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Potential impact of climate change on rainfed agriculture of a semi-arid basin in Jordan

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ABSTRACT

Rainfed agriculture in Jordan is one of the most vulnerable sectors to climate change, as the available water and land resources are limited and most of the country's land is arid. In this study, a crop simulation model (DSSAT) was used to assess the impact of different climate change scenarios on rainfed wheat and barley in the Yarmouk basin in Jordan. Analysis of observed crop data showed differences between cultivated and harvested areas for both crops in the study area with variations among years. Results from DSSAT model for years showed that it was able to capture the trend of yield over the years realistically well. The model predicted an average yield of wheat of 1176 kg ha^{-1}, which was close to the average (1173 kg ha^{-1}) obtained from the data of department of statistics (DOS), and an average predicted yield of barley was 927 kg ha^{-1} while the DOS average was 922 kg ha^{-1}, with higher RMSE for barley (476 kg ha^{-1}) than for wheat (319 kg ha^{-1}). Results for predicting future yield of both crops showed that the responses of wheat and barley were different under different climate change scenarios. The reduction of rainfall by 10–20% reduced the expected yield by 4–8% for barley and 10–20% for wheat, respectively. The increase in rainfall by 10–20% increased the expected yield by 3–5% for barley and 9–18% for wheat, respectively. The increase of air temperature by 1, 2, 3 and 4 °C resulted in deviation from expected yield by −14%, −28%, −38% and −46% for barley and −17%, +4%, +43% and +113% for wheat, respectively. These results indicated that barley would be more negatively affected by the climate change scenarios and therefore adaptation plans should prioritize the arid areas cultivated with this crop.

1. Introduction

Climate change is seen as the main threat to agricultural sector in developing countries; as vulnerability of this sector is high and adaptation measures are restricted by the limited resources of these countries (Mendelsohn and Dinar, 1999). The vulnerability of the agriculture sector to both climate change and variability is well established. The general consensus is that changes in temperature and precipitation will impact plant growth and crop yield. In many developing countries, climate change is also expected to lead to changes in farming systems and will put more pressure on the rural community to cope with these changes and to build up their adaptive capacities (Reilly and Schimmelpfenning, 1999; Liwenga, 2008).

According to the fourth assessment report of the intergovernmental panel on climate change (IPCC, 2007), the possible climate changes that had occurred or expected to occur in mid latitudes and tropical areas would be an incremental decrease in precipitation associated with increased variability and higher air temperatures. Using the UK Hadley Center's global climate model at a spatial scale of 2.5 latitude by 3.75° longitude, Ragab and Prudhomme (2002) simulated the global climate change according to scenarios of greenhouse gas concentration emission for the 2050s time horizon. Results of the study showed that by the 2050s the east Mediterranean countries would have reduced winter rainfall amounts of 10–15% and a temperature rise of 1.5–2.75 °C in summer seasons (Ragab and Prudhomme, 2002). In another germane study by Partal and Kahya (2006), results of the non-parametric test of Mann–Kendall showed significant decrease in rainfall in western and southern parts of Turkey. Implementing four non-parametric trend tests, Kahya and Kalayci (2004) indicated that the western and southeastern parts of Turkey were facing a downward trend in stream flow, which could be attributed to adverse climate change. Implementing the non-parametric test of Mann–Kendall on historical climatic records of Jordan, showed decreasing trends (8–20%) in precipitation and increasing trends for temperature (1.0–2.8 °C) in the northern and western parts of Jordan (MoEnv, 2009).

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Generally, most of the attention in the Mediterranean region was given to the impact of climate change on the increase in temperature through the global warming or greenhouse effect. According to Food and Agriculture Organization (FAO, 2005), the predicted impacts of climate change were increased crop water requirements, increased competition between weed and crops, spread of pests and nematodes and increased salinization of soils. The combination of increased temperature and decreased rainfall would be expected to result in reducing yield of agricultural crops in these areas. In other agroecological areas, crops were expected to experience a beneficial increase in productivity under moderate changes in climate (Bazzaz and Sombroek, 1996; FAO, 2005, 2007; Cruz et al., 2007). In Saudi Arabia, the decline of woodland production and health was related in some way to climate changes (Fisher, 1997).

In Jordan, rainfed agriculture is likely to be the most sensitive sector to climate change. The country, located in the eastern Mediterranean region between 29°11′–33°22′N and 34°19′–39°18′E, is predominantly arid to semi-arid and characterized by dry hot summers and mild wet winters with extreme variability in rainfall within and among years (Tarawneh and Kadıoğlu, 2003; Freiwan and Kadioglu, 2007). Jordan has three distinct ecological zones (Al-Bakri et al., 2008): (i) Jordan Valley which forms a narrow strip located below the mean sea level, and has warm winters and hot summers with irrigation being mainly practiced in this area; (ii) the western highlands where rainfall is relatively high (300–600 mm) and climate is typical to the Mediterranean areas; and (iii) the arid and semi-arid inland to the east, known as the "Badia", where the annual rainfall is below 200 mm. Badia is an Arabic word describing the open rangeland where Bedouins (nomads) live and practice seasonal grazing and browsing.

The most prominent impact of climate change on rainfed agriculture is the reduction in crop productivity that is attributed to crop efficiency in fixing CO_2 through the photosynthesis process (Wolfe and Erickson, 1993; Sombroek and Gommes, 1996; Hay and Porter, 2006). In Jordan, wheat is the main rainfed field crop in areas that receive more than 350 mm, while barley is cultivated in areas where rainfall is between 100 and 350 mm. Both of wheat and barley are important for local farmers and Bedouins. In dry seasons, hay is usually used as an important source of fodder to support the grazing herds of sheep and goats. Most of cereal crops grown in Jordan, like wheat and barley as well as fruit trees, have C3 photosynthetic metabolism pathway. Elevated CO_2 levels in the absence of biotic or abiotic stresses may increase yield due to increased photosynthesis and growth. However, at above optimum temperatures, and reduced precipitation which are associated with climatic change, the beneficial effects of elevated CO_2 do not compensate the offset by negative effects of temperature on yield and yield components (Lehnherr et al., 1997; Hay and Porter, 2006). Therefore, investigating the impact of climate change on cereal crops is still needed to assess the levels of crop yield under the different scenarios of change.

