Chapter 12
Interactive Effects of Elevated CO_2 and Climate Change on Wheat Production in the Mediterranean Region

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Abstract Global climate change could be harmful to agriculture. In particular, water availability and irrigation development under changed climatic conditions already pose a growing problem for crop production in the Mediterranean region. Wheat is the major significant crop in terms of food security. Therefore, in relation to these issues, this review gives an overview of climate change effects on wheat production in the Mediterranean environment of Turkey. Future climate data generated by a general circulation model (e.g., CGCM2) and regional climate models (e.g., RCM/MRI, CCSR-NIES and TERCH-RAMS) have been used to quantify the wheat growth and the soil-water-balance around the Eastern Mediterranean region of Turkey. The effects of climate change on the water demand and yield of wheat were predicted using the detailed crop growth subroutine of the SWAP (Soil-Water-Atmosphere-Plant). The Soil evaporation was estimated using the E-DiGOR (Evaporation and Drainage investigations at Ground of Ordinary Rainfed-areas) model. This review revealed that the changes in climatic conditions and CO_2 concentration have caused parallel changes in the wheat yield. A close correspondence between measured and simulated yield data was obtained. The grain yield increased by about 24.7% (measured) and 21.9% (modelled) under a two-fold CO_2 concentration and the current climatic conditions. However, this increase in the yield was counteracted by a temperature rise of 3 °C. Wheat biomass decreases under the future climatic conditions and the enhanced CO_2 concentration,

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regardless of the model used. Without CO_2 effects, grain yield also decreases for all the models. By contrast, the combined impact of elevated CO_2 and increased temperature on grain yield of wheat was positive, but varied with the climatic models. Among the models, the CCSR-NIES and TERCH-RAMS denote the highest (24.9%) and lowest (6.3%) increases in grain yield respectively. The duration of the regular crop-growing season for wheat was 24, 21, and 27 days shorter as calculated for the future, mainly caused by the projected air temperature rise of 2.2, 2.4, and 3 °C for a growing period by the 2070s for CGCM2, CCSR-NIES and TERCH-RAMS respectively. The experimental results show large increases in the water use efficiency of wheat, due to the increases in CO_2 concentration and air temperature. Despite the increased evaporative demand of the atmosphere, the increases in water use efficiency can be attributed to the shorter growing days and a reduction in the transpiration due to stomata closure. Unlike reference evapotranspiration and potential soil evaporation, actual evaporation from bare soils was estimated to reduce by 16.5% in response to a decrease in rainfall and consequently soil wetness in the future, regardless of the increases in the evaporative demand. It can be concluded that to maintain wheat production in the future, the water stress must be managed by proper irrigation management techniques.

Keywords CO_2 · Crop growth · Crop water use · Growth chamber Soil evaporation

12.1 Introduction

In recent decades, the issue of climate change has been at the centre of many scientific studies at global level (Southworth et al. 2000; IPCC 2001a; Ibrahim 2014; Alpert et al. 2008). Global climate change may have serious impacts on water resources and agriculture in the future. The concerns about these issues have stimulated interdisciplinary research (Rosenzweig 1985; Rosenberg 1992; Maytin et al. 1995; Wolf/Van Diepen 1995; El Maayar et al. 1997; Alexandrov/ Hoogenboom 2000; Olesen/Bindi 2002; Aggarwal 2003; Jones/Thornton 2003; Izaurralde et al. 2003; Quinn et al. 2004; Yano et al. 2007a; Guo et al. 2017; Ibrahim 2014). In the past, researchers began to use crop and agro-ecosystem models to assess how agricultural production could be affected according to the projections of climate models. This approach has been proven useful because it also yields insights into some of the extended impacts of climate change on ecosystem processes (Mearns et al. 1992; Brown/Rosenberg 1999; Guerena et al. 2001; Izaurralde et al. 2003; Steduto et al. 2009; Asseng et al. 2013). Based on a range of several climate models, the mean annual global surface temperature is projected to

increase by 1.1–6.4 °C over the period of 1990–2100 (IPCC 2007), with changes in the spatial and temporal patterns of precipitation.

Climate change is a long-term issue with short-term risks for the production systems in each Mediterranean country. The updated report of IPCC (2013) indicates that increased temperature and droughts, and decreased precipitation, as well as a decline in soil moisture, would dramatically influence agricultural production. Projections from the General Circulation Model-Regional Climate Model (GCM-RCM) reveal the changes in mean and extreme temperature and precipitation for Europe and the Mediterranean (van der Linden/Mitchell 2009). In terms of mean annual temperature, projections show a warming of 0.5–1.5 °C (2046–2065) and 1–5 °C (2081–2100), over the land portion of the Mediterranean. Moreover, decreased precipitation in the Mediterranean of 10–20% in 2046–2065 and 10–30% in 2081–2100, is likely under the "Representative Concentration Pathways" scenario (IPCC 2013). Based on the multi-model projections of the 21st century, the mean annual soil moisture is estimated to decrease in the Mediterranean region. In other words, the risk of agricultural drought will increase in the future. A group of regional climate models (RCMs) driven by several general circulation models (GCMs) using the A1B scenario foresees a significant decrease in runoff emerging only after 2050 (Sanchez-Gomez et al. 2009) for the Mediterranean basin. Thus, considerable increases in meteorological drought are also projected (IPCC 2013). Furthermore, Giorgi/Lionello (2008) presented a review of climate change projections over the Mediterranean region, based on the most recent and comprehensive group of global and regional climate change simulations. These simulations represent substantial drying and warming of the Mediterranean region between 2071 and 2100, especially in the warm season (precipitation decrease exceeding −25 to –30% and warming exceeding 4–5 °C). The only exception to this picture is an increase in precipitation during the winter over some areas of the northern Mediterranean basin and most noticeably in the Alps. Inter-annual variability is projected to experience a general increase, as is the occurrence of extreme heat and drought events.

