under field conditions in arid and semi arid regions were around 40% of ETc. Indeed, under the same conditions, the contribution of 450 mm of water per year could cover the Chemlali olive tree needs [19].

Differences in fruit weight between the two treatments were not statistically significant. Comparing the patterns of Pn between the two most important periods (June and August corresponding respectively to the active growth phase and the partial plant rest); we could conclude that during June, Pn was active for a long period of day.

In August, in irrigated plants the decrease from maxima of Pn was more rapid and more severe than that occurring in June. So, harsh environmental conditions triggered the mechanism that limits photosynthetic activity and reduced it to almost zero.

CONCLUSIONS

Decrease of physiological activities in irrigated plants under severe conditions was a clear evidence that water supply in such periods would not be the only survival factor for these plants. Besides, gas exchange parameters showed that they do not depend only on water availability for the plant. They seemed to be determined by some environmental factors such as light intensity, atmospheric humidity and air temperature. This work provided some further evidence that the olive tree rests in summer and during severe climatic conditions in order to survive even under well water availability. These findings may serve to better manage water resources by stopping unnecessary irrigation during summer time. When applying a complementary irrigation, this works suggests that the adequate quantity of water that meets the needs of the olive tree should not exceeds 600 mm of water per year.

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POTENTIAL IMPACTS OF CLIMATE CHANGE ON IRRIGATED CROP WATER REQUIREMENTS IN TURKEY: A MODELING STUDY

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ABSTRACT

It is becoming increasingly clear that the water sector that will be most influenced by projected climate change is irrigation. What is less known however is the magnitude of climate change impacts on irrigation water requirements and crop productivity, particularly in the Middle East, where water shortages are already a significant problem. Climate model projections into the next century predict a significant rise in temperature and evaporation in the region with little or no change in precipitation. To better understand the impacts of these projections on irrigated crop water demand, we have recently developed a spatially explicit model that requires information on irrigated areas, climate, and crop type. Our model is partially based on the popular CROPWAT algorithm. Using our model, we investigated the impact of climate change, in particular doubled atmospheric CO_2 concentrations, on irrigation water requirements in Turkey. Our results indicate significant increase in monthly ET caused by increased near surface temperature and decreased summer precipitation. The enhanced ET leads to increased crop water requirements under the future climate change scenario, leading to overall 30-40% increase in monthly irrigation needs with wide geographic variation. The results of this study also provide the opportunity to develop agroclimatic zone maps under different future climate change scenarios. The future work will also incorporate crop physiological effects to determine the interactions between increased CO_2 concentrations and yield and crop quality.

INTRODUCTION

Significant evidence for human induced climate change, namely increased CO_2 levels and associated changes in temperature and precipitation rates, has been accumulating in the scientific literature over the past two decades [1][2][3][4]. At current emissions rates, Earth's climate is likely to change even further, well into the 21st century. What is less known however are the impacts these changes in climate will have on sectors that are important to human well-being. One such sector is irrigation, particularly in semi-arid regions like the Middle East that already face severe water shortages [5]. While climate model projections late into this century predict a significant rise in temperature and evaporation with little or no change in precipitation in the region, there is very little information on potential changes in irrigation patterns, irrigation water requirements in the Middle East region.

To better understand the impacts of climate change projections on irrigated crop water demands and productivity, we have recently developed a spatially explicit irrigation water model that requires information on irrigated areas, crop type, and current and future climate. Using our model, we investigated the impacts of climate change on irrigation water requirements and crop productivity in Turkey under a doubled CO_2 climate scenario. In the research presented here, we present results from only two experiments: a) current irrigation extent and current climate; and b) current irrigation extent and future (2 x CO_2) climate.

METHODOLOGY

The impact of climate change on crop water requirements and crop productivity requires careful consideration of change at various levels [6]. Firstly, the changes in atmospheric CO_2 levels have a direct impact on plant physiology, directly affecting how they grow and how much water they transpire. Secondly, impacts via changes in local weather, particularly rainfall and evapotranspiration, affect the soil water balance and hence the irrigation needs. While both of these impacts equally affect the conditions of growing and irrigating crops, in the research presented here, we specifically concentrate on impacts of local weather changes brought about by climate change (i.e. theme two above) on crop irrigation water requirements as well as production. Moreover, we concentrate only on average crop irrigation requirements under changing climate, not necessarily on individual crop types grown in Turkey. In the nest two sections, we present the datasets and the modeling tools.

Description of the Study Domain

The simulation domain is located between 25 and 47 degrees East longitudes and 34 and 43 degrees North latitudes, squarely fitting over Turkey. Irrigation is an important part of agriculture in Turkey, practiced on over 4 million hectares of land, making Turkey one of the largest irrigators in Middle East. Irrigation is primarily practiced in wide east-west oriented river valleys in the West, central Anatolian plains, in South-Central Cukurova Plain and increasingly in the Southeast. The Southeastern Anatolia Project (GAP as the Turkish Acronym) is one of the largest irrigation development projects in the world. When completed, it is expected to irrigate roughly 1.7 million hectares with mainly water diverted from the Euphrates and Tigris rivers. While there are several major studies investigating the climate change impacts on irrigation within the GAP Project, there has been a lack of country-wide studies on climate change impacts on irrigation water requirements. One goal of this study is to fill that gap.

Datasets

For this study, we utilized a portion (over Turkey) of global datasets for assessing irrigation requirements under contemporary and doubled CO_2 climate. For example, the International Geosphere–Biosphere Program (IGBP) has promoted the development of several global datasets, including a 1-km-resolution land-cover classification dataset [7] and a 5-minute resolution (approximately 10 km on a side) global soil dataset [8]. In this study, we use the land-cover and soil datasets to examine the relationships between cultivated land and soil water availability.

A continuous, globally consistent dataset on irrigation was developed recently by [9] also at 5-minute resolution. This dataset was created by calibrating the FAO country specific irrigation information against a worldwide collection of irrigation data. The dataset describes the fraction of each 5-minute grid cell equipped to be irrigated *ca.* 1995. Similarly, a global database of crop types were recently developed by [10] at the same spatial resolution. Originally developed for 19 crop types, we used only 6 crops, including wheat, barley, maize, sunflower, cotton, and pulses, common for Turkey. This crop type database was used to describe crop coefficients to further develop crop evapotranspiration.

To derive the climatic impacts of irrigation we use the newly developed WorldClim climatological dataset of [11] and [12] for both contemporary and doubled CO_2 climate, respectively. The contemporary climate dataset represents the mean-monthly climate conditions for the 1961–1990 period, while the future climate dataset represents the mean-monthly climate conditions under a doubled CO_2 atmosphere. Both datasets are provided in a gridded form with a resolution of 5-minute latitude by longitude. The variables of interest used in this study are monthly temperature and precipitation. To describe the soil effects on irrigation, we use the recently developed IGBP-DIS global soil dataset [8], which contains various soil properties including soil water holding capacity, at a 5-minute resolution in both latitude and longitude.

Model Description

The structure of our irrigation water requirements (need depths) IWR model is based on the popular CROPWAT crop water model [13] schematically represented in Figure 1. The model is driven using the observed monthly mean climate data (surface air temperature and precipitation) of [11] and [12] and estimates spatial patterns of irrigation water requirements. The monthly mean values are linearly interpolated to obtain daily mean values to drive the model. The model runs on a daily time step, except for the reference evapotranspiration calculations that run on a quasi-hourly time step (i.e. solar radiation, a component of evaporative demand is calculated on an hourly time step although the supply term is calculated daily). The first step in the model is to compute Penman-Monteith reference evapotranspiration (ET_0) using a very simple surface energy balance model [14]. More specifically, the net absorbed solar radiation, SW_{net}, is calculated as

$$SW_{net} = S_0(1-\alpha)(c+dn)\cos(\zeta) \qquad (W/m^2) \tag{1}$$

where S_0 is the solar constant (1370 W/m^2), α is the average land albedo (0.17), c and d are the constants (0.25 and 0.50, respectively), n is the fractional potential sunshine hours (based on latitude and day of the year) and cos (ξ) is the cosine of the solar zenith angle. The net upward long-wave radiation, LW_{net}, is calculated as

$$LW_{net} = (b+(1-b)(1-n)(A-T) \qquad (W/m^2) \tag{2}$$

where b and A are the constants (0.2 and 107.0, respectively), and T is the air temperature (°C).

Equilibrium evapotranspiration (ET_{eq}) is a function of net radiation, and is calculated using the Penman equation:

$$ET_{eq} = \left(\frac{s}{s+\gamma}\right)\left(\frac{SW_{net} - LW_{net}}{L}\right) \qquad (mm/h) \tag{3}$$

where s is the rate of change of saturated water-vapor pressure with respect to temperature, γ is the psychrometer constant (65 Pa/K) and L is the latent heat of vaporization of water (2.5 x

10^6 J/Kg). SW_{net} is calculated on an hourly time step, while LW_{net} is calculated daily and assumed to be the same throughout the day.

Reference evapotranspiration (ET_0), or evaporative demand, is calculated following [15] as:

$$ET_0 = ET_{eq} a_m [1 - \exp(-g_s / g_c)] \qquad (mm/h) \qquad (4)$$

where a_m = 1.26 is the Priestley-Taylor coefficient [16], g_s is the canopy integrated stomotal conductance, and g_c is a scaling conductance (chosen to be 0.2 mol/m^{2}s^{-1} based on [15]). A study by [17] suggest g_s value of 0.8 mol/m^{2}s^{-1} for present-day concentrations and 0.6 mol/m^{2}s^{-1} for doubled CO_2 conditions based on a coupled photosynthesis-stomatal conductance model.