In Jordan, the impact of climate change on agriculture was indirectly investigated by assessing the adverse impacts on water budget and irrigation water demand and supply (GCEP, 1999; Abu Taleb, 2000; Abdulla and Al-Omari, 2008; Abdulla et al., 2009). Predicting the impact of climate change on crop yield is needed, as it provides quantitative information on possible reduction or increase in yield under the different climate change scenarios. This study, part of the country's second national communication (SNC) report to United Nations Framework Convention on Climate Change (UNFCCC), aims to assess the vulnerability of rainfed agriculture in Jordan by modeling the impacts of different scenarios of temperature and rainfall changes on crop yield of wheat and barley. A previous study in Jordan (GCEP, 1999) showed that all rainfed crops were adversely affected by projected temperature increase and rainfall decrease. Results, however, would not be necessarily accurate, as crop yield prediction was carried out by applying simple production functions that consider one factor at a time. Therefore, detailed studies are needed to simulate crop yield under the different climate change scenarios. In this study, a crop simulation model (Decision Support System for Agrotechnology Transfer, DSSAT) was used for this purpose.

2. Study area

The study was carried out on Jordan's part of the Yarmouk River basin (Fig. 1). The basin represents a semi-arid Mediterranean ecosystem where rainfall and temperature gradients are obvious. Nevertheless, it is important with respect to its contribution to the country's rainfed agriculture and. The climate of this Mediterranean study area is characterized by cool rainy winters and hot dry summers. Annual rainfall varies between 600 mm in the western parts of the basin to less than 150 mm in the east. The rainy season starts in November and ends by early May. The mean annual minimum and maximum temperatures for Irbid weather station, in the west, are 12.3 °C and 23.1 °C, respectively. The mean annual minimum and maximum temperatures for Mafraq weather station, in the east, are 9.3 °C and 24.0 °C, respectively. The mean annual potential evaporation ranges between 1500 mm in Irbid to 2160 mm in Mafraq.

The total area of the Jordan's part of the basin is 1200 km^2. From administrative perspectives, most of the basin is located within Irbid governorate, which is the major producer of wheat and barley in the country, with an annual average of 6460 tonnes of wheat and 3339 tonnes of barley. The basin has a wide range of soil types, reflecting the wide range of its physical characteristics. In the western half of the basin, the dominant soil subgroup is typic xerochrepts with low content of carbonates and high content of clay. In eastern parts of the basin, calcixerollic and lithic subgroups are dominant, with high contents of carbonates and silt fraction. Deep vertisols are dominating the area between Irbid and Ramtha cities on the undulating plateau and in some wadi floors (MoA, 1994).

Rainfed and irrigated agriculture is practiced in this basin. Existing land use/cover map (Fig. 1) of the basin was prepared by visual interpretation of a high resolution image of the advanced spaceborne thermal emission and reflection radiometer (ASTER) and verified by several field visits. The map showed that the western parts of Yarmouk basin were mainly rainfed areas of wheat, olives and vegetables. The eastern parts of Yarmouk basin were extending in the low rainfall zone of the country where open grazing was practiced and rainfed barley was cultivated. Irrigation was taking place in the eastern parts of the Yarmouk basin using groundwater. Analysis of the land use/cover map within the geographic information system (GIS) showed that 49% of the total area was rainfed, 7% was irrigated, 33% was an open rangeland, 2% of the area was protected and 9% of the area was urbanized. Due to over-pumping of groundwater and construction of dams on Syria's part of the basin, the river (at the northwest of the country) witnessed sharp drop in base flow during late 1990s and early 2000s. Currently, the summer base flow of this river is less than 5 m^3/s (MoEnv, 2006).

3. Methodology

3.1. Data collection

Crop yield data for Irbid governorate, which covers most of the basin, was downloaded from the official site of the Department of Statistics, DOS. The DOS compiled crop production surveys for about 8000 holdings distributed throughout the country. All