Despite intensive research efforts, many aspects of climate change are still unpredictable, particularly at site scale and regional level (Zhang/Liu 2005). Therefore, numerous simulation studies have been carried out by some interdisciplinary teams under many scenarios (Evrendilek et al. 2005, 2008; Yano et al. 2005, 2007a, b, c; Aydın et al. 2008; Önder et al. 2009a; Hu et al. 2015) projected by the general circulation models (GCMs) and regional climate models (RCMs) to predict the impacts of climate change on the soil-water balance and crop growth in the Mediterranean environment of Turkey. In this chapter, the changes in biomass and grain yield of wheat under future climatic conditions and a two-fold CO_2 increase scenario are discussed.

12.2 Climate Change Scenarios

The Special Report on Emission Scenarios (SRES) produced forty future emission scenarios for greenhouse gases and sulfate aerosols. These scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. The GCMs are the best available tools to study the possible change in the future climate globally. Many climate change studies use downscaled results from GCMs to estimate the future climate (Alexandrov/Hoogenboom 2000; Schulze 2000; Eckersten et al. 2001; Van Ittersum et al. 2003; Kimura et al. 2007; Kitoh 2007; Yano et al. 2007a; Hu et al. 2015), and some of these projections are available on the IPCC website (http://ipcc-ddc.cru.uea.ac.uk). However, GCMs sometimes do not provide accurate data for the specific site due to downscaling from data in the surrounding grid points and due to the inherent model performance. Thus, it is sometimes assumed that while data for the present climate differs between the control simulation and the actual observation, the change between the present and the future climate remains accurate. On the other hand, the RCMs are developed to evaluate climate change on a regional scale (Sato et al. 2007). In order to predict the impacts of climate change on the soil-water balance components and crop production, Yano et al. (2007a, b, c) have obtained the climate change data for a Mediterranean environment of Turkey from the outputs of the three GCMs [the second version of the Canadian Global Coupled Model – CGCM2 – (Flato/Boer 2001), the model developed from the atmospheric model of the European Center for Medium-Range Weather Forecasts, and parameterized at Hamburg – ECHAM4 – (Roeckner et al. 1996), and the general circulation model developed at the Meteorological Research Institute of Japan – MRI – (Yukimoto et al. 2001; Kitoh et al. 2005)] for the A2 scenario in the SRES. The data of the two RCMs [RCM/MRI and RCM/CCSR-NIES] were additionally used for complementarity. The A2 scenario describes a very heterogeneous world of high population growth, slow economic development and strong regional cultural identities. Scenario A2 is one of the emission scenarios with the highest projected CO_2 increase (up to 800 ppm) by the end of the 21st century (Nakicenovic/Swart 2000).

   In the present chapter, we compared the climate change data of CGCM2, RCM/MRI, RCM/CCSR-NIES and TERCH-RAMS for the period of 2070–2079. The forcing data for the boundary conditions of the RCM/MRI are given by MRI. Hereafter, the RCM/CCSR-NIES is referred to as CCSR-NIES, which represents the Center for the Climate Systems Research and the National Institute for Environmental Studies of Japan. The acronym TERCH-RAMS stands for the Terrestrial Environmental Research Center-Regional Atmospheric Modelling System. The projection years for wheat production were 1994–2003 (baseline) and 2070–2079. Using the daily data for the baseline period, the future climate changes have been applied to the available baseline climate series in a straightforward way. Temperature changes have been added as absolute changes to the baseline series; the other climate parameters have been adapted according to their relative changes

(Tao et al. 2003; Dhungana et al. 2006; Yano et al. 2007a). In other words, the future climate data have been created by superimposing the observed values on the change between the present and the future estimated values.

All the models projected a temperature rise by the 2070s in the Eastern Mediterranean region of Turkey. Rises in air temperature projected by different climatic models for the future (2070–2079) compared with the baseline (1994–2003) are depicted in Fig. 12.1. Among the four models, the TERCH-RAMS and RCM/MRI denote the highest and lowest increases in temperature respectively. The averaged air temperature is estimated to increase by 2.2, 2.4, 1.6, and 3.0 °C based on the projections of CGCM2, CCSR-NIES, RCM/MRI and TERCH-RAMS, respectively, for a growing period of wheat. Önol/Unal (2012) have projected climate change over the Mediterranean region of Turkey using the RegCM3 regional climate model for A2 IPCC scenario and reported that a 2–4 °C temperature increase was detected which is similar to the findings of the models mentioned in this review.

Although the annual precipitation denoted noticeable variations year-by-year, it was not likely that it will have increased in the future. Percentage changes in the mean annual precipitation projected by different climatic models for the future are shown in Fig. 12.2. The mean annual precipitation during 2070–2079 compared with 1994–2003 is projected to decrease by 11%, 42%, 46%, and 25% according to the CGCM2, CCSR-NIES, RCM/MRI and TERCH-RAMS models respectively. On average, regarding the models, future precipitation is predicted to decrease by 31%. This average is similar to the results obtained by some of the other researchers. For example, according to Kimura et al. (2007), precipitation is expected to decrease by 27% over the basin. Önder et al. (2009a) have reported that the projected precipitation is 29.6% less compared to the present for the southern region of Turkey, especially along the coast of the Mediterranean by the 2070s.
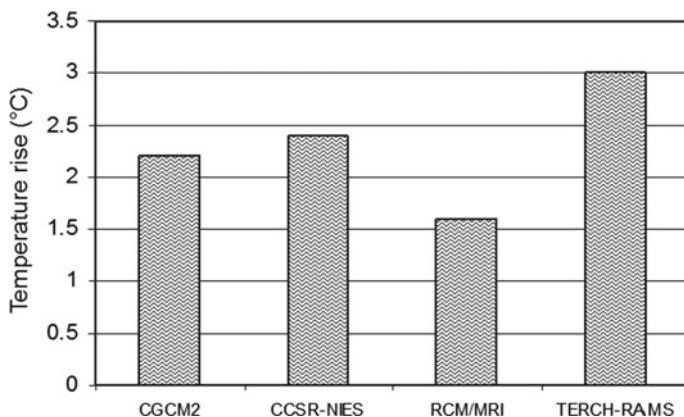