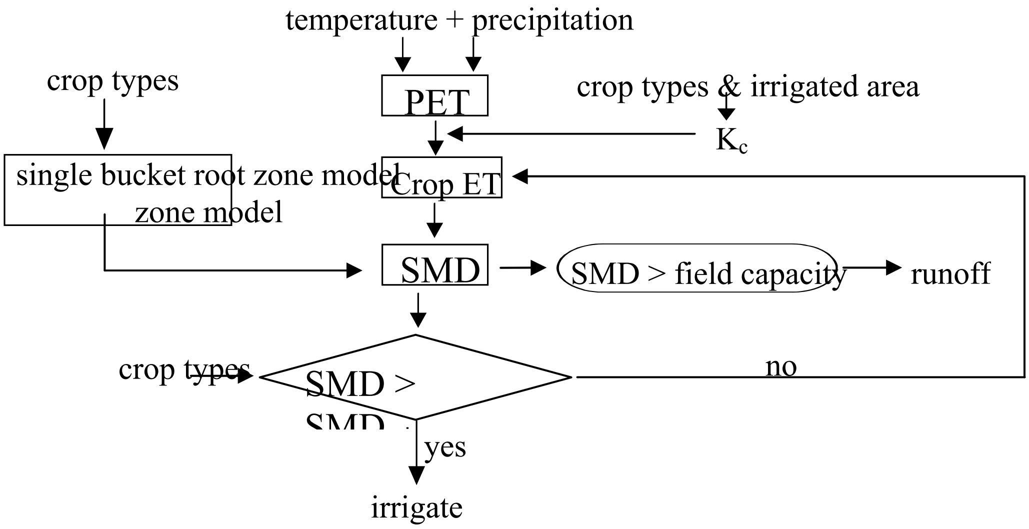

Figure 1. Schematic representation of the irrigation water model structured on the popular CROPWAT method.

The next major step in the irrigation model is to define crop types (based on the 6 crop type maps) and crop coefficients (K_c) and planting dates, obtained from the FAO tables. Associated data for this are the root depth vs. time after planting, critical water fraction (P) and yield response data. The K_c growth stage values are then interpolated from the K_c curves into daily values and crop evapotranspiration (ET_c) computed as

$$ET_c = ET_0 x K_c \qquad (5)$$

In the next step, the model defines a single bucket root zone model based on soil type (e.g. medium soil holds 140 mm of water per m of active root depth) and computes daily water balance to calculate ET_c - *rainfall*. At this stage, the model also computes the soil moisture deficit (*SMD*), and decides if there is any runoff and continually updates the *SMD*. Depending on the *SMD*, the model also decides if the *SMD* is greater than the *P* fraction (e.g.

if P= 0.4 and the soil is medium then the critical SMD is 0.4 x 140 mm). Irrigation is applied if SMD is greater than critical SMD (e.g. 0.4x140 mm) in the amount to bring the soil to full saturation. At the same time, potential ET is reduced to actual ET using a linear sliding scale and is used to update the SMD value in place of ET_c. Note that this algorithm does no take into account any groundwater contribution to/from the root zone.

The grid-scale irrigation requirements (IRR_{sum}) are computed as the weighted sum of all individual crop types and associated irrigation requirements on a daily basis as follows:

$$IRR_{sum} = I_A \sum_{n=1}^{c} IWR_c x A_c \tag{6}$$

In (6), IWR_c is each crop's daily irrigation requirements and A_c is that crop's fractional area. This is applied to only the irrigated portion of the grid (I_A). The model is ran for two experiments, the first one using the datasets representing the contemporary climate and the second one using datasets under doubled atmospheric CO_2 conditions.

RESULTS

The changes in mean monthly precipitation, temperature, ET, and net radiation, averaged over the entire domain are shown in Figure 2. With climate change (under conditions of doubled CO_2), summer rainfall decreases markedly while temperature increases throughout the entire year. Increased temperatures also lead to enhanced evapotranspiration from the land surface, on the average 2-4 percent per month. There is very little change in the way of net radiation at the surface. It is important to note that all variables mirror closely the pattern of the current baseline climate except for precipitation where, in the winter months, marginal increases in rainfall are shown. The temporal pattern of ET remains broadly similar to the baseline, but with overall higher rates of ET. As expected, the highest increases in ET rates are in the summer months.

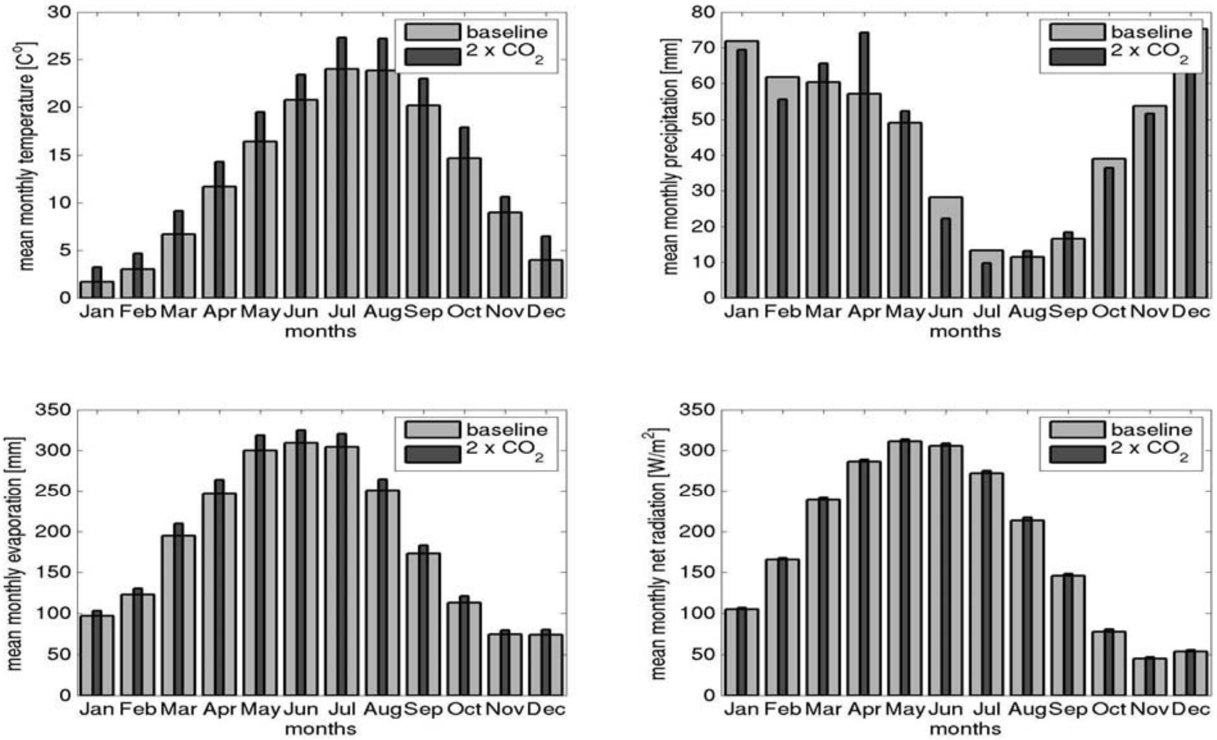

Figure 2. Monthly mean changes in temperature (top left), precipitation (top right), ET (bottom left) and net radiation (bottom right) under doubled atmospheric CO_2 concentrations from the contemporary climate.

For irrigation, the changes in Precipitation and ET are significant. They suggest much higher evaporative demands during the growing season and drier summers, and therefore a net increase in the requirement for irrigation. In winter, however, the increases in rainfall offer a reduction and hence greater conservation of irrigation water.

When the irrigation model was run under today's climate conditions, the monthly irrigation water requirements show expected patterns (Figure 3). In April, the cereal crops (e.g. wheat, barley) represent the largest irrigation withdrawals (possibly in the form supplemental irrigation) primarily in cereal centers of the country. In the summer months, however, irrigation requirements shift to traditionally dry places such as Western regions, the Cukurova Plain and the Southeast following heavy maize and cotton irrigation.

To illustrate the potential impact of climate change on major irrigated crops the model was also run for the entire domain and the geographic distribution of changes in irrigation need is given in Figure 4. Under the doubled CO_2 conditions, at all irrigated grids, an increase in contemporary climatic conditions irrigation need is shown. The changes, however, vary geographically across the country, reflecting the varying regional impact of climate change. On average, however, especially for the summer months, the increases "changed" year irrigation needs from the current trend are in the order of 30-40%.

FUTURE WORK

Impacts of Increased Atmospheric CO_2 on Plant Physiology

While not considered in this study, changes in atmospheric CO_2 have been shown have direct impacts on crop physiology and could be a potentially significant driver on irrigation water demand [18]. Potential impacts include changes to stomatal resistance, transpiration rates transpiration efficiency, photosynthesis, and yield and crop quality. Hence, in the near future, the irrigation water requirements model will be modified to include these physiological changes to determine their interaction with other limiting resources such as temperature and precipitation changes.

Agroclimatic Zone Mapping

One outcome of our study is the possibility of defining and delineating Agroclimatic zones to delimit areas of common irrigation water need changes. For example, using the baseline climate data, it is possible to map potential soil moisture deficit as a monthly balance between Precipitation and ET. In months where Precipitation>ET, no deficit occurs. In months where ET>Precipitation, the deficit that accrues in that month is then carried forward to the following month. Since water deficit is a good indicator of irrigation water needs, this procedure could be repeated for future climate change scenarios to map future soil moisture deficit and by classifying these maps, it is possible to generate maps of future Agroclimatic zones under "changed" climate conditions. For example, it is expected that in Turkey, the arid southeast, south central and west will show the highest changes in soil moisture deficit, corresponding to regions where irrigation needs will be the highest.