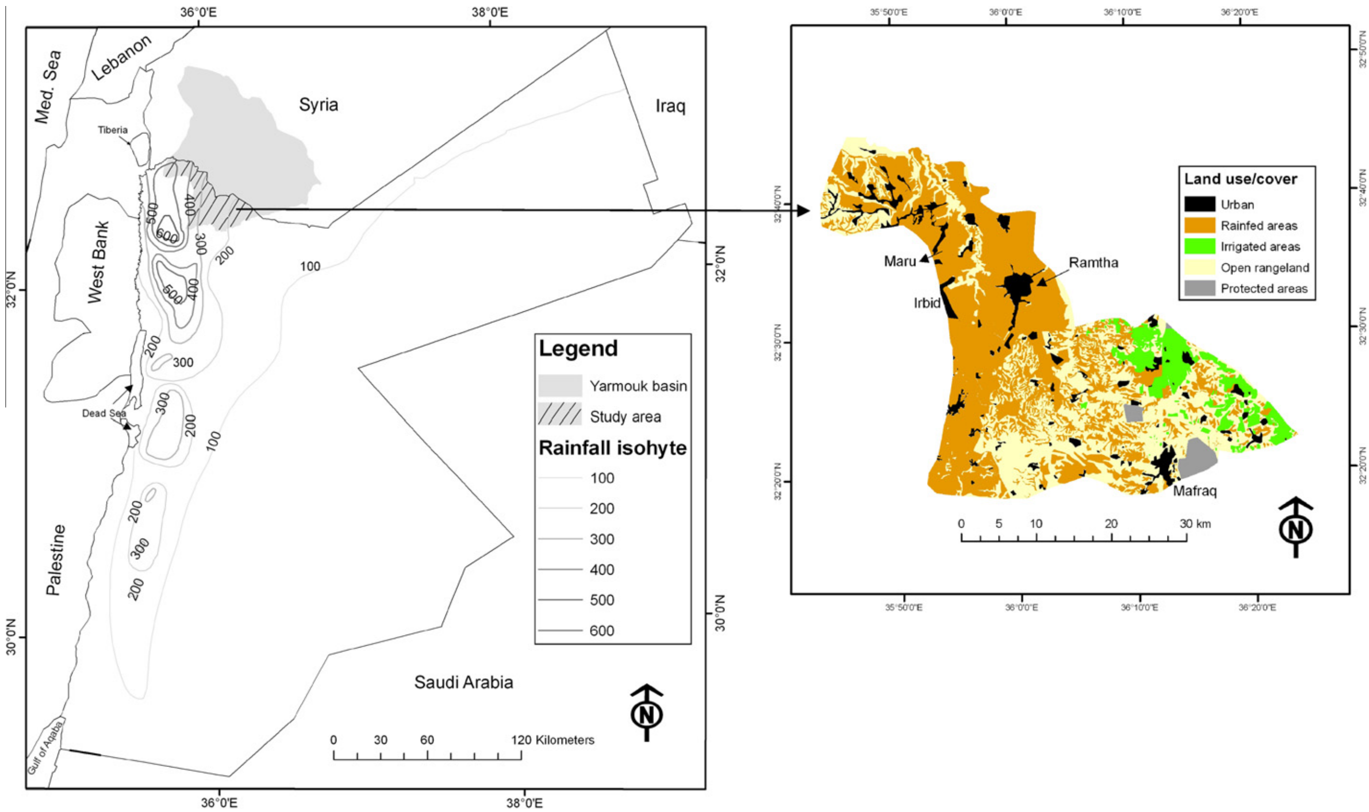

Fig. 1. Location of the study area within Yarmouk basin (left) and its existing land use/cover (right).

landholdings which had an area of more than 50 ha were completely enumerated. For the other holdings, the stratified multi-stage sampling technique was adopted. Details on the survey method are available at the official website of the DOS (http://www.dos.gov.jo).

The data for the period of 1996–2006 was used to analyze crop yield for both wheat and barley and to calibrate the crop model (DSSAT) prior to its use for predicting crop yield under different climate change scenarios. Additional yield data for both wheat and barley was obtained from the annual reports of the National Center for Agricultural Research and Extension (NCARE) (http://www.ncare.gov.jo) for Maru and Ramtha agricultural research stations, respectively. This data was used to compare the levels of yield obtained from farmers and those obtained under supervised cultivation practices inside both stations.

Daily weather data of solar radiation, maximum and minimum temperatures and precipitation, available for the period 1970–2005, were acquired from the meteorological department of Jordan (JMD) (http://www.jmd.gov.jo). The data of JMD complies by the requirement of the World Metrological Organization (WMO) regulations, which state that the latest ‘normal period’ extends from 1970 to 2000 (Freiwan and Kadioglu, 2007). Data on soil types and their physical and chemical properties were obtained from the national soil maps and land use project (MoA, 1994). The data of soil was available for the whole basin at a semi-detailed level (1:50,000) with an average of 3.5 observations per km^2. The layer of soil map was available in GIS format and the data on soil were extracted for the soil mapping units of Irbid (area of wheat cultivation) and for Ramtha and Mafraq (areas of barley cultivation).

3.2. DSSAT model

Models are considered important tools that enable the understanding of process and can exploit full information content of different data sources (Fenicia et al., 2008). Crop simulation models are tools for research, education and outreach. They are considered holistic in nature since they combine soil, plant, and climate systems together, which facilitates the understanding of the role of the different variables and their interaction. Recently, many researches (e.g. Popova and Kercheva, 2005; Magombeyi and Taigbenu, 2008; Twomlow et al., 2008) had used these models to assess crop yield risk and the vulnerability of agriculture to climate change, in addition to developing adaptive capacities to cope with the possible vulnerability. Crop simulation models are usually preferred over production function models that test crop yield under one variable while assuming optimum conditions and inputs for crop growth.

Among the different crop models is the DSSAT (Ritchie et al., 1986; Tsuji et al., 1994; Boote et al., 1998) which simulates the impact of different management strategies on diverse crops in diverse environments (soils and weather). The DSSAT has been widely used in the US and worldwide over the last two decades because it is reasonably accurate, process-oriented, simple and requires minimum inputs. The model requires daily weather values of solar radiation, maximum and minimum temperatures and precipitation. The other input parameters for the model include soil properties, crop characteristics and management practices. The DSSAT has been widely used to simulate the impact of climate change on crops worldwide (e.g. Guerena et al., 2001; Holden and Brereton, 2003; Brassard and Singh, 2007; Kalra et al., 2007). In Jordan, this study is the first attempt to simulate the impact of climate change on crop yield using DSSAT.

3.3. Testing and calibration of DSSAT model

Prior to model implementation, it was necessary to check the weather data and to test and calibrate the model. Weather data was checked by applying different statistical functions to detect

Table 1
Increments used to construct the 20 climatic change scenarios.

Scenario				Rainfall increment Temperature increments			
1 – Scenarios 1–8 (dry)							
−20% Rainfall				−10% Rainfall			
+1 °C	+2 °C	+3 °C	+4 °C	+1 °C	+2 °C	+3 °C	+4 °C
2 – Scenarios 9–12 (normal, change in rainfall is 0%)							
+1 °C	+2 °C	+3 °C	+4 °C				
3 – Scenarios 13–20 (wet)							
+20% Rainfall				+10% Rainfall			
+1 °C	+2 °C	+3 °C	+4 °C	+1 °C	+2 °C	+3 °C	+4 °C

abnormal values. Some gaps in solar radiation were observed for some periods. These were estimated for each missing day from the difference between maximum and minimum temperatures using the Bristow and Campbell (1984) equation. The daily clear-day radiation and total extraterrestrial insolation on a horizontal surface were computed using the equations reported in FAO-56 (Allen et al., 1998). The B (0.083) and C (1.468) parameters for the Bristow and Campbell equation were obtained using the least square errors for the days with observed daily solar radiation and maximum and minimum temperatures. For these days, the coefficient of determination (r^2) and the slope of zero-intercept line between the estimated and observed daily solar radiation were 0.88 and 0.99, respectively. Abraha and Savage (2008), on a study on seven stations with a range of latitude, longitude and elevation around the world, found that Bristow and Campbell equation generally performed well. This was also confirmed by the high values of r^2 obtained in this study.