Fig. 12.1 Rises in air temperature projected by different climatic models for the future (2070–2079) compared with the baseline (1994–2003) during the wheat-growing period. *Source* The authors
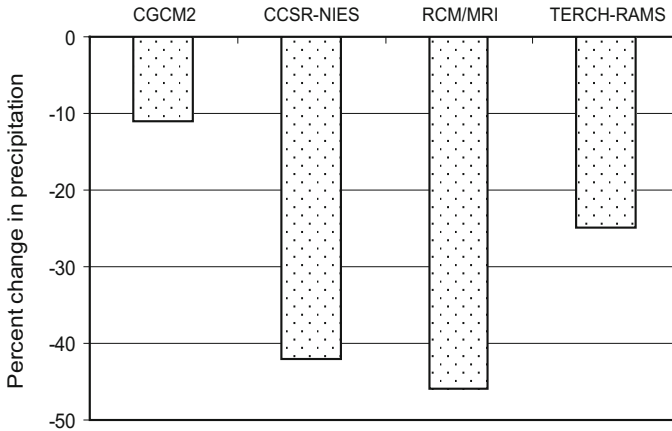
Fig. 12.2 Changes in precipitation projected by different climatic models for the future (2070–2079) compared with the baseline (1994–2003). *Source* The authors

Moreover, Lionello/Scarascia (2017) indicated that the precipitation decrease would affect most of the Mediterranean region, where a 7% decrease in annual precipitation for each degree of global warming is expected for the southern parts of Mediterranean, according to CMIP5 estimates.

For a specific region, if the climate models show consistent results, then they can be used to predict potential impacts (Van Ittersum et al. 2003). From this point of view, it seems that using the RCM/MRI data would not correctly reflect the effect of climate change on crop growth. Therefore, further comparisons have been conducted with CGCM2, CCSR-NIES, and TERCH-RAMS data due to the consistency of their results. In other words, the climate change data projected by these models have been used for quantifying potential impacts of climate change on wheat growth. Although it is generally difficult to downscale GCMs data with large grid point distances to the study area accurately, using the CGCM2 data to predict the future change in crop growth is more appropriate under the present situation than using the less reliable RCM/MRI data (Yano et al. 2007c).

12.3 Crop Growth

Crop yields are affected by variations in climatic elements such as air temperature and precipitation and CO_2 concentration. Moreover, the changes in both the total seasonal precipitation and its pattern are important (Alexandrov/Hoogenboom 2000; Olesen/Bindi 2002; Asseng et al. 2015) in crop yield studies concerning climate change. Thus, sites which are already at the limit with respect to water supply under current conditions are likely to be most sensitive to climate change, leading to an

increase in the need for irrigation in dry areas, while more humid areas may be less affected (Brumbelow/Georgakakos 2001; Fuhrer 2003; Hatfield/Prueger 2015). In agro-ecosystems under a changing climate, water deficit stress could cause decreasing yield or require irrigation to maintain crop production. This negative effect of climate warming may be counteracted by effects of elevated CO$_2$ on the crop tolerance to water stress (Lawlor/Mitchell 2000; Young/Long 2000; Robredo et al. 2011; Bencze et al. 2014; Pazzagli et al. 2016). Changes in atmospheric CO$_2$ levels have important physiological effects on plants. Elevation in CO$_2$ affects photosynthesis by increasing the photosynthetic rate (Heinemann et al. 2006; Bencze et al. 2014). In Australia, the impact of elevated CO$_2$ and increased temperature on grain yield of wheat was on average positive, but varied with seasonal rainfall distribution (Asseng et al. 2004). According to Richter/Semenov (2005), simulated scenarios for the 2020s and 2050s show that in comparison to the baseline, wheat yields in England are likely to increase more until the 2020s than in the following 30 years in spite of CO$_2$ and temperature increasing linearly. Erice et al. (2014) concluded that the stimulation of plant growth by elevated CO$_2$ was found in durum wheat genotypes with high harvest indices and optimal water supply.

Future cereal production will depend not only on climate change effects, but also on further developments in technology and crop management, including changes in the sowing dates, plant densities, and irrigation applications (Olesen/Bindi 2002; Dhungana et al. 2006; Godfray et al. 2010). Technological innovations, including the development of new crop hybrids and cultivars that may be developed to match the changing climate, are considered to be a promising adaptation strategy (Alexandrov/Hoogenboom 2000; Jones/Thornton 2003; Tester/Langridge 2010). The semi-arid regions differ in socio-economic development, technological possibilities and climatic regime, but all have relatively ample water supplies for agriculture in the current climate (Krol/Bronstert 2007). However, the continued population growth will cause an increasing demand for food and water alongside the rising temperatures and CO$_2$, and uncertainties in rainfall associated with global climatic change (Aggarwal 2003; Godfray et al. 2010). Thus, the estimates of future food production and demand are associated with high uncertainties (Olesen/Bindi 2002). Major agricultural regions may be developed under changing climate conditions, since they may become even more important as food-producing centres relative to agricultural areas in more marginal, semi-arid regions that have been found to be vulnerable to climate change (IPCC 2001b). In this regard, Olesen/Bindi (2002) reported that developing countries would be more severely affected by climate change than the developed countries that are generally located in temperate regions. At conditions yielding higher climate change impacts that were tested in the A1 and A2 SRES scenarios, the disparities in cereal yields between the developed and the developing countries are likely to increase (Parry et al. 2004). Consequently, based on some scenarios, the yield impact studies using crop response models have been conducted for many countries (Table 12.1). For example, the effects of the projected climate change on the wheat yield in a Mediterranean environment of Turkey, have been studied by Yano et al. (2007a, b, c). The results of these studies have revealed a wide variation concerning the climatic scenarios, the methods used