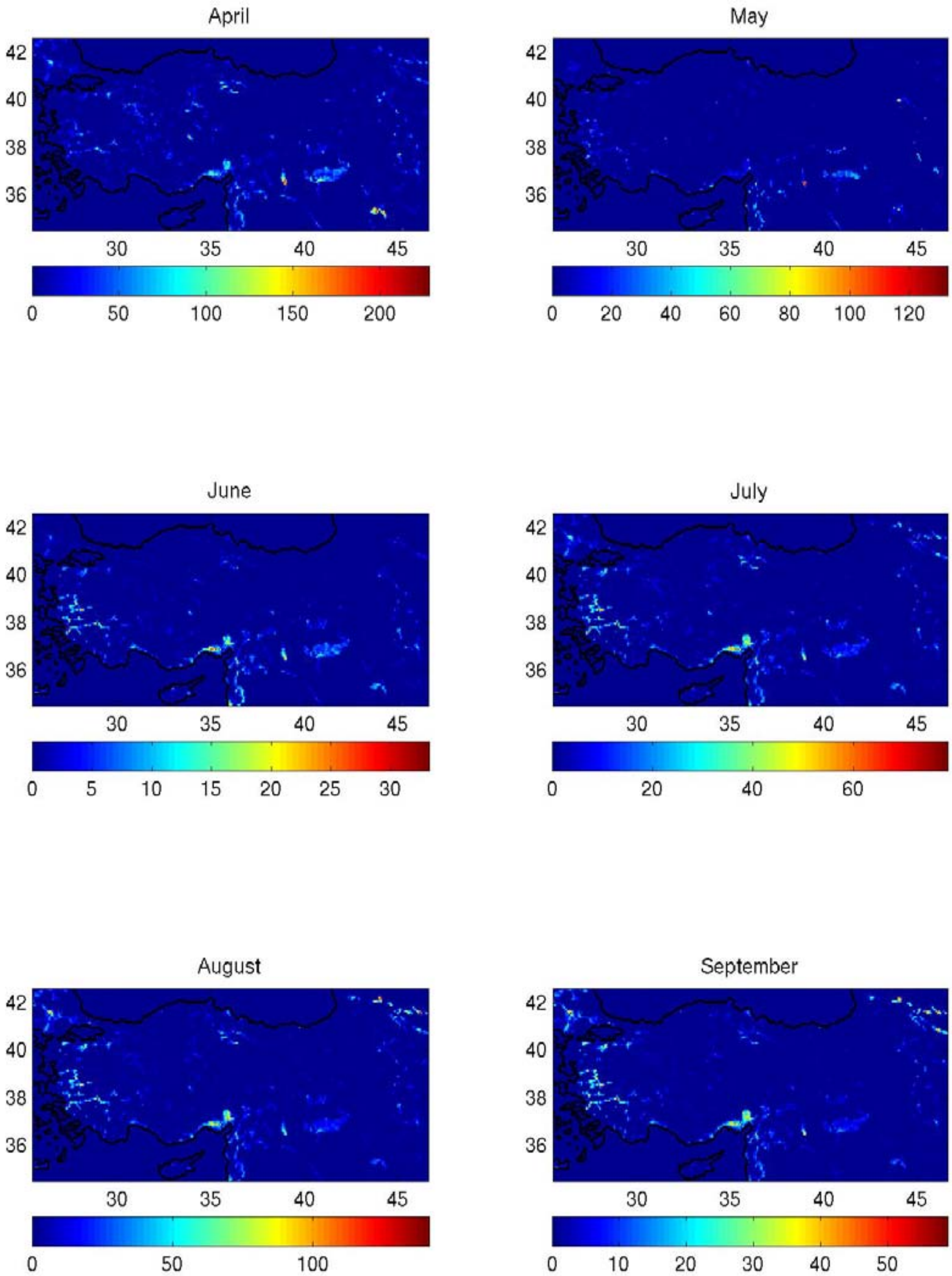

Figure 3. Geographic patterns of monthly irrigation water requirements under contemporary climate. The left and bottom numbers indicate latitude and longitude, respectively. Note that the scale for irrigation need changes in each month.

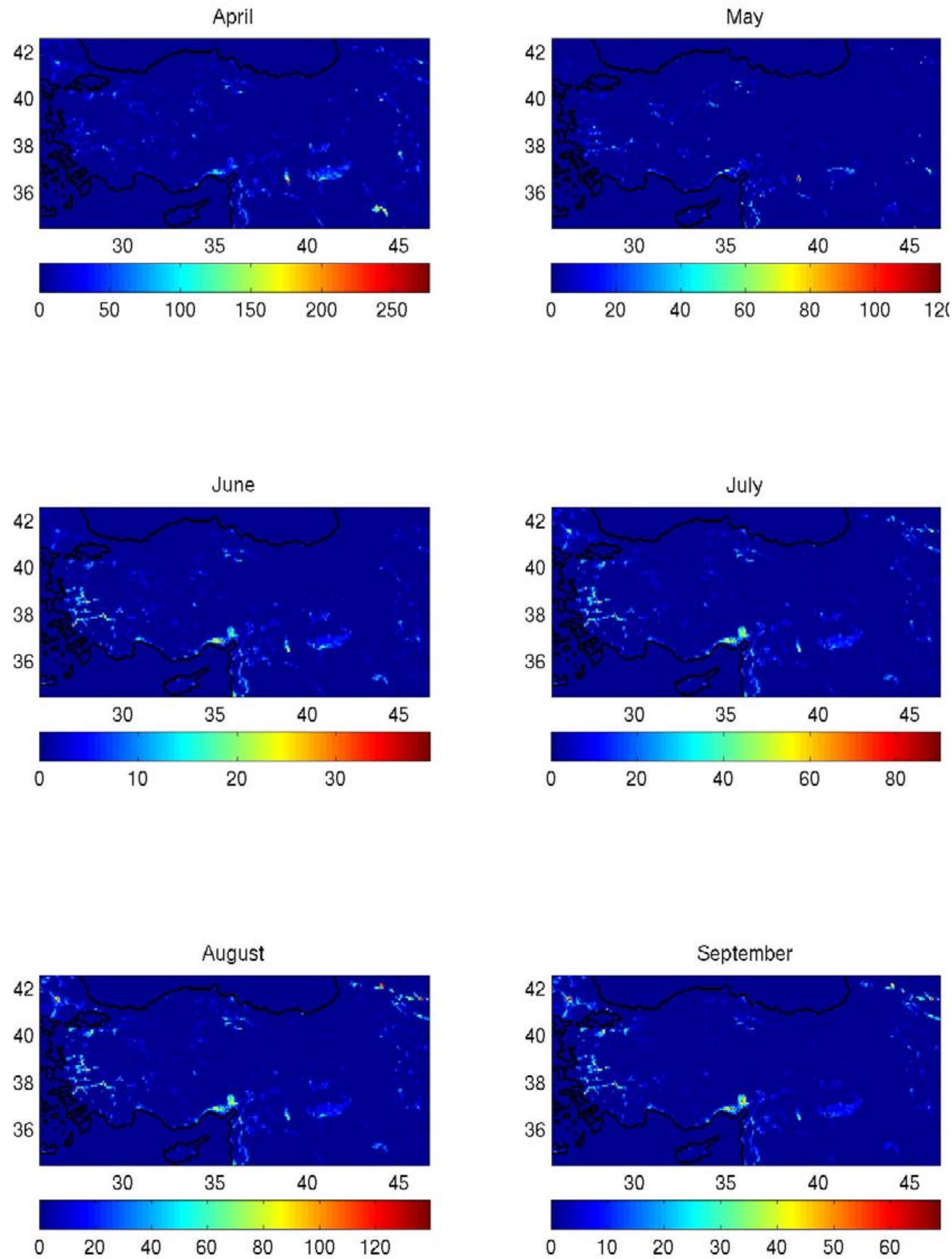

Figure 4. Geographic patterns of monthly irrigation water requirements under "changed" (doubled CO_2) climate. The left and bottom numbers indicate latitude and longitude, respectively. Note that the scale for irrigation need changes in each month.

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LAND USE CHANGES IN THE JORDAN VALLEY AND THE IMPACT OF A CLIMATE CHANGE ON IRRIGATION WATER REQUIREMENTS

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ABSTRACT

The Jordan Valley which is part of the Glowa Jordan River has been experiencing substantial land use changes during the past 50 years. The various development plans along with the construction of dams on side "rivers" and the introduction of drip irrigation have substantially increased the size of planted areas in the J.V. Political, economic, managerial and social issues have contributed to land use changes during the past 50 years. A substantial shift from planting grains and vegetables has been taking place during the last 15 years or so because of the emergence of new political-economic realities. Area planted with vegetables dropped by about 30% during the period 1990 and 2002. On the other hand, areas planted with banana and citrus increased in size by about 55% during the same period. The sharp land use changes reflect the economic realities of produce marketing locally and regionally. Although fruit trees enjoy stable prices (e.g., banana and certain citrus types), they put more strains on the available freshwater resources. The current water deficit for vegetables ranges from 250 mm in the northern J.V to 320-400 in the central and north of the Dead Sea. The corresponding figures for trees range from 950 mm in the northern J.V to 1100 mm in the central and southern areas. With the current percentage of areas planted with trees and vegetables in the J.V., a climate change would increase irrigation water needs by about 20-25 million m^3. The additional irrigation water needs resulting from a climate change is sufficient to provide around 600-700 thousand people with domestic water needs year around.