For calibration purposes, the daily weather data of Irbid for 1996–2005 was used to run the model for wheat and barley and to compare model predicted yield with DOS data. An intercalibration of the model was then carried out assuming different varieties of wheat. In the study area, most of the farmers were cultivating the durum wheat (*Triticum turgidum*) with different local varieties and barley (*Hordeum vulgare*) of two rows in Mafraq and six rows in Irbid and Ramtha. Therefore, the step of intercalibration for wheat was necessary to reduce the root mean square error (RMSE) and to increase the accuracy of predicting crop yield under different scenarios of climate change. The only management practice at farm level for both crops was primary tillage for wheat and secondary tillage for barley. For both crops, stubble mulch was collected (as hay) and used in the late summer, while crop residues were grazed shortly after harvesting. Neither fertilization nor supplemental irrigation was practiced by farmers.

Following the stage of model intercalibration, daily weather data for the period 1970–2005 was used to run the model and to predict crop yield for wheat and barley under normal (baseline) climate, which was expected to describe average or normal conditions and to provide a benchmark against which future changes in yield would be measured (Section 3.5). Therefore, daily weather data of 27 years, during 1970–2005, were used to run the model for both wheat and barley. Output from the model included 27 values of crop yield for each of wheat and barley. Average, minimum and maximum yield and RMSE were calculated for the output data.

3.4. Climate change scenarios

Twenty-three climate change scenarios, representing the possible average climatic conditions around year 2050 (MoEnv, 2009), were used in the study. Twenty of these scenarios were incremental and were suggested as potential scenarios of climate change by year 2050 (Table 1). These incremental scenarios included four-temperature changes of +1 °C, +2 °C, +3 °C and +4 °C. Changes in rainfall of 0%, +10%, +20%, −10%, and −20% were incorporated in combinations with each level of the temperature increase. The other three scenarios (Table 2) were based on the monthly temperature and precipitation projections from the following coupled ocean–atmosphere general circulation models (GCMs):

1. CSIROMK3: Commonwealth Scientific and Industrial Research Organization (CSIRO) Model, Australia.
2. ECHAM5OM: The 5th generation of the ECHAM general circulation model, Max Planck Institute for Meteorology, Germany.
3. HADGEM1: Hadley Center Global Climate Model, UK.

These three models were the only GCMs that had grid points inside the study area. The first two models had a spatial resolution of 1.875° latitude × 1.875° longitude, which was approximately 200 km × 200 km, while the third model had a spatial resolution of 1.25 latitude × 1.875° longitude. Outputs of these GCMs models were retrieved and extracted from the IPCC data distribution center for climate change studies (http://www.ipcc-data.org/). More details on the models, scenarios and variables for which climatologies are available can be found at (http://www.ipcc-data.org/ar4/gcm_data.html). In this study, the monthly temperature and precipitation from the three GCMs were used to simulate the current conditions (1 × CO_2) and were compared with observed data of daily air temperature and precipitation for the period 1960–2005. Models outputs were in good agreement with mean monthly air temperatures of the study area. All models, however, failed to match precipitation patterns. Similar findings were also observed by a previous study in Jordan (Abdulla and Al-Omari, 2008). Outputs from the models, adjustment statistics for temperature and precipitation (Table 2), were used in DSSAT to predict yield of wheat and barley.

Table 2
Summary of the average precipitation ratio (PPT) and temperature difference (Temp.) generated by the three general circulation models (GCM's).

Month	GCM model					
	CSIROMK3		ECHAM5OM		HADGEM1	
	PPT	Temp.	PPT	Temp.	PPT	Temp.
January	1.03	1.43	0.89	0.91	0.94	0.95
February	1.06	0.60	0.94	0.45	1.13	0.85
March	1.03	0.83	0.71	0.84	1.75	0.67
April	1.26	0.85	0.37	0.98	1.40	1.38
May	1.39	0.95	1.04	1.02	1.23	1.18
June	0.76	1.49	1.10	0.53	0.26	1.27
July	0.78	1.17	0.56	1.22	0.04	1.65
August	0.77	1.12	1.93	1.22	0.07	1.49
September	0.80	1.32	0.65	0.78	0.20	1.52
October	1.02	1.67	1.09	0.93	0.70	1.45
November	1.00	1.17	0.69	0.98	0.71	1.37
December	1.12	0.34	0.85	0.89	1.43	1.46

3.5. Implementation of the DSSAT model

The DSSAT model was implemented under the future scenarios of climate change to predict changes in wheat and barley yields. This was carried out by modifying the daily weather data of the 27 years according to the proposed changes in rainfall and temperature using the incremental scenarios (Table 1) and the three GCMs (Table 2). The incremental scenarios were useful for analyzing the sensitivity to a wide range of potential climate changes (such as hotter and wetter or hotter and drier scenarios) and for identifying sensitivity to changes in a specific variable, such as temperature and rainfall. The disadvantage of incremental scenarios was that uniform changes over entire year or over large areas were not always likely to occur. Therefore, GCMs and incremental scenarios could complement each other.

The 27 weather files were prepared and used to run the model for each scenario. The total number of files that were used to run the incremental scenarios was 540 (27 years by 20 scenarios) while 81 files were used to run DSSAT under the three GCMs scenarios. The predicted yield of wheat and barley was calculated for each year and the average value for the 27 years was calculated for each scenario. This value was assumed to represent the yield in year 2050, i.e. the year for which GCMs and incremental scenarios were used to project future climate change. The model was also run assuming different vernalization periods for wheat. Vernalization is the period of low temperature that is needed for wheat and barley plants to initiate flowering, and usually differs according to variety. After examining the weather data, the three vernalization periods were 40, 50 and 60 days.