Table 12.1 The impact of the two-fold increased CO_2 and raised temperature on the yield of wheat in different parts of the world. *Source* IPCC (1995: 33), Kapur (2010: 15)

Region	Percentage change in yield	Countries
Europe	–10 to +10	France, England, and Northern Europe
Latin America	–61 to +5	Argentina, Brazil, Chile, and Mexico
Former Soviet Union	–19 to +41	–
North America	–100 to +234	USA and Canada
Africa	–65 to +6	Egypt, Kenya, South Africa, and Zimbabwe
South Asia	–61 to +67	Bangladesh, India, Philippines, Thailand, and Indonesia
China	–78 to +28	–
Australia and Far East Asia	–41 to +65	Australia, Japan

for crop response, and the site-specific conditions (Peiris et al. 1996; Wolf et al. 2002).

Crop growth was simulated using the detailed crop growth sub-model of the SWAP (Soil-Water-Atmosphere-Plant) incorporated from WOFOST (WOrld FOod STudies) with a daily time step from sowing to maturity (van Dam et al. 1997; Boogaard et al. 1998). As a rule, experimentation is needed to obtain specific parameters and to calibrate and verify the model results. Therefore, the SWAP model was parameterised for wheat and calibrated with the crop growth measurements (Yano et al. 2006, 2007a) in addition to photosynthesis and transpiration rates of the plant leaves measured under Mediterranean field conditions, using the Photosynthesis Monitor system (PM-48M). As reported by Evrendilek et al. (2008), the net photosynthetic rate of wheat, especially, exhibited a peak at mid-morning, and a photosynthetic midday depression under the limiting effects of high evaporative demand. On the other hand, to evaluate the positive effect of the elevated CO_2 concentration and the negative effect of the risen air temperature on the wheat yield, the confidence level in the model used can be obtained through the simulation of the measured data. Therefore, the measured data under the controlled conditions and estimated data by the SWAP model are compared in Fig. 12.3, for a two-fold CO_2 increase scenario, as well as for an increased temperature of 3 °C. Similar results were obtained in this study between the measured and the modelled wheat yield data for the enhanced CO_2. For example, the grain yield of wheat increases were about 24.7% (measured) and 21.9% (modelled) under a two-fold CO_2 increase scenario and the current climatic conditions. By contrast, the increase in temperature without the effects of CO_2 caused decreases in the wheat yield.

A further simulation was done by a two-fold CO_2 scenario and by increasing the maximum and minimum temperatures by 1 and 3 °C relative to the current conditions. The yield of wheat estimated by the SWAP model is shown in Fig. 12.4. The increases in both the biomass and grain yield obtained via the use of the two-fold CO_2 scenario experimentation under the conditions of current climate are
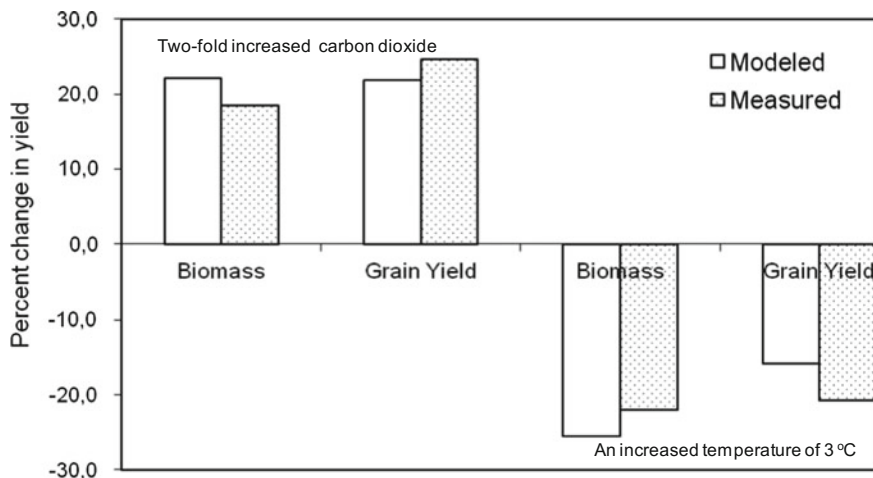
Fig. 12.3 A comparison of estimated versus measured wheat yield, for a two-fold CO$_2$ increase scenario, as well as for an increased temperature of 3 °C. *Source* The authors
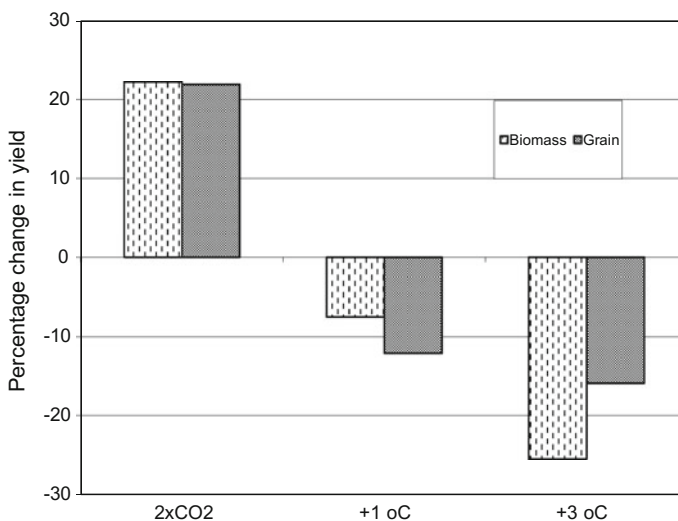