INTRODUCTION

Political and economic factors were the major players during the second half of the 20^{th} century in shaping land use transformation in the Jordan Valley (J.V.). Until recently, the availability of irrigation water has not been a limiting factor in dictating land use patterns, but current and future realities are quite different from the past years. Besides the political-economic factors, two additional major constraints are emerging which will lead to compulsory land use changes. The first one is linked to the rapid population growth and changes to the economic sector (a shift to industrialization, focus on tourism). These changes require additional water supplies which must come at the expense of the agricultural sector. The second one is the possible global climate change resulting from anthropogenic activities. Observational results (Zhang et al., 2005) and numerical models indicate that the eastern Mediterranean will face warmer and/or drier conditions in the near future. Such physical changes will alter the availability of freshwater and impose further limitations on the agricultural potential of the eastern Mediterranean. Thus, the objective of the present paper is to provides an outline of current and future irrigation water needs in the J.V. which represents the largest area consuming irrigation water in Jordan. The effects of a climate change on irrigation water needs and deficits are presented in this paper.

PAST AND CURRENT LAND USE IN THE JORDAN VALLEY

The Jordan Valley represents the largest area in Jordan consuming irrigation water. Irrigated lands in the J.V increased substantially during the past 50 years. The establishment of the King Abdullah Canal in the J.V., along with the construction of dams and the introduction of drip irrigation in the early 1980's have substantially increased the area of irrigated lands there. Figures 1 and 2 show the size of land planted with citrus and banana during the period 1950-2001.

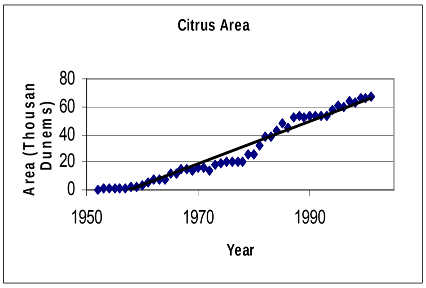

Figure 1. The size of land planted with citrus in the J.V. during the period 1950- 2001 (Ministry of Agriculture, 2005).

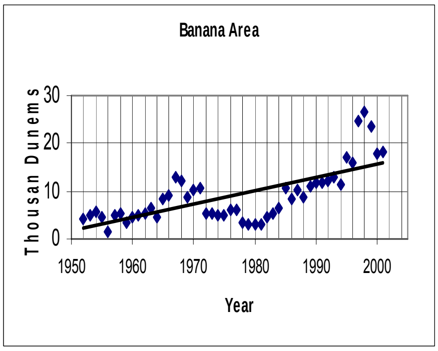

Figure 2. Same as Figure 1 but for banana.

During the early years of the second half of the 20th century, farmers in the J.V planted grains (mainly wheat) at a large scale. After the implementation of the J.V development plans, land use changed dramatically. Instead of planting grains, farmers there planted vegetables on a large scale. Later on, farmers started to plant trees such as citrus orchards, vineyards and banana. Land use patterns have been directed by the open market policy and the government did not interfere with what farmers chose to plant. The rapid land use changes in the J.V reflect the dynamics of produce marketing locally and in the neighboring countries. During the past 15 years and following the Iraqi- Kuwaiti crisis in 1990, marketing of Jordanian agricultural produce in the Gulf countries was virtually stopped. Instead of importing their vegetable needs from Jordan as was the case before the crisis, the Arab Gulf Countries imported their vegetable needs from Egypt, Lebanon, Syria, Turkey, and even from South Africa. The impact of this political turmoil reflected badly on the agricultural sector in the Jordan valley. The complete halt of exporting vegetables to the nearby Gulf Countries led to over production of vegetables and flooding of the local market. As such, the prices of vegetables collapsed and the agricultural sector in the J.V suffered serious setbacks. As a result, farmers there started to adjust to the new market realities, and compulsory land use transitions had emerged. Figure (3) shows the development of land use during the recent past, 1990-2002. The area planted with vegetables dropped from 21000 in 1990 to about 15 thousand hectares in 2002 (Ministry of Agriculture, 2005). Fruit trees, particularly citrus and banana, experienced an opposite trend, with their cumulative areas increased from 7 thousand hectares to about 12 thousand hectares. The continuous spread of water- consuming plants year around is accompanied with a steady decline of river flow to the Jordan River. Figure (4) illustrates the surface water supplies of the main river systems within the Jordan side during the period 1992-2002. This trend is connected to activities in the upper streams such as building dams on the Yarmouk River within the Syrian borders, and pumping more water to meet the growing demands for domestic water use, and natural rainfall variability.

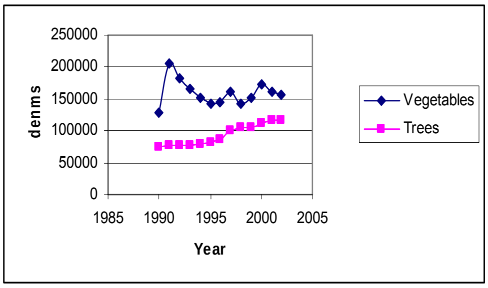

Figure 3. Recent development of areas planted with vegetables and trees in the J.V. during 1990-2002.

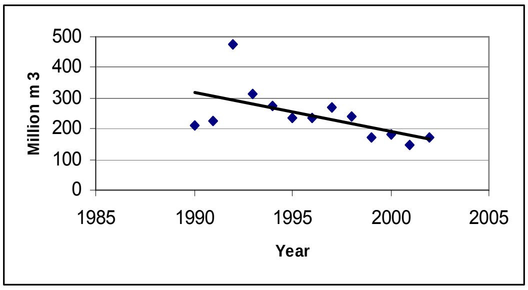

Figure 4. Water supplies to the J.V. from the river systems on the Jordanian side during 1990-2002. (Ministry of Water and Irrigation, 2003).

METHOD OF INVESTIGATION

A water balance analysis is carried out during the period November through May, and for the entire year. The first period coincides with the planting of vegetables and grains, and the second one represents water needs for trees (e.g., banana, citrus, etc). A detailed discussion of

the procedure used is described in detail elsewhere (Allen et al., Oroud, 1995; Oroud, 1998; Oroud, 2001; Oroud, 2006). The present analysis is carried out for two stations, (Baqura) in the northern J.V. and Jordan University Farm in the central part of the J.V. (Figure 5).

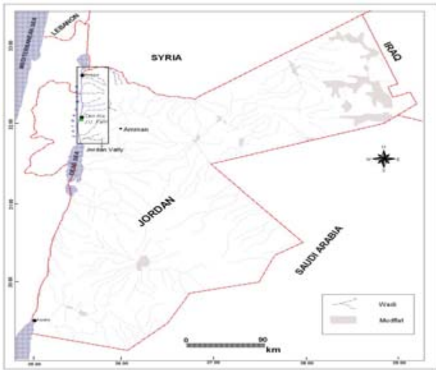

Figure 5. Study area and location of the two stations.

CLIMATE CHANGE AND IRRIGATION WATER REQUIREMENTS

The J.V. is located in a hot dry environment, and the climate prevailing there ranges from a Mediterranean type near the northern tip to very arid near the Dead Sea. Average daily air temperature ranges from 15/17 °C in winter to more than 31/33 °C. Rainfall ranges from 400 mm/year in the Baqura station near the Tiberias lake near the Syrian borders to less than 100 mm near the Dead Sea (Department of Meteorology, 2002)..

Water balance and irrigation water needs were evaluated using two climate change scenarios. It is assumed in the first one that the mean average monthly temperature during the course of the year increased by 2°C, and that precipitation did not change from its current "normal" conditions. In the second scenario, it was assumed that the average monthly temperature increased by 2°C along with a 15% reduction in precipitation with no other climatic changes (e.g., relative humidity, wind speed, sunshine duration, cloud cover, etc…). The drop in precipitation was assumed uniform during the rainy season. This analysis may not depict exactly a real climate change because precipitation variability is expected to increase following a climate change.

Tables [1 & 2] show irrigation water needs with current climate conditions and following a climate change for the period November through May and for the entire year. A substantial difference exists between water needs of vegetables, grown November through May, and trees which require irrigation year around.

Unlike vegetables which require irrigation during the growing season, November till the end of May (the cool period of the year) and sometime to the middle of June, trees such as citrus, grapes and banana require irrigation year around. The annual irrigation water needs ranges from 935 mm in the northern J.V. to 1150 mm in the UF. A 10-15% is usually added to the above figures to avoid the accumulation of salts at and near the soil surface, to account for improper distribution of irrigation water on plots, and for lost water through conveyance. As such irrigation water needs for trees range from ≈1050-1100 mm in the northern J.V. to about 1300-1400 mm in the central and southern parts of the J.V. It should be indicated, however, that banana trees demand relatively more irrigation water than reference evaporation by around 30-40%**.**

Table 1. U.F. (Central J.V.) Water balance components with and without a climate change

U.F	Normal	2^{O} C	2^{O} C; 85%p
Annual ET	1250	1320	1320
Deficit (annual)	1080	1140	1155
ET (Nov-May)	495	535	535
Deficit (N-M)	335	360	375

.

Table 2. Same as Table 1 except for Baqura (north J.V.).