4. Results and discussion

4.1. Crop production

Analysis of the DOS data showed variations in the total production and yield among the different years (Table 3). For wheat, the average cultivated area was 7830 ha while the average harvested area was 5286 ha. The average ratios of the harvested to cultivated areas for wheat and barley were 68% and 44%, respectively. The coefficients of variation for harvested areas and yield were always higher for barley than for wheat. This could indicate the high risk associated with cultivation of barley when compared to wheat.

Comparing the annual rainfall with total production and yield indicated that the impact of rainfall on the total production was more than its impact on the average yield. Increased rainfall resulted in increasing the harvested area and total production in Irbid. This was obvious in year 2002 and 2003 when total production was relatively high for both wheat and barley. In year 1999, the total production and average yield for wheat and barley were the lowest among the years. This could be explained by the low rainfall during this year, which was 30% of the average. These results would reflect the vulnerability of both crops to climatic variations. This was also indicated by the ratios of cultivated to harvested areas.

4.2. Results from DSSAT model

Results from the DSSAT model showed that the model was able to detect the trend of yield for the period 1996–2005. For wheat, the maximum absolute difference between the DSSAT predicted grain yield and the observed one was less than 530 kg ha^{-1} (45% of the DOS average), with an average RMSE of 586 kg ha^{-1}. Although in some years the DSSAT overestimated and in other years underestimated the grain yield, the model captured the trend over the years realistically well. This was a prerequisite for the crop model to estimate the impact of climate change on grain yield. For barley, similar trends were obtained between predicted yield and the yield reported by the DOS. In most years, the absolute difference between predicted and the actual yield was less than 300 kg ha^{-1}. The average yield obtained from the model was very close to the average of the data of DOS, with a difference of about 5 kg ha^{-1} (<0.5% of the DOS average) and an RMSE of 476 kg ha^{-1}.

For both crops, the predicted yield in 1999 was very close to the average yield reported by the DOS. This could be explained by the low rainfall amounts in 1999 (30% of long-term average) which resulted in low variations in the data of DOS. Before intercalibration of the model, the predicted yield of wheat was higher than the average yield obtained from DOS, except in year 2001. This could be explained by the variations in yield along the gradient of rainfall and climate within Yarmouk basin. Calibrating the model (Fig. 2) resulted in improving the prediction of wheat yield, as the RMSE decreased to 319 kg ha^{-1} and the mean of the simulated grain yield for the 10 years was 1176 kg ha^{-1}, which was rather close to the DOS average of 1173 kg ha^{-1}.

The use of data of DOS to calibrate the yield of barley did not improve the modeled yield. This could be attributed to the high variations in the data of cultivated barley in areas with insufficient precipitation coincided with long periods of drought. The data of

Table 3
Totals of cultivated areas (CA), harvested areas (HA), production (TP), and average yield (AY) for wheat and barley during 1996–2006.

Year	Wheat					Barley				
	CA (ha)	HA (ha)	TP (tonnes)	AY (kg ha^{-1})	Seasonal rainfall (mm)	CA (ha)	HA (ha)	TP (tonnes)	AY (kg ha^{-1})	Seasonal rainfall (mm)
1996	4665	4036	4603	1140	381	1648	764	520	681	132
1997	10,753	9511	6586	692	502	5043	3621	6014	1661	244
1998	7014	5630	7671	1363	529	4028	2820	2577	914	277
1999	9578	766	444	580	215	28,834	879	441	501	99
2000	7185	5146	6977	1356	366	4751	2051	1354	660	138
2001	7288	5466	8473	1550	278	9495	7121	5341	750	153
2002	9507	7130	9384	1316	494	14,790	11,092	10,238	923	295
2003	8909	7127	10,833	1520	882	4011	2407	3851	1600	398
2004	7213	2164	1839	850	392	4326	1081	1157	1070	208
2005	6803	6123	8143	1330	500	4742	3700	4183	1131	232
2006	7214	5050	6110	1210	352	3379	2298	1057	460	169
Minimum	4665	766	444	580	215	1648	764	441	460	99
Maximum	10,753	9511	10833	1550	882	28,834	11,092	10,238	1661	398
Average	7830	5286	6460	1173	445	7732	3439	3339	941	213
Standard deviation	1697	2394	3121	327	176	7864	3101	3009	402	88
Coefficient of variation (%)	22	45	48	28	40	102	90	90	43	41
Harvested/cultivated	0.68						0.44			