Fig. 12.4 Effects of the two-fold CO$_2$ increase scenario and temperature rise separately on wheat growth. *Source* The authors

about 22% for wheat as a C3 crop. The increases in biomass and grain yield are counteracted by a temperature rise of 3 °C. Although several variations of temperature rise are recognised among the models, more than 1 °C of temperature rise is estimated in the 2070s when the CO$_2$ concentration is assumed to increase two-fold (See Fig. 12.1). Yields were also simulated using climate inputs generated

Table 12.2 Percentage changes in biomass and grain yield of wheat under future (2070–2079) climatic conditions and a two-fold CO_2 increase scenario compared with the baseline (1994–2003). *Source* The authors

Climate model	Percentage change in biomass		Percentage change in grain yield		Shortness in growth duration (days)
	Without CO_2 effects	With CO_2 effects	Without CO_2 effects	With CO_2 effects	With CO_2 effects
CGCM2	−24.1	−3.3	−11.9	+15.3	−24
CCSR-NIES	−9.2	–	−6.0	+24.9	−21
TERCH-RAMS	−22.0	−2.3	−20.8	+6.3	−27

from GCM and RCM climate data. Changes in yield were evaluated by comparing the future yields with the current ones of the same crop varieties, and then stating the change as difference in per cent. Biomass and grain yield predictions for wheat during the period of 2070–2079 denoted the complicated results in accordance with the different photosynthesis rates and air temperature rises in the future. Wheat biomass decreases under the future climatic conditions and the elevated CO_2 concentration, regardless of the model used. Without CO_2 effects, grain yield also decreases for all the models. However, the combined impact of elevated CO_2 and increased temperature on grain yield of wheat was positive, but varied with climatic models (Table 12.2). Since the rise in temperature for TERCH-RAMS is higher than the other two models, the lower increase in grain yield is expected to occur. It is assumed that the use of climatic data alone would cause erroneous results, because the CO_2 is the fundamental parameter for crop growth prediction. Thus, the effects of increased CO_2 on the plants should be imposed on the model simulations. Although wheat is a C3 plant and raised CO_2 concentration promotes photosynthesis, the risen temperature may partially compensate with stomatal closure. That is to say, stimulation of photosynthesis does not directly translate to increased biomass, or yield. The reason why grain yields increase for all the models cannot be fully explained. However, in determinate crops such as cereals, the grain yield not only depends on photosynthesis but also on the length of the active phase of leaf photosynthesis and the sink capacity of the grains (Fuhrer 2003). Kapur (2010) reported that the grain yield was dependent on differences in the tillers rather than the main spike. The positive effects of elevated atmospheric carbon dioxide on wheat were lower at the main spike. Consequently, the substances produced during the process of photosynthesis were stored in the vegetative organs and especially in the roots (Parry et al. 2011). Thus, the yield increase depends on the sink capacity of the wheat variety, rather than the amount of assimilated resources.

Climate change data used in the SWAP model have projected shorter growing seasons for wheat during the period 2070–2079 compared to 1994–2003 (Table 12.2). These changes are caused by the predicted temperature rises during the growing periods of the 2070s. The duration of the regular crop-growing season

for wheat was 24, 21, and 27 days shorter in the future, mainly caused by the projected air temperature rise of 2.2, 2.4, and 3 °C for a growing period by the 2070s, according to CGCM2, CCSR-NIES, and TERCH-RAMS respectively. In other words, high temperatures accelerate the phenological development of plants, resulting in quicker maturation. This may cause a shift in harvest maturity dates for wheat from May to April in nearly three-quarters of this century. Without the positive effects of the elevated CO$_2$ the shortened growth cycle may reduce crop yield (Yano et al. 2007a; Hatfield/Prueger 2015). Similarly, Alexandrov/Hoogenboom (2000) reported that the GCM scenarios for the 21st century projected a decrease in yield of winter wheat in Bulgaria, caused by a shorter crop-growing season due to higher temperatures and precipitation deficit. When the direct effects of CO$_2$ were included in the study above, all GCM scenarios resulted in an increase in winter wheat yield. They emphasised that the selection of a suitable sowing date will probably be the appropriate response to offset the negative effect of a potential increase in temperature. This change in the planting date will allow for the crop to develop during a period of the year with lower temperatures, thereby decreasing developmental rates and increasing the growth duration, and especially increasing the grain-filling period (Yano et al. 2007a). On the other hand, Brown/Rosenberg (1999) emphasised that regardless of the GCM scenario used, an enhancement in atmospheric CO$_2$ increased the yield of winter wheat. In their study, the crop was negatively influenced by the increasing temperature, and yields fell dramatically when global mean temperatures increased by 5 °C. Moreover, Barlow et al. (2015) revealed that increased temperature caused reduction in grain number and reduced duration of the grain-filling period of wheat.