Northern J.V	Normal	2^{O} C	2^{O} C; 85%p
Annual ET (mm)	1175	1255	1255
Deficit (annual)	930	990	1015
ET (Nov-May)	485	530	530
Deficit (N-M)	250	280	300

With a 2 °C temperature increase, annual crop reference evapotranspiration increases by about 5-7% in the J.V. If we assume that 36% of the J.V is planted with trees (≈ 12300 hectares), then the additional water needed to compensate for this climate change would be around 10-12 million m^3. The climate change impact on irrigation water needs for vegetables is relatively less. The additional irrigation water needed for vegetables grown in the J.V in the period November through May following a climate change of 2^{O} C and 85% of current normal annual precipitation will increase by about 8 million m^3. The combined irrigation water amount is sufficient to provide domestic water supplies for about 600-700 thousand people with the current water consumption rates (≈ 0.1 m^3/day).

DISCUSSION AND CONCLUSION

The impact of a climate change on irrigation water demands shows that additional irrigation water needs are around 20-25 million m^3 per year. Increased irrigation is an obvious mechanism of coping with drier and/or warmer conditions. Unfortunately, such a measure is not feasible in the J.V. because this region already exceeded the limits of existing irrigation water supplies. Additionally, the irrigated agriculture will suffer another setback resulting from the rapid population increase and a growing demand by tourist and industrial sectors. Naturally, any additional demands by domestic or other sectors will come at the expense of irrigation water.

In summary, land use in the J.V. is primarily dictated by purely economic return. To shift land use from water- demanding plants such as banana to less water- demanding plants is not an easy recipe that can be readily implemented. The attempts of the government to enforce land use changes have had so far very limited, if any, success. The picture becomes gloomier when taking into account water status in the mountainous areas following a climate change. Analysis elsewhere (Oroud, 2006) shows that excess water in the mountainous region overlooking the J.V. will decline sharply following a climate change. The governments in the eastern Mediterranean, however, must cooperate and set an agenda to harness the growth of tropical plants which are suitable somewhere else but not in this dry region. They also should encourage the use of greenhouses because they are more efficient in transforming drops to crops.

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OPPOSITE TRENDS IN LIFE STAGES OF ANNUAL PLANTS CAUSED BY DAILY RAINFALL VARIABILITY — INTERACTION WITH CLIMATE CHANGE

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ABSTRACT

Global Circulation Models of climate predict not only a change of annual precipitation amounts but also a shift in the daily distribution. To improve the understanding of the importance of daily rain pattern for annual plant communities, which represent a large portion of semi-natural vegetation in the Middle East, I used a detailed, spatially explicit model. The model explicitly considers water storage in the soil and has been parameterized and validated with data collected in field experiments in Israel and data from the literature. I manipulated daily rainfall variability by increasing the mean daily rain intensity on rainy days (MDI, rain volume/day) and decreasing intervals between rainy days while keeping the mean annual amount constant. In factorial combination, I also increased mean annual precipitation (MAP). I considered five climatic regions characterized by 100, 300, 450, 600, and 800 mm MAP. Increasing MDI decreased establishment when MAP was >250 mm but increased establishment at more arid sites. The negative effect of increasing MDI was compensated by increasing mortality with increasing MDI in dry and typical Mediterranean regions (c. 360–720 mm MAP). These effects were strongly tied to water availability in upper and lower soil layers and modified by competition among seedlings and adults. Increasing MAP generally increased water availability, establishment, and density. The order of magnitudes of MDI and MAP effects overlapped partially so that their combined effect is important for projections of climate change effects on annual vegetation. The effect size of MAP and MDI followed a sigmoid curve along the MAP gradient indicating that the semi-arid region (≈300 mm MAP) is the most sensitive to precipitation change with regard to annual communitie

INTRODUCTION

Drylands are characterized in the first place by the limitation of plant growth by low quantity of water. Another important characteristic is the spatial and temporal distribution and great variability of water, which play important roles in structuring ecosystems and maintaining biodiversity [17,35,44]. Comparisons of historic climate trends in the Mediterranean basin showed a more or less clear shift in the distribution of rainfall intensities from light to heavy or torrential rains [1]. Present global climate models suggest that these trends will continue [9]. Many vegetation processes are affected by daily rain variability: germination [11,23], plant growth [19], litter decomposition [37,39], and litter mineralization [4]. Despite the well-documented importance of water in drylands and their wide global distribution [32], just a quarter of the studies reviewed by DiTommaso and Aarssen [6] included a water treatment and only a single study assessed the variability of water. Only a handful studies have been added since this review. Thus, our knowledge about the effects of climate change with regard to changes in daily precipitation patterns remains limited [42]. Experiments to study the effect of daily water availability on plant growth and survival have concentrated on crop species or used unnaturally long intervals or only parts of the plants' life cycle. The majority of results from these studies suggest that greater rain intensities and longer intervals between rains, *i.e.*,

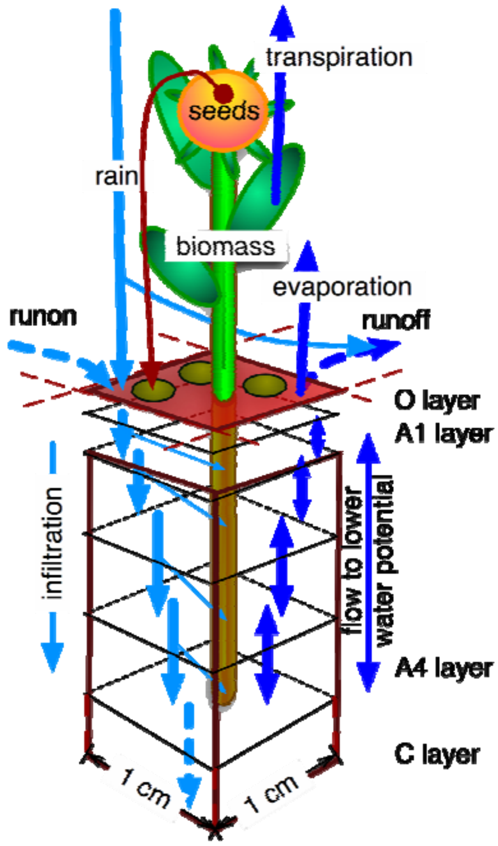

Figure 1. **Schematic overview of processes simulated in one cell of the model.**

while keeping the total amount of rain constant, reduce plant performance [5,12,27,34,38]. The exceptions, however, suggest that the negative effect of daily rain variability may be caused by a low water holding capacity of the soil, confined rooting space or a shallow rooting habit [21,31,38,43]. Since the systematic variation of rain fall in field experiments while maintaining realistic rain intervals and intensities is a logistic challenge, I used a spatially explicit model to investigate the effect of daily rainfall variability on plant performance. The importance of rainfall variability is likely to decline from arid to mesic ecosystems. Therefore, I assessed its importance for a gradient of aridity. Furthermore, I compared the effect of changing daily variability to that of changing the annual rain volume.

Methods

I used a spatially explicit model to simulate the influence of daily rainfall variability on plant growth of individual annual plants on a 25 cm × 25 cm area subdivided in 1 cm² cells (Fig. 1).

Annual plants are the dominant herbaceous life form along a gradient from 100 to 800 mm mean annual precipitation in Israel. Furthermore, annual plants generally do not store water in their tissue and can therefore be expected to be especially responsive to daily rainfall variation. The model comprises four modules using equations or rules describing physical processes for time steps of one day. Seed bank processes, in contrast, use annual time steps. The climate module generates deterministically the daily temperature and stochastically the daily rainfall amount. The soil module simulates in each cell for five soil layers the infiltration, vertical movement, drainage, and evaporation of water. Excess water runs off the cell. The seed bank module tracks the density of seeds, their moisture and temperature-dependent germination, seed mortality, and density-dependent granivory. The plant growth module simulates the increase of individual biomass based on available moisture, competition for water, and temperature. Biomass is allocated to vegetative and reproductive tissue. The seeds produced by the plant are dispersed according to a negative exponential distribution. Details of the modules are described in [25]. The model has been validated with data from four field sites in Israel (Sede Boqer, 90 mm mean annual precipitation [MAP], Lahav, 300 mm, Matta, 537 mm, 'En Ya'qov, 780 mm [18]).

I used the stochastic time series generator ReGen [26] to vary the mean daily rain intensity on rainy days (MDI, rain volume/day) from –20 to +20% in 10% steps. For comparison, current regional climate change models project a change ranging from –3 to + 29% of the current intensity in the Middle East [2]. Further, I varied MAP from –20 to +20% in 10% steps in a factorial way with MDI to provide a comparison for the magnitude of the effect of changing daily rainfall intensity. The simulations were performed for 5 sites on an aridity gradient: 100 (arid), 300 (semi-arid), 450 (dry Mediterranean), 600 (typical Mediterranean), and 800 mm MAP (mesic Mediterranean) to examine how the effect of daily rainfall intensity changes with climatic region.

I conducted the simulations for 30 years with five replications for each combination of change of intensity and annual precipitation for each point on the aridity gradient. To exclude inter-annual autocorrelation I reset the seed bank density each year to the same value (arid: 2000, semi-arid: 16'000, dry Med.: 17'000, typical Med.: 18'000, mesic Med.: 20'000 seeds/m^2 corresponding to typical values observed in the field). Runon (but not runoff) between cells in the model was excluded so that the direct effect of rainfall could be examined.

I report results for three variables: longest wet period (*LWD*, maximum number of consecutive days where soil water potential >–1.5 MPa [nominal permanent wilting point]), establishment (the ratio of seedlings to the number of seeds), and density of mature individuals. I examined the means of each variable for each 30-year series with analyses of covariance (ANCOVA). The full-factorial ANCOVA, using change of mean daily rain intensity and change of MAP as covariates and site as a nominal factor, had 605 degrees of freedom for the error term. Post-hoc comparisons of slopes and means were done using 95% confidence intervals. In addition, I calculated the change of each variable per 10% change of MDI and per 10% change of MAP.