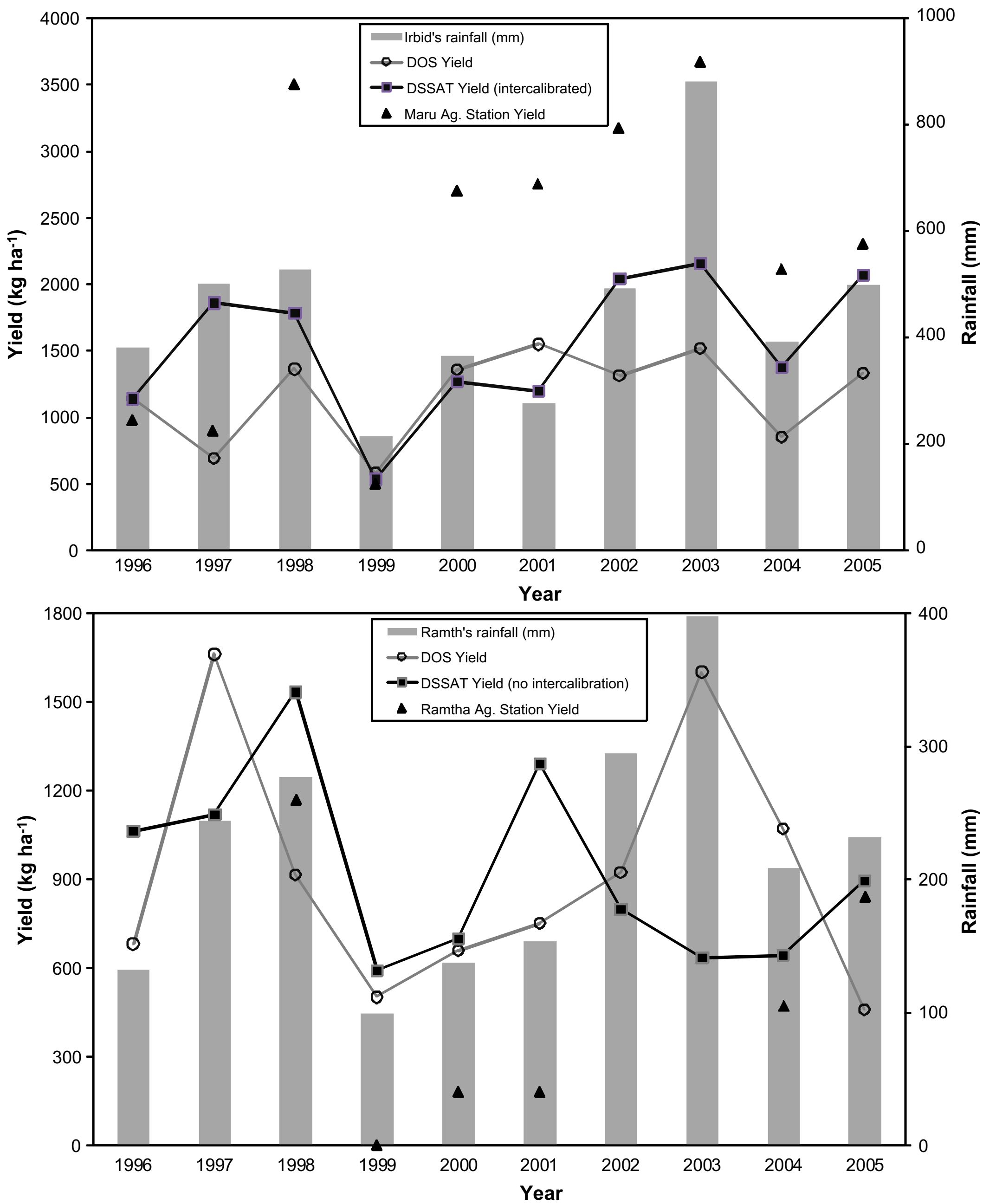

Fig. 2. Simulated and actual grain yield for wheat (top) and barley (bottom).

DOS (Table 3) showed higher variations in cultivated and harvested areas, as well as in the total production and average yield for barley than for wheat. Generally, yield of wheat was more stable than that of barley; since wheat was grown in areas with relatively high rainfall. The variations between DSSAT predicted yield and DOS-yield were higher for barley than for wheat, with RMSE of 476 kg ha^{-1} and 319 kg ha^{-1} for barley and wheat, respectively. These variations would be expected in the modeling approach and would not limit the use of DSSAT to trace the trends of yield under future scenarios, particularly after the intercalibration of the model.

It should be noticed that the data sets from the NCARE for wheat showed higher yield than the average yield obtained from the surveys of DOS, particularly after the year 1999 (Fig. 2). This could be attributed to the supervised management practices followed in Maru agricultural station primarily; tillage operations, fertilizers application and weed control. Therefore, the data of NCARE was not used in calibrating the model as they represented ideal situations of cultivation that might not be followed by local farmers. However, the data would be useful in suggesting adaptation plans following the practices of this station. As for barley, variations in yield were observed even inside Ramtha agricultural station, where the yield varied among years and did not follow certain trend, primarily because of the seasonal variation in rainfall. Results from DSSAT showed that predicted yield of barley was always higher than the actual yield obtained from Ramtha agricultural research station. These variations among years and among the different sources showed that this crop would be highly vulnerable to climate change; as it was cultivated in the dry areas of Yarmouk basin.

4.3. Climate change and crop yield

Summary of air temperature and precipitation adjustment statistics that were generated by the three GCMs is shown in Table 2. In this table, temperature difference represents the increase in temperature as predicted by the GCM, while precipitation ratio represents the ratio between the GCM predicted value and the baseline value. Generally, the three models predicted an increase in air temperature in the range of 0.34–1.67 °C. The average monthly increase, however, was different among the three models. This could be attributed to several factors, including the resolution of models and the type of variables and scenarios used by each. The