Unfortunately, there are several limitations in such simulations. The crop models assume that nutrients are not limited. Also, pests (insects, diseases, weeds) are assumed to pose no limitation to crop growth and yield under both current and future climate scenarios (El Maayar et al. 1997; Scherm et al. 2000; Tubiello/Ewert 2002; Asseng et al. 2015). Yano et al. (2007a) have stated that simulated quantitative effects with the models should be interpreted cautiously based on the decadal time studies, limited field experimentation, and the large possible range of factorial interactions that are not tested. As an alternative to assessing climate change impacts over decadal timescales, climate variability impacts may be more useful for more immediate decision-making at inter-annual time scales (Schulze 2000). Present results are what we would expect if farmers continue to grow the same varieties in the same way in the same locations. However, the research and plant breeding studies may mitigate many of the detrimental effects. Similarly, Kapur (2010) indicated that irrigation must be considered an important application for eliminating the yield losses in the future. New varieties are also expected to benefit more from the high assimilate due to the increasing carbon dioxide. Though the results are clearly not conclusive, they certainly suggest the potential impacts of climate change on crop production in the region. As the relationships between climate, crop growth and soil are complicated, this cannot be described in terms of simple and average relationships. Despite the mentioned drawbacks, the results

from such studies not only improve our understanding of the possible impacts of climate change, but may also provide valuable information to adapt a strategy for mitigating the detrimental effects.

12.4   Crop Water Use

Agriculture is the largest consumer of water resources in the semi-arid to arid regions. The demand for irrigation water is projected to rise in a warmer climate (Olesen/Bindi 2002). According to Mehta et al. (2013), the warmer and drier A2 climate scenario ultimately encourages higher irrigation demand than the B1 scenario. This indicates the need to assess the effects of global warming on irrigation water requirements. In Mediterranean countries, cereal yields are limited by water availability, heat stress and the short duration of the grain-filling period. Irrigation is important for crop production in Mediterranean countries (Alexandrov/ Hoogenboom 2000; Olesen/Bindi 2002; Fader et al. 2015), including Turkey, due to high evapotranspiration and restricted rainfall (Yano et al. 2007a). Soil and climatic conditions in Turkey are suitable for the cultivation of cereals. However, sometimes a precipitation deficit and high air temperatures occur during the critical period of crop development. Both factors are the ones that most limit the growth and final yield of crops. Agricultural production in the Mediterranean region of Turkey is vulnerable to changes in precipitation; and agriculture is dependent on irrigation for its viability. Projected future changes foreseen in water use for irrigation in this region, based on the predicted climate change, may have serious consequences for the economic situation of the country. Thus, the studies with global and regional climate change projection models are necessary to assess the full range of potential climate change impacts and adaptation strategies. The selection of this area has been based on its significance in current or potential crop production in Turkey, and on its sensitivity to current and future climate regimes. On the specific site or regional scale, the variability of climate, soils and management need to be superimposed and tested for their relative impacts. Climate data needs to be generated, which includes changes in climatic variability, as predicted by GCMs. Introducing changes in variability may have profound impacts on the predictions of crop yield in areas with an inherent water shortage (Richter/Semenov 2005). Simulation models are useful tools to analyse the potential effects of climate change on crop growth, but testing model performance against measured data under such scenarios is essential for such an analysis to be meaningful (Asseng et al. 2015). Some preliminary studies have indicated that decreased precipitation and increased temperature will lead to increased irrigation water requirements. On the other hand, some other studies have suggested that increased CO_2 concentrations will increase the water use efficiency of the crops and in turn decrease the growing days due to the increased temperature ultimately decreasing the irrigation water

requirements. Yano et al. (2007a) and Fujihara et al. (2008) have also stated that the effects of global warming on irrigation water requirements should be offset by increased CO$_2$ concentrations. In addition, to obtain some realistic estimation for the future, all the water balance components, including precipitation, irrigation, losses by runoff, soil evaporation, crop transpiration, and percolation from the root zone, should be taken into account in further studies. In other words, the models should take climate-crop-soil interactions into consideration, thereby facilitating a differential crop development and yield under the varying environmental conditions.