RESULTS

The longest wet period (*LWP*) varied significantly among sites, with MAP, MDI, all two-way interactions except MDI × MAP, and the three-way interaction between sites, MAP, and MDI (all $P < 0.0001$, Fig. 2a, b).

LWP (averaged across rain treatments) differed most strongly among sites (F = 17802) and increased along the humidity gradient (Fig. 2b). Within sites, *LWP* (averaged across all other factors) increased linearly with MAP (F = 3886) and with MDI (F = 245). The rates of increase differed among sites. The increase with MAP was steepest at the dry Mediterranean site and became flatter towards the arid and mesic ends of the climate gradient (F = 35, Fig. 2b). The increase with MDI was largest around 200 mm MAP and became smaller towards the ends of the climatic gradient (F = 29). Although the interaction between MAP and MDI was not significant across all sites, this interaction varied significantly among sites (F = 5.9), because the rate of increase of *LWP* with MDI rose with MAP at the arid site but sank with MAP at all other sites (Fig. 2b). At the moistest site, *LWP* did not change significantly with MDI. The relative increase of *LWP* with change of MAP and change of MDI was strongest at the arid site and decreased to the mesic Mediterranean site.

Establishment fractions varied significantly among sites, with MDI, with MAP, with the interaction of sites with MDI, with the interaction of sites and MAP, and with the three-way-interaction of all factors (all $P < 0.0001$, Fig. 2c, d). Establishment (averaged across MDI and MAP levels) varied around 18% depending on site (F = 330, Fig. 2c). Averaged across sites, establishment increased with MAP ($F = 292$). An interaction of MAP with site ($F = 410$), however, arose because establishment decreased with increasing MAP at the Mediterranean sites (Fig. 2d). Increasing MDI at constant nominal MAP generally decreased establishment ($F = 6.8$), but this effect differed among sites ($F = 49$). At the arid site, a higher MDI increased establishment, whereas MDI generally caused establishment to decrease at the other sites (Fig. 2d). Since the density of seeds increased along the humidity gradient, the declining establishment suggests that density-dependent germination became more important as water supply increased. The three-way interaction ($F = 3.5$) indicated a maximum effect of MDI on establishment around 100 mm MAP and a minimum of MDI around 350 mm MAP.

The effects of rain manipulations on density of mature plants were similar to that on *LWP*. Density varied significantly with site, MDI, and MAP and their interactions (all $P < 0.0001$, Fig. 2e, f). The greatest absolute differences among levels were among sites ($F = 13381$). Density (averaged across sites and MDI) increased with MAP ($F = 936$, Fig. 2e). This slope of increase (averaged across daily patterns) differed among sites ($F = 275$). It was maximal at the semi-arid site (Fig. 2f). Further, density (averaged across sites) increased with increasing MDI ($F = 45$), but the rate was generally smaller than that caused by a similar change in MAP. The rate of increase with MDI (averaged across levels of MAP) varied among sites ($F = 20$). The greatest average slope occurred in the semi-arid site (Fig. 2f). The confidence interval of the average slope at the typical Mediterranean site included zero. The effects of MDI and MAP on density interacted ($F = 16$). Inspection of means indicated that the effect of MDI was the stronger the more MAP was reduced. This interaction further varied among sites ($F = 8$). At the arid site, the effect of increasing MDI was positive and increased with MAP (Fig. 2f). At the three intermediate sites the effect of MDI decreased with increasing MAP so that it became insignificant. At the mesic Mediterranean site, the effect of increasing MDI was negative, but the size of this effect also decreased with MAP. Generally, the effect of MDI was smaller than that of MAP at each site. In summary, increasing mean daily rain intensity and, more strongly, mean annual precipitation both increased density, but their relative effects generally decreased from the semi-arid to the mesic Mediterranean site.

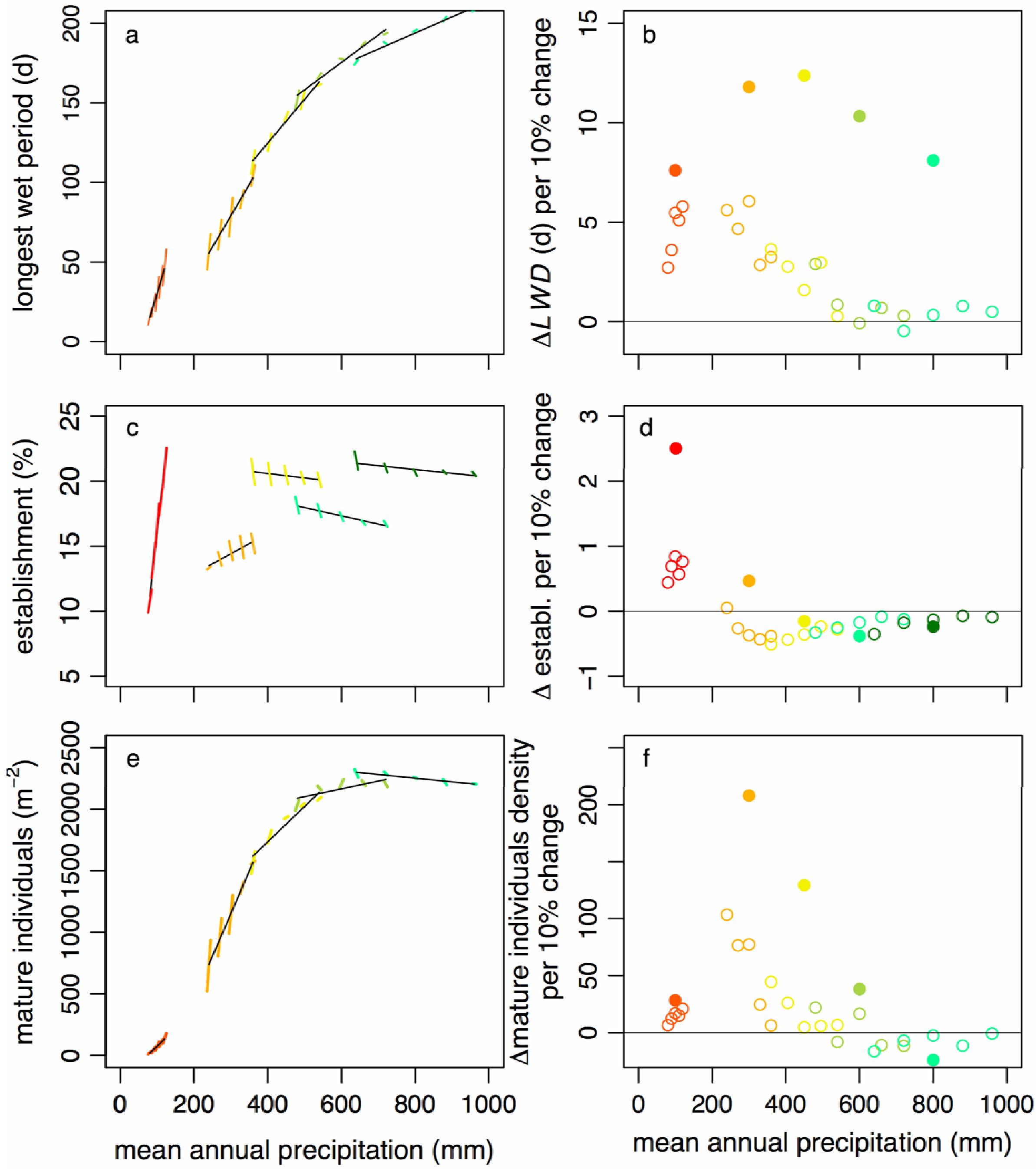

Figure 2. Change of (a) longest wet period (*LWP*, maximum number of consecutive days with soil water potential > –1.5 MPa), (c) establishment fraction, and (e) density of mature individuals with mean annual precipitation (MAP, thin, black lines) and with daily mean rain (MDI, thick, grey lines, 20% change of MDI scaled to 10 mm MAP). The slope of the thin lines corresponds to the effect of absolute change of MAP. b), d), f) Slopes of panels in the left column expressed per 10% change of MAP (filled circles) or 10% change of MDI (outline circles). This corresponds to the effect of the relative change of MDI and MAP.

DISCUSSION

Global climate change models predict a change in the daily rain pattern characterized by a shift to more high-volume rain events [22]. I simulated this shift by increasing the seasonal variation of mean daily rain volume (MDI) matched by a decrease in the seasonal variation of likelihood of rainy days so that the mean annual volume remained unchanged.

Changing annual rain volume and daily rain pattern clearly affected the average longest wet period (*LWP*, number of consecutive days where moisture in at least one soil layer >–1.5 MPa) (Fig. 2a, b). A change of mean annual precipitation (MAP) had a stronger effect than a change of MDI and keeping MAP constant. As expected, average *LWP* increased among sites along the humidity gradient. The slope of increase of *LWP* with *relative* change of MAP was greatest at the dry Mediterranean site (Fig. 2b). Thus, this region is the most sensitive with regard to water availability. Based on the *absolute* change of MAP, however, the slope of increase of *LWP* became flatter with the humidity of the climate (Fig. 2a). This pattern is due to the roughly reciprocal relationship between soil water potential and soil water content. At the arid site, soil moisture is on average low and almost each additional rainfall raises the soil water potential considerably and prolongs the wet period. With increasing climatic humidity, the soil is moister on average. The moister the soil, the more water is needed to raise the water potential by the same magnitude. In addition, the soil becomes saturated and additional water drains to lower soil layers or runs off at the surface. Changing MDI produced a complex response of *LWP*. In almost all instances, a greater amplitude of MDI, *i.e.*, more days with rainstorms, extended the wet period because a rainstorm fills up the soil immediately and to a greater depth than light rains. This is confirmed by measurements at the field sites. Water stored at greater depths evaporates more slowly than it does near the surface because soil dries out from the surface downwards and soil permeability decreases as the soil dries out [30]. Thus, both the responses of *LWP* to a change in MDI and to a change in MAP are strongly tied to the non-linear relation between soil water potential and soil water content.