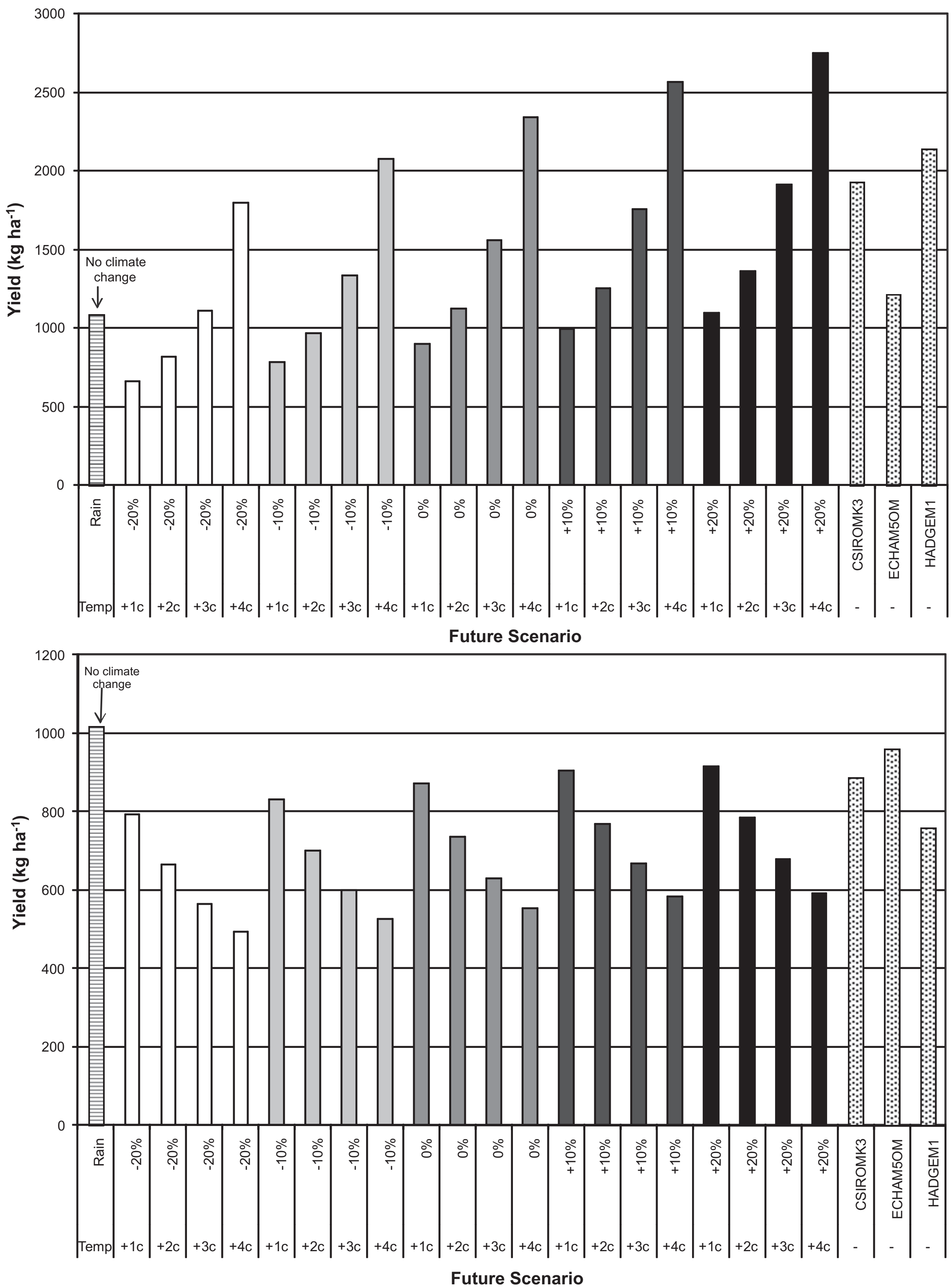

Fig. 3. Simulated grain yield by year 2050 for wheat with 60 days vernalization (top) and barley (bottom) under the different climate change scenarios.

trends of increased air temperature agreed with those of Ragab and Prudhomme (2002), who indicated a possible rise (1.50–2.75 °C) in the air temperature of the east Mediterranean countries.

Results from the DSSAT model showed variations in the predicted yield of wheat and barley under the different scenarios of climate change (Fig. 3). For both crops, however, it was found that the reduction of rainfall by 10–20% had a negative impact on grain yield, while the increase in rainfall by 10–20% had a positive impact on grain yield for both barley and wheat (60 days vernalization) at the different temperature regimes (Table 4). This showed that water was the limiting growth factor for wheat and barley under rainfed conditions. The reduction of rainfall by 10–20% reduced the expected yield by 4–8% for barley and 10–20% for wheat, respectively. The increase in rainfall by 10–20% increased the expected yield by 3–5% for barley and 9–18% for wheat, respectively. The increase of air temperature (with no change in rainfall) by 1, 2, 3 and 4 °C resulted in deviating the expected yield by −14%, −28%, −38% and −46% for barley and −17%, +4%, +43% and +113% for wheat, respectively. The extreme scenario of climate change (+4 °C temperatures and −20% rainfalls) resulted in decreasing the average yield of barley by 51%.

Interestingly enough, all scenarios had negative impacts on barley (Fig. 3). This would suggest that the increase in yield due to the increase in rainfall was less than the reduction in yield due to the increase of temperature by 1 °C or more, i.e. the increase in rainfall amount could not alleviate the adverse impacts of increased air temperature on barley yield. For all incremental scenarios, the reduction of barley yield was more than 400 kg ha^{-1} when the temperature increase was 4 °C.

The trend for wheat was different from barley, as the increase of temperature was more advantageous for yield when the rainfall increased. The increase of temperature by 1–2 °C for wheat had adverse impacts on yield for dry scenarios, particularly for 60 days vernalization, while it had positive impacts under normal or increased rainfall. These findings could be attributed to the fact that most rainfall was occurring in the period of December–February, when moisture was available and temperatures were relatively low. These findings were also found by Parry et al. (2007) who indicated that some studies, within the IPCC framework, showed that yield of cereal crops and pasture of the mid to high-latitude regions would benefit from moderate warming. In our study, the positive impact could be also attributed to the cultivation of wheat in the heavy clay soils (vertisols) which had high water holding capacity. The high water holding capacity could mitigate the adverse impact of climate change during dry periods of the season, as indicated by Popova and Kercheva (2005).

Any increase in temperature was expected to reduce the length of the growing season as a whole, as well as the grain filling period. Reducing the length of the growing season would reduce the crop water requirements and that should reduce the water stress under rainfed conditions. Although this should improve the yield, however the reduction of grain filling period had a negative impact on grain yield because it would result in smaller grains. In the case of barley, this could be the main reason why the grain yield decreased when temperature increased by 1–4 °C. In the case of wheat, the length of the growing season decreased, but the length of the grain filling period was not getting shorter as the crop benefited from the colder days, which became warmer. This was more evident in wheat because it was harvested in June while barley was harvested in May.