Experimental data indicating considerable decreases in the actual evapotranspiration (*ETa*) due to stomatal closure under elevated CO$_2$ concentration have received wide recognition (Ainsworth/Long 2005; Asseng et al. 2015). Cure/Acock (1986) reported a decrease of 17% in the transpiration of wheat. In fact, elevated atmospheric CO$_2$ concentration increases photosynthesis in C3 plants and reduces evapotranspiration in both C3 and C4 plants due to reduced stomatal conductance, thereby improving water use efficiency (Thomson et al. 2006). Kapur (2010) observed that actual evapotranspiration of wheat decreased about 11% (from 304.7 to 269.9 mm) because of a shorter growing period under an increased temperature of 3 °C and CO$_2$ concentration of 700 ppm. Evrendilek et al. (2008) concluded that diurnal variations in water use efficiency and light use efficiency of wheat showed a bimodal behaviour with the maximum values in the early morning and late afternoon. As the impacts of global climate change become increasingly felt, continuous measurements of climate-crop-soil-management interactions under natural conditions play a pivotal role not only in exploring changes in eco-physiological properties of strategic crops for food security such as wheat but also in devising preventive and mitigative management practices to ensure sustained agricultural productivity. The experimental data obtained by Kapur (2010) indicated large increases in the water use efficiency of wheat, due to an increase in the CO$_2$ concentration, as well as due to a rise in temperature (Fig. 12.5). The comparisons of the variations in water use efficiency were made between the current (about 400 ppm) and future (700 ppm) CO$_2$ concentrations based on the SRES A2 scenario for the 2070s. It is well-known that the *ETa* decreases considerably due to stomatal closure under elevated CO$_2$ concentration and risen temperature (Ainsworth/Long 2005; Bernacchi/VanLoocke 2015; Gao et al. 2015), in spite of the increased evaporative demand of the atmosphere. However, in this study, increases in water use efficiency can be attributed to the shorter growing days and reduction of transpiration due to stomatal closure, regardless of the increase in evaporative demand. In brief, plant water stress would cause the irrigation requirement to maintain wheat production in the future, since precipitation is projected to dramatically decrease.
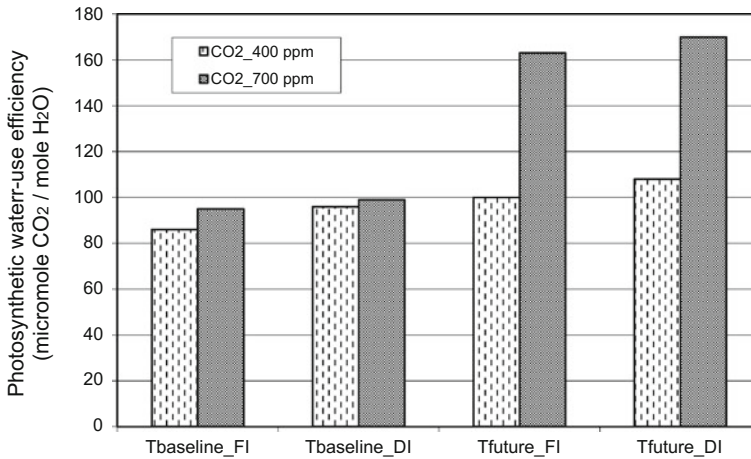
Fig. 12.5 The combined effects of the increased air temperature, elevated CO_2 concentration, and applied irrigation on the water use efficiency of wheat [modified from Kapur (2010). (Tbaseline: Baseline Temperature, Tfuture: Future Temperature, FI: Full Irrigation, DI: Deficit Irrigation)]. *Source* The authors

12.5 Soil Evaporation

Arid and semi-arid regions comprise almost 40% of the world's land surface. The low and erratic precipitation pattern is the single most significant contributor for limiting crop production in such lands (Aydın 1995). Evaporation from bare soils has a direct impact on crop yield in rainfed agriculture of the semi-arid to arid regions. The soil surface remains bare under field crops for many weeks during the periods of seed germination, seedling establishment and subsequent growth of the young crop when the moisture content of the upper soil layer can be of critical importance. In the orchards, the soil surface between the trees is kept bare by frequent tillage and continuously subjected to evaporation (Mellouli et al. 2000; Aydın et al. 2008). Some earlier results indicated that estimates of soil evaporation in semi-arid environments ranged from 30% to more than 60% of the seasonal rainfall (Jackson/Wallace 1999). Similarly, some other results have demonstrated that in regions where summer fallow is practised, direct evaporation from the soil surface accounted for about 50% or more of total precipitation (Hillel 1980; Hanks 1992). Önder et al. (2009b) reported that the actual soil evaporation in different parts of Turkey accounted for 34–83% of the incoming precipitation. In most parts of Turkey, the present precipitation is hardly adequate for good crop yields, and a further decrease in precipitation may seriously damage agriculture and the ecosystems (Kimura et al. 2007), although these areas have relatively ample water supplies for agriculture under the conditions of the current climate.

Evaporation from a bare soil surface is a complex process. The most important transport processes are characterised by a simultaneous change in the amount of

energy or material with time and place (Aydın/Huwe 1993; Aydın 1994). In general, soil evaporation is modelled by limiting potential evaporation (e.g., from Penman-Monteith) with soil and/or aerodynamic resistance, although newer approaches (e.g., the Aydın model) derive soil evaporation successfully from the soil water potential (Aydın et al. 2005; Falge et al. 2005). However, many researchers distinguish two different stages of evaporation, related to the soil water content as: (1) when the actual water content is high, evaporation is controlled by the atmospheric evaporative demand; (2) when the amount of water is low, the evaporation is limited by the actual soil water content and, therefore, driven by the hydrodynamic characteristics of the soil. In this context, the Aydın model developed to address this contemporary issue is based on energy fluxes and soil properties, and experimental data are used to define a threshold separating the two stages of evaporation (Quevedo/Frances 2007; Romano/Giudici 2007; Bellot/Chirino 2013).

The quantification of the components of the water balance is still questionable in the assessment of soil water management under fallow conditions. In the present study, evaporation from bare soils was estimated using the E-DiGOR [Evaporation and Drainage investigations at Ground of Ordinary Rainfed-areas] model developed by Aydın (2008). The E-DiGOR model, as a helpful tool, incorporates the quantification of runoff, drainage, actual soil evaporation, and soil water storage (Aydın 2008; Aydın et al. 2014, 2015). The model also takes into account the important physical processes to quantify these components (Önder et al. 2009b; Aydın/Kececioglu 2010; Aydın 2012; Aydın et al. 2012a, b). The model part for actual evaporation had been previously validated by Aydın et al. (2005, 2008) using measured data. The model has been additionally adapted to provide a method of assessing drainage losses from the soil profile using field capacity concepts. The theory of the processes simulated by the E-DiGOR program has been extensively described by Aydın (2008). The model requires the input of daily climate data and information on soil properties (Aydın/Polat 2010). In principle, the E-DiGOR model can simulate the components of the soil-water balance on the scale of a plot. The drainage rates, actual soil evaporation, and soil water storage for a ten-year period in the future (2070–2079) were estimated by Aydın et al. (2008) using the E-DiGOR model with a daily time step.