The average percentage of established seeds was 18% across sites (Fig. 2c, d). The increase of establishment with MAP within sites was positive at the arid and semi-arid sites but negative at the three Mediterranean sites (Fig. 2d). This is the outcome of combining the concept of hydrothermal time for germination [26] with density-dependent germination fractions [16] in the model. Evidently, additional rain enhanced the number of days when conditions for germination were met and increased establishment at the two arid sites. In contrast, more frequent rainfalls at the Mediterranean sites did not greatly improve the conditions for germination. On the other hand, more rain raised the potential germination fraction, intensifying the competition among germinating seeds. As a consequence establishment along the Mediterranean part of the humidity gradient decreased. Independent of changes to MAP, increasing MDI increased seedling density till about 200 mm MAP and decreased establishment beyond that point on the humidity gradient. This indicates that under arid conditions establishment is improved by heavy rainfalls that penetrate the soil more deeply and provide the opportunity to grow deep roots. Under moister conditions, this effect becomes less important so that germination and establishment are enhanced by more regular rainfalls. Without density regulation, heavy rainfalls would cause mass germination and strong competition among adult plants. Therefore, density-dependent germination is an evolutionary stable strategy [40]. Evidence for density-dependence in natural communities is accumulating

[3,8,16,20,33,40]. In summary, seedling establishment is determined mostly by seed availability, number of rainstorms under arid conditions, and regularity of rain under more mesic conditions.

Generally, the effect of rain manipulations on the density of mature individuals followed a similar pattern as that on *LWP* (Fig. 2e, f). Thus, density increased in a sigmoid way with mean annual precipitation along the gradient (Fig. 2e), was more strongly affected by a change in MAP than by a change in MDI (Fig. 2f), and increasing either MAP or MDI had positive effects on density, except in the mesic Mediterranean region. The tight correlation between density and *LWP* indicates the strong control that water as a limiting resource exerts on plant growth. In the arid and semi-arid regions, individuals grew sparsely so that competition was weak. With increasing MAP the importance of rainstorms and *LWP* for growth decreased, while that of competition among the more densely growing individuals increased. This resulted in a negative effect of increasing MAP on density. At the dry and typical Mediterranean sites establishment fractions had decreased with MAP due to seedling competition. This was compensated later by higher mortality of established plants at lower MAP and thus *LWD*, resulting in an increase of density of mature individuals with MAP. At the mesic Mediterranean site, the small increase of *LWP* was less effective so that the density of mature individuals still decreased with increasing MAP. Similarly, the decrease of establishment with increasing MDI was not changed by the increase of *LWP* at the mesic Mediterranean site during growth so that the density of mature individuals also decreased with MDI. The decrease of density, however, was compensated by higher production per individual so that peak community shoot mass increased with MAP at this site as it did at the other sites [24]. To summarize, the sigmoid increase of plant density with mean annual precipitation MAP resulted from non-linear relations between soil water volume and soil water potential, a larger effect of rainstorms on establishment in arid than in mesic regions, and increasing importance of competition for water. The increase of density with daily mean rain MDI was the net effect of a positive effect on establishment at arid sites, a negative effect on germination at Mediterranean sites, and a positive effect on the longest wet period *LWP* resulting in more intense competition but also higher production with increasing MAP.

Experiments that manipulate rainfall frequency in natural vegetation [12] or use wild species are rare [27,34,38,43]. More effort has been invested in studies of irrigation frequency of crops [5]. Most of these studies agree that established plants perform better when the same amount of water is distributed in more frequent, smaller volumes than in fewer, larger volumes, especially when roots are close to the surface [5]. Exceptions [21,27,31,43] suggest that positive effects are observed predominantly in intact natural vegetation, whereas negative effects are found when root space is limited as in pot experiments or roots are concentrated near the soil surface as in crop species. This conclusion is corroborated by irrigation experiments [10] and the model's sensitivity analysis [24] that showed that soil depth is the fourth most important factor across all sites controlling the longest wet period *LWP*. Seeds and seedlings in my simulation were in a similar situation as plants in pot experiments. They had access only to water in the surface and A1 layer. Consequently, I found a negative effect of rainstorm frequency on seedling density (Fig. 2d) but positive effects on the density of mature individuals in all regions but the mesic Mediterranean (Fig. 2f).

My study showed that effects of precipitation pattern in more arid climates are primarily related to the time soil moisture is available to plants. The length of the moist period depends not only on soil characteristics that vary with soil texture, but also on the “context” of rain events [36], *i.e.*, on the soil moisture before rains and on the clustering of events. Therefore, my results support Reynolds et al. [36] that in terms of the pulse-reserve hypothesis [35] “pulse” must refer directly to the form of the resource as it is available to the plant and not to the resource as it is supplied. Thus, pulse here must refer to the available soil moisture and not to the rain event.

Using the simulation results one can estimate the effect of precipitation changes projected by global circulation models. The RegCM3 model generally predicts a 10 to 20% increase of MDI, but the change of MAP varies between –20 and +10% in simulated regions [2,14,15]. Although the community response to an increase of MDI has an opposite trend to the response to a decrease in MAP (Fig. 2), the latter is much stronger. Consequently, the net effect is negative. At sites with soils that might cause a negative response of community mass to the increase of MDI the effect of decreasing MAP would be amplified. In contrast, where the decrease in MAP is small and the increase in MDI is strong, the net effect might be even positive. Projected changes of mean temperatures, CO_2 concentrations or nitrogen deposition from the atmosphere may interact with effects of precipitation changes. A multi-factorial experiment in an annual grassland, however, showed that interactions among these factors become rare and nitrogen deposition produced the strongest effect [7]. Nonetheless, in the long-term, aboveground production of herbaceous arid communities is most strongly correlated with annual precipitation [28], which is also shown by the tight correlation of community biomass with annual precipitation along my gradient [24].

Among the communities along the humidity gradient from arid to mesic Mediterranean, those in the semi-arid region are the most sensitive to changes in annual precipitation as shown by my simulations (Fig. 2) and field data [18]. Despite its low mass, annual vegetation is important in drylands. Annual plants represent the bulk food for livestock, reduce soil erosion, and increase rain infiltration. The attractiveness of their species diversity is an economical factor in the tourism industry [13,41]. Therefore, this “marginal” vegetation must be included in regional assessments of global change to provide a full picture of the effects on regional ecosystems and socio-economy[29].

In conclusion, my simulations demonstrate that changes to daily rain patterns have strong effects on annual plant communities in arid regions through the amount of water stored in the soil. These effects were smaller but of the same order of magnitude as changes to mean annual precipitation. Therefore, these effects should be included in assessments of global climate change.

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ADAPTING A LAND USE CHANGE MODEL TO THE JORDAN RIVER REGION

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INTRODUCTION

The interdisciplinary GLOWA Jordan River project, financed by the German Federal ministry of Education and Research, addresses the vulnerability of water resources in the Jordan River Basin due to global change. With an integrative research approach, the project aims at scientific underpinning for sustainable and cooperative management practices [1].

With reference to current and future water scarcity, the project region is one of the most critical regions. Currently having one of the lowest per capita water availabilities worldwide [2], the region experiences an increasing water demand due to high population growth rates and economic growth. At the same time available water is decreasing. Climate prognoses for the Eastern Mediterranean predict further aridification and increasing variability of regional precipitation. The agricultural sector, especially irrigation, consumes a major part of the regional water resources [1]. In addition, agriculture and urbanization substantially degrade the quality of water resources [3].

To obtain a sustainable water resource management, the depicted processes and connections have to be taken into account. Hence, one part of the GLOWA-Jordan River project is the integration of land use information into land use scenarios[1] for the territories of the Gaza Strip, Israel, Jordan and the West Bank. For this purpose, we adapt the integrated modelling system LandShift[2].

There is a wide variety of spatially explicit modelling approaches to simulate land use change processes on the regional scale [4]. The strength of LandShift lies in its modular structure which permits a high degree of integration with various sub-modules for impact assessment. Another important characteristic of LandShift is the transparency of model dynamics caused by its process oriented structure and usage of methods from the field of Multi Criteria Analysis.

In this extended abstract, we present the basic conceptual design of the LandShift model and describe the essential steps of adapting LandShift to the Jordan River region.

LANDSHIFT – MODEL DESCRIPTION

Overview

The LandShift model has a highly modularised structure (Fig. 1). This allows the integration of functional model components, covering key parts of land use systems. The current version

[1] We use the term "scenario" as a plausible description of how the future may unfold based on 'if-then' propositions.

[2] **Land s**imulation to **h**armonize and **i**ntegrate **f**reshwater availability and the **t**errestrial environment.

of LandShift includes three modules: one productivity module for grassland, one for cropland and a Land Use Change-module (LUC-module).