The DSSAT model predicted an increased yield of wheat under the three GCM scenarios, particularly for HADGEM1. Oppositely, an obvious decrease in barley yield was predicted under HADGEM1 scenario and a slight decrease was predicted for ECHAM5OM scenario. Incorporating outputs from the three GCM models within DSSAT, for the weather data of the 27 years, showed that both CSIROMK3 (+7%) and HADGEM1 (+19%) had positive impacts on wheat grain yield while ECHAM5OM resulted in about 1/3 reduction in yield, compared to the average of the 27-years. This could be attributed to the future increase in rainfall for December,

Table 4
Predicted yield of wheat, with 60 days vernalization requirements, and barley and its change under the different scenarios.

Scenario		Wheat		Barley	
Temperature change (°C)	Rainfall change (%)	Predicted yield (kg ha^{-1})	Change in yield (kg ha^{-1})	Predicted yield (kg ha^{-1})	Change in yield (kg ha^{-1})
+1	−20	660	−423	794	−223
+2	−20	813	−269	664	−353
+3	−20	1108	25	563	−454
+4	−20	1798	715	494	−523
+1	−10	786	−297	830	−187
+2	−10	969	−114	702	−315
+3	−10	1336	253	600	−417
+4	−10	2073	990	528	−489
+1	0	899	−184	872	−145
+2	0	1123	40	736	−281
+3	0	1558	475	629	−388
+4	0	2343	1260	554	−463
+1	+10	996	−86	905	−112
+2	+10	1249	166	768	−249
+3	+10	1756	673	668	−349
+4	+10	2565	1482	585	−432
+1	+20	1096	13	915	−102
+2	+20	1364	281	784	−233
+3	+20	1912	830	678	−339
+4	+20	2750	1668	592	−425
GCM model					
CSIROMK3		1931	848	886	−131
ECHAM5OM		1213	130	960	−57
HADGEM1		2143	1060	758	−259
Maximum change			+1667		−523
Minimum change			−423		−57
Average modeled yield (kg ha^{-1}) under no climate change			1083	1017	

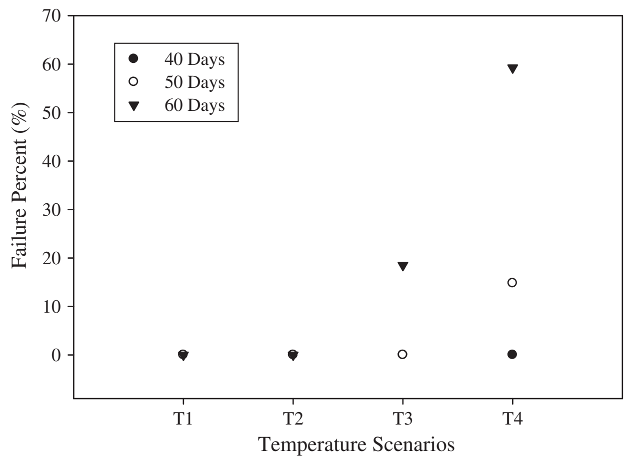

Fig. 4. Simulated crop failure of wheat with 40, 50 and 60 days of vernalization requirements under the different climate change scenarios of air temperature.

February and March, as predicted by CSIROMK3 and HADGEM1, and the expected decrease in rainfall, as predicted by the ECHAM5OM. For barley, the DSSAT model predicted yield reduction under the three GCMs scenario. According to HADGEM1, an average decrease of 33% in barley yield would occur by year 2050. These results could be explained by the predicted increase in air temperature and the decrease in rainfall.

Considering the outputs from the different scenarios (Table 4), the reduction in barley yield would range from 52 kg ha^{-1} under ECHAM5OM to 523 kg ha^{-1} under the extreme incremental scenario of +4 °C temperatures and −20% rainfalls. The maximum reduction in the yield of wheat (60 days vernalization) reached 423 kg ha^{-1} under a rainfall decrease of 20% and a temperature increase of 1 °C. The possible increase in the yield of wheat reached 1667 kg ha^{-1} under the extremely wet scenario of 20% increase in rainfall and 4 °C increase in temperature (Table 4). These results disagreed with the findings obtained from the production functions used in the previous studies in Jordan (GCEP, 1999). Obviously, results from our study showed that the impact of temperature and rainfall on rainfed wheat and barley could not be separated. Also, response to climate change varied between wheat and barley and among the different scenarios. Such variations, with trends towards reduction in yield, were also indicated by research in arid parts of India (e.g. Lal et al., 1998; Aggarwal, 2003) and in South and South-East Asia (Fischer et al., 2002).

Results from DSSAT showed that the predicted crop failure would be high for winter varieties of wheat that required vernalization periods of more than 40 days (Fig. 4). For spring varieties, crop failure due to vernalization requirements would not be expected under the different temperature scenarios. This was confirmed by the DSSAT which showed that wheat varieties with 50 days vernalization would have a yield reduction of 8–20% under the dry scenarios while spring varieties with 40 days vernalization would only have 10% reduction in yield under the dry scenario of −20% rainfall and +4 °C temperature. Therefore, all winter varieties should be replaced with spring varieties to avoid possible crop failure under the expected increase of temperature.

5. Conclusions

Results presented in this study showed that rainfed agriculture had high vulnerability to climatic change of increased air temperature and decreased precipitation. The increased air temperature under the different future scenarios had adverse impacts on barley yield, while reduction of precipitation had negative impacts on both wheat and barley. Therefore, adoption of soil water conservation to increase available water to crop could be seen as an important adaptation measure to climate change. Also, the selection of drought tolerant genotypes with shorter growing seasons than the present genotypes is another adaptation measure that should be considered to alleviate the adverse impact of climate change. When compared with yield of farmers, the higher levels of wheat yield for agricultural stations implied that management practices followed in these stations should be transferred to farmers through extension services within planned adaptation. Results of this study also showed that the use of DSSAT simulation model was useful in tracing the general trend of yield and its possible changes under the different climate change scenarios. The implementation of such models for other crops in different areas, after proper calibrations, should be an objective for future studies in this field. By this, critical information would be transferred to decision makers to formulate appropriate adaptation measures.

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