The actual soil evaporation (Ea) is jointly dominated by the atmospheric evaporative demand and soil water availability, as well as the size of rainfall events. In this section, therefore, the future climate data of the RCM/MRI model have been used to calculate Ea rates, because this model projected a dramatic decrease in precipitation by the period of 2070–2079. Percentage changes in the mean annual evaporation for the present and future are compared in Fig. 12.6. Both potential evapotranspiration from a reference crop (ETr) and potential evaporation from bare soils (Ep) are projected to increase by 8.0% and 7.3% (equivalent to 92 mm and 69 mm increase), based on calculations from RCM/MRI data respectively. This change would be caused by the predicted temperature increase, as well as changes in the other climatic variables (data not shown). Both reference evapotranspiration and potential soil evaporation can serve the purpose of comparison of the climatic
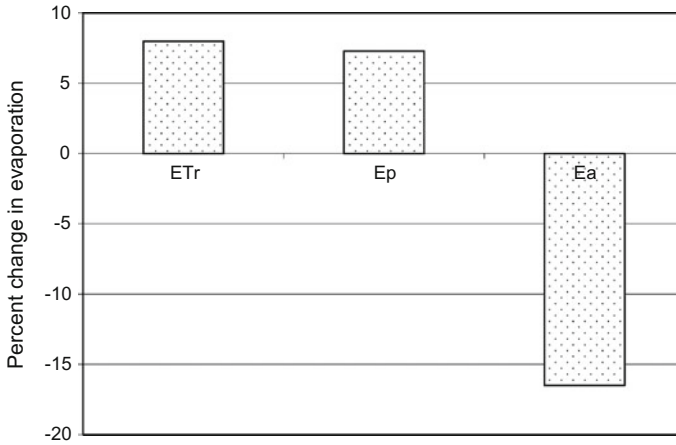
Fig. 12.6 Percentage changes in reference evapotranspiration (*ETr*), potential (*E*p) and actual (*Ea*) soil evaporation by 2070s. *Source* Derived from Aydın et al. (2008: 128)

conditions. Unlike both, however, the actual soil evaporation (*Ea*) is largely influenced by the soil wetness. In other words, the magnitude of *Ea* is strongly related to the temporal rainfall pattern, because the contribution of rainfall to soil water content is considerably dependent on the size of the rainfall events. The size of the rainfall events may play a key role in the magnitude of the actual soil evaporation, whereas, on the other hand, the variations in actual soil evaporation may reflect the effects of the rainfall pattern (Aydın et al. 2015). The projected annual actual soil evaporation (*Ea*) during 2070–2079 would decrease by 16.5% (equivalent to 50 mm decrease) relative to the baseline period of 1994–2003. This result, without any validation, may not allow such a clear-cut conclusion; however, the credibility of the E-DiGOR model has been demonstrated by different researchers in Japan and Turkey, using field-based measurements in a wide range of environments (Aydın 2008; Aydın et al. 2005, 2008; Kurt 2011). Since the projected mean annual precipitation during 2070–2079 compared with the baseline would decrease by 46% according to the RCM/MRI data, in a warmer climate and under lower precipitation, increased evaporative demand of the atmosphere favours soil dryness.

In fact, the simulation of the soil evaporation rates from bare soils in a Mediterranean region under a changing climate has revealed a reduction in *Ea* during the hot and dry summer season and an increase in *Ea* during the mild and rainy spring season, depending mainly on soil wetness. During the wet period of November to May, when *Ea* is close to *Ep*, the fields should be kept cropped to increase beneficial use of soil water by crops and consequently prevent water loss through evaporation from soils. Alternatively, adoption of such agronomic practices as retention of crop residues or formation of a natural layer of mulch on the soil surface by proper and timely tillage when the evaporation rate is most rapid plays a

significant role in the magnitude of reducing the soil water loss. Summer fallow is not practised under the current climatic conditions of the study area but may be adopted in the case of a decrease in rainfall. In that case, beneficial effects of fallowing in terms of the amount of water stored in the soil before planting depend on the timing, length and type of the fallow period. Fallowing with crop residue cover is most likely to be more beneficial in terms of increased soil water storage during the period of highest evaporation rate than lowest (Aydın et al. 2008).

As mentioned above, in the future, potential evapotranspiration from the reference crop (Allen et al. 1994) and potential evaporation from bare soils in the Mediterranean environment was found to increase, whereas actual soil evaporation was found to decrease, mainly due to lesser and erratic rainfall pattern, presumably soil wetness.

12.6 Conclusions

The climate change effects would be harmful, particularly for the water and agriculture sectors. The effects vary from ordinary to scary, as in the case of water limitations and increased temperature, thus hitches in the context of global food security via wheat production. In a changing global climate, the regions under the Mediterranean climate would increasingly face the challenges of water scarcity and of devising innovative and adaptive ecosystem management practices to make efficient use of the water available in the soil profile for plant growth. Moreover, expected temperature rises are likely to affect the maturation of wheat, thereby reducing total yield potential, with high temperatures causing more severe losses. Thus, temperature effects are increased by water stress, so water will be needed to develop more strong adaptation options to counterbalance the impacts of the raised temperatures associated with a changing climate. The foremost adaptation strategies are the conservation of water, the improvement of sustainable water projects and proper cultivation practices. The effects of climate change on water resources are part of a more comprehensive environmental problem. Adaptations to climate change will thus have to be part of a more extensive strategy to surpass the environmental problems of the present, as well as the future. The strategy could be clarified as the conservation and active use of water in a conscious and forceful approach. In addition, the response of individual producers to changes in the climate regime will need to include the selection of stress-tolerant wheat species, and innovation and investments in environmentally sound technologies for cultivation and irrigation techniques. Consequently, further studies are needed to assess the full range of climate change impacts and mitigative and adaptation strategies under the projections of climate change models.

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