Based on a modified grid version [5] of the ecosystem model DayCent [6], the two productivity modules deliver net primary production for grassland and accordingly yields for cropland to the core element of LandShift, the LUC-module. DayCent is driven by data on current and future climate, what allows accounting indirectly for climate change effects on land use change. A hydrological model provides information on water availability and water stress to the LandShift system.

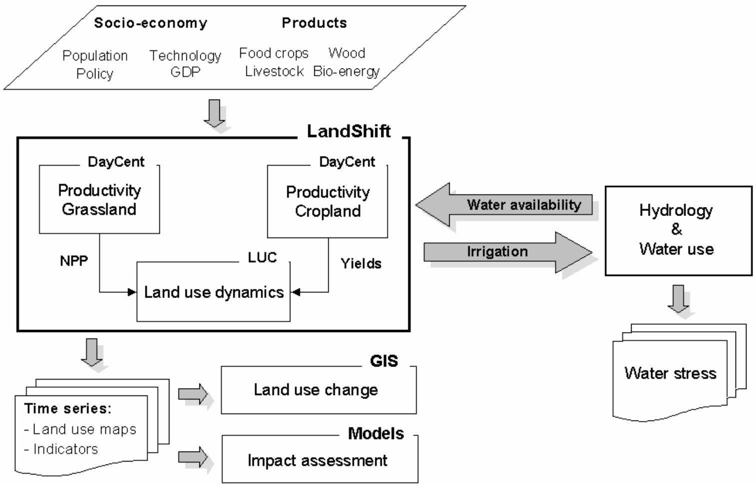

Figure 1. Flow diagram of the LandShift model. The LandShift model currently consists of three functional model components: two productivity modules and the Land use change-module. Amongst others, LandShift is driven by time series on socio-economic data and production of agricultural commodities. The model output consists of time series on raster maps of land use as well as a set of indicators, e.g. rates of deforestation.

Main model inputs are driving forces of land use, e.g. time series on socio-economic data and production of agricultural commodities. Model output consists of time series on raster maps of land use as well as a set of indicators. These indicators serve as aggregated documentation of land use changes. To facilitate further processing with standard GIS software, the land use maps are created in well-established file formats like ASCII.

The LandShift model operates on a spatial multi-level hierarchy, composed of a macro-level and a micro-level. The specification of exogenous model drivers, including demands for agricultural commodities, happens on the macro-level (territories of the Gaza Strip, Israel, Jordan and the West Bank). The LUC-module regionalizes these demands to the micro-level (resolution according to GLC2000 Land Cover Map [7], about 1 square kilometre at the equator), where suitability analysis and land allocation are carried out. The chosen resolution is a trade-off between computational effort and accuracy and is additionally affected by the availability of input datasets covering the whole project area.

The LUC-Module

As mentioned above, the LUC-module is the core element of the LandShift system. This module consists of five sector processes (Fig. 2). The LUC-module's main task is to regionalize macro-level demands for agricultural commodities and services (e.g. housing), derived from exogenous model drivers, to the micro-level.

The basic principle is to allocate land use requirements to the grid cell with the highest suitability value. Each grid cell contains a vector with specific productivity functions for each commodity. The land use type of as many cells as needed to fulfil the demand for a certain commodity has to be changed.

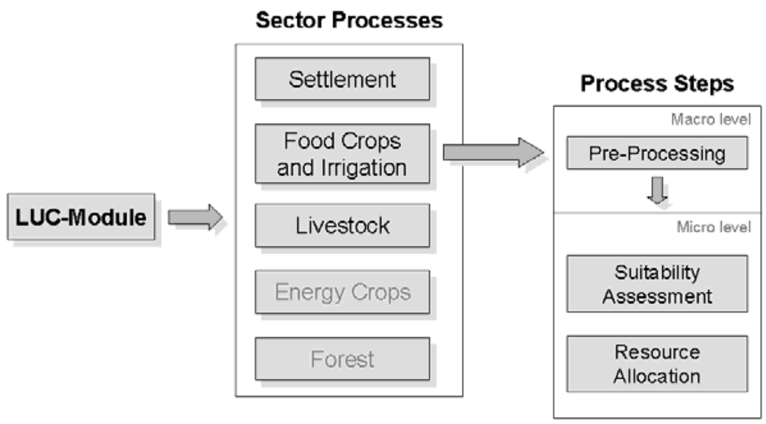

Figure 2. Sector oriented structure of the LandShift model. The LUC-module has a sector oriented strucure. The module's main task is to regionalize macro-level demands for commodities and services, derived from the exogenous model drivers, to the micro-level (Resource Allocation).

There are two levels of competition for land resources inside the LUC-module, a competition between the different sector processes and a competition between different land use types within each sector process. The former is handled by a ranking of the sector processes according to their economic importance. Here, ranking defines the sequence of sector process execution. The latter is accommodated by a subsequent execution of the three functional components "Pre-Processing", "Suitability Assessment" and "Resource Allocation" at each time step (Fig. 2).

Pre-Processing. This procedure serves for preparation of macro-level demands from exogenously provided driver variables. The other two functional components are carried out on the micro-level.

Suitability Assessment. We use Multi Criteria Analysis (MCA), based on a set of local cell properties, to generate suitability values for the different land use types within a sector process. For this purpose, we use the modified version of a MCA-method developed by Eastman et al. [8]:

$$suit = \sum_{i=1}^{n} w_i p_i \times \prod_{j=1}^{m} c_j \qquad (1)$$

Equation 1 consists of the sum of weighted (w_i) factors (p_i) that contribute to the suitability (*suit*) of a certain land use type, multiplied by the product of land use constraints (c_j). Land use constraints are e.g. protected areas or specifications of possible land use type conversions. Different from the original approach, LandShift not only allows for Boolean constraint values but also for values between 0 and 1, to facilitate a gradual implementation of a constraint. Factors, weights and constraints are implemented as time dependent variables on the macro-level.

Resource Allocation. This functional component distributes macro-level demands to the micro-level grid cells with highest suitability values for the particular land use type. For the "Settlement" sector, this happens by a strictly rule-based algorithm [9]. For the "Food crops and irrigation" sector, we apply a modified version of the Multi Objective Land Allocation Algorithm [8], abbreviated MOLA. Deviating from the original version, this modification allocates territory level crop demand instead of a given area. In addition to suitability we also take into account pattern stability as a second modification. Then a production function (Equation 2) determines the production (P) of a grid cell for a particular crop type (c) at a time step (t):

$$P_{tc} = base * tech_t * \left(Y_{tc} * Area_{tc}\right) \qquad (2)$$

The product of the yield (Y) and the according grid cell area (*Area*) is multiplied with the two factors *tech* and *base*. The *tech* factor marks the influence of technology on a certain crop type and *base* serves as a proxy for management intensity. Additionally, *base* is required for calibration purposes. A similar procedure is used for resource allocation within the "Livestock" sector.

More detailed descriptions of the LandShift model can be found in Alcamo and Schaldach, 2006 [10] as well as in Schaldach et al., 2006 [11].

INPUT DATABASE

The construction of the input database proceeded as follows. Based on the GLC2000 Land Cover Map clipping [7] for the territories of the Gaza Strip, Israel, Jordan and the West Bank, we created a polygon shape and constructed a GIS-database that contains the following input information for each grid cell: grid cell area, x/y coordinate of grid cell centre, and country affiliation. As a first step, we appended additional input information like elevation [12], slope [13], population densities [14] and road/river network density for each grid cell. FAO Terrastat datasets [15] were used to derive information about soil parameters (e.g. dominant soil type). In a second step, we will substitute these datasets for selected regions by project-internal datasets with a more appropriate spatial resolution.

The software design makes use of GIS interfaces and Relational Database technology. For example, we use the freely available data base management system MySQL to manage the input database. The direct database access by LandShift is enabled through the use of the mysql++ wrapper. This allows a seamless workflow.

EXPECTET INSIGHTS

We use the modelling system LandShift to integrate land use information from our project partners and from other available sources and simulate different, in this way new, land use/land cover scenarios for the territories of the Gaza Strip, Israel, Jordan and the West Bank. The modular structure of LandShift facilitates the (indirect) incorporation of climate change effects to the land use/land cover scenarios, playing an important role especially in the Eastern Mediterranean region. The temporal resolution of LandShift (5-year time steps), in contrary to simulations with only two time slices (start and end year), allows the adjustment with driving forces of the model at each time step, and thus a better suitability assessment.
We currently are in the phase of simulation. Concrete results are expected by the end of November 2006 and will be fed into the iterative process of SAS[3] scenario exercise [16], leading to an improvement of the comprehensive and coherent scenario assumptions and, as a result, to improved land use/land cover scenarios.

The scenario assumptions, developed especially for the project region with incorporation of stakeholders and experts, focus on key issues in water and land management. The different land use/land cover scenarios, resulting from the application of these scenario assumptions, show different possible future distribution of land use types. Thus, they illustrate the results of activities and decisions taking into account inter-linkages and connections between land and water resources. This contributes to explore strategies of sustainable land and water management under consideration of all available water resources (also treated wastewater), and the associated impacts on land and water resources, considering the consequences of climate change and socio-economic impacts as well as agricultural commodities.

NEXT STEPS

Our further work concentrates on three issues:

- We are currently implementing a new micro-level with a resolution of about one square kilometre at the equator, according to the resolution used for the GLC2000 Land Cover Map [7] on which our starting conditions are based on.
- Since the Middle East is a region suffering from water scarcity, the reuse of treated wastewater is an important factor. For this reason, we are heading for the introduction of treated wastewater reuse as a new aspect of suitability assessment.
- We go for a first simulation run with scenario data derived from the SAS approach.

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[3] **S**tory **a**nd **S**imulation approach.

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