

Review

Climate change impacts on crop yield, crop water productivity and food security – A review

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Abstract

This paper provides a comprehensive review of literature related to the assessment of climate change impacts on crop productivity using climate, water and crop yield models. The existing studies present that climate change models with higher spatial resolution can be a way forward for future climate projections. Meanwhile, stochastic projections of more than one climate model are necessary for providing insights into model uncertainties as well as to develop risk management strategies. It is projected that water availability will increase in some parts of the world, which will have its own effect on water use efficiency and water allocation. Crop production can increase if irrigated areas are expanded or irrigation is intensified, but these may increase the rate of environmental degradation. Since climate change impacts on soil water balance will lead to changes of soil evaporation and plant transpiration, consequently, the crop growth period may shorten in the future impacting on water productivity. Crop yields affected by climate change are projected to be different in various areas, in some areas crop yields will increase, and for other areas it will decrease depending on the latitude of the area and irrigation application. Existing modelling results show that an increase in precipitation will increase crop yield, and what is more, crop yield is more sensitive to the precipitation than temperature. If water availability is reduced in the future, soils of high water holding capacity will be better to reduce the impact of drought while maintaining crop yield. With the temperature increasing and precipitation fluctuations, water availability and crop production are likely to decrease in the future. If the irrigated areas are expanded, the total crop production will increase; however, food and environmental quality may degrade.

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1. Introduction

Global food security threatened by climate change is one of the most important challenges in the 21st century to supply sufficient food for the increasing population while sustaining the already stressed environment [1]. Climate change has already caused significant impacts on water resources, food security, hydropower, human health especially for African countries, as well as to the whole world

[2]. Studies on climate impacts and adaptation strategies are increasingly becoming major areas of scientific concern, e.g. impacts on the production of crops such as maize, wheat and rice [3–9], water resources in the river basin catchments [10–13], forests [14], industry [15] and the native landscape [16,17]. Crop productivity and soil water balance have been studied with crop growth models by using parameters from different climate models. Meanwhile, climate variability is one of the most significant factors influencing year to year crop production, even in high-yield and high-technology agricultural areas. In recent years, more and more attention has been paid to the risks

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associated with climate change, which will increase uncertainty with respect to food production [18]. Water availability will be one of the limiting constraints for crop production and food security. Fujihara et al. [19] pointed out that water scarcity will not occur if water demand does not increase; however, if the irrigated area is expanded under present irrigation efficiency rates, water scarcity will occur. Therefore, it is urgent to determine the impacts of climate change on crop production and water resources in order to develop possible adaptation strategies.

The objective of this paper is to review the role of global climate models and crop growth models for the study of climate change impacts on crop growth, crop yield and soil water balance under different future climate conditions. It is intended to provide useful background information for scientists as well as policy makers who are interested in understanding the impacts of climate change on irrigated agriculture and food security and to devise suitable adaptation options.

2. Climate scenarios and models

A climate scenario is a reasonable description of the future climate based on a range of climatological relationships and assumptions of radioactive forcing [20]. It can be visualized by global climate models (GCMs) and regional climate models (RCMs), which are complicated three-dimensional mathematical representations to show the processes of interactions between the atmosphere, land surface, oceans and sea ice which resulted from climate [21]. Climate projections should be considered as efficient methods to figure out the possible futures under given particular emission scenarios rather than a forecasting tool [22]. GCMs are useful tools to simulate the important aspects of current and future climates although they still have significant errors [23]. Table 1 shows a chronological summary of GCMs used for climate scenario projections. The GCMs with higher spatial resolutions can perform reasonable regional climate simulations, consequently, they pro-

Table 1
General circulation models used for scenarios.^a

Model	Vintage	Country	Sponsors	Horizontal resolution	Simulated data used in slope analysis
BCC-CM1	2005	China	Beijing Climate Center	$1.9 \times 1.9L16$	1871–2100
BCCR-BCM2.0^b	2005	Norway	Bjerknes Center for Climate Research	$1.9 \times 1.9L31$	1850–2099
CCSM3	2005	USA	National Center for Atmospheric Research	$1.4 \times 1.4L26$	1870–2099
CCC3.1(T 47)	2005	Canada	Canadian Center for Climate Modelling & Analysis	$2.8 \times 2.8L31$	1850–2100
CCC3.1(T 63)	2005	Canada	Canadian Center for Climate Modelling & Analysis	$1.9 \times 1.9L31$	1850–2100
CNRM-CM3	2004	France	Météo-France/Centre National de Recherches Météorologiques	$1.9 \times 1.9L45$	1860–2090
CSIRO-Mk3.0	2001	Australia	CSIRO Atmospheric Research	$1.9 \times 1.9L18$	1871–2100
ECHAM5/MPI-OM	2005	Germany	Max Planck Institute for Meteorology	$1.9 \times 1.9L31$	1860–2100
ECHO-G	1999	Germany/Korea	Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model	$3.9 \times 3.9L19$	1860–2100
FGOALS-g1.0	2004	China	LASG/Institute of Atmospheric Physics	$2.8 \times 2.8L26$	1850–2099
GFDL-CM2.0	2005	USA	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	$2.0 \times 2.5L24$	1861–2100
GFDL-CM2.1	2005	USA	US Dept. of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	$2.0 \times 2.5L24$	1861–2100
GISS-AOM	2004	USA	NASA/Goddard Institute for Space Studies	$3.0 \times 4.0L12$	1850–2100
GISS-EH	2004	USA	NASA/Goddard Institute for Space Studies	$4.0 \times 5.0L20$	1880–2099
GISS-ER	2004	USA	NASA/Goddard Institute for Space Studies	$4.0 \times 5.0L20$	1880–2100
INM-CM3.0	2004	Russia	Institute for Numerical Mathematics	$4.0 \times 5.0L21$	1871–2100
IPSL-CM4	2005	France	Institut Pierre Simon Laplace	$2.5 \times 3.75L19$	1860–2100
MIROC3.2 (hires)	2004	Japan	Center for Climate System Research	$1.12 \times 1.12L56$	1900–2100
MIROC3.2 (medres)	2004	Japan	Center for Climate System Research	$2.8 \times 2.8L20$	1850–2100
MRI-CGCM2.3.2	2003	Japan	Meteorological Research Institute	$2.8 \times 2.8L30$	1851–2100
PCM	1998	USA	National Center for Atmospheric Research	$2.8 \times 2.8L26$	1890–2099
UKMO-HadCM3	1997	UK	Hadley Center for Climate Prediction and Research/Met Office	$2.5 \times 3.75L19$	1860–2099
UKMO-HadGEM1	2004	UK	Hadley Center for Climate Prediction and Research/Met Office	$1.25 \times 1.9L38$	1860–2098

^a Source from [22].

^b The 15 models in bold letters are the models which can best reproduce the Australian average (1961–1990) patterns of temperature and rainfall [22].

vide climate scientists with the ability to acquire better insights into climate change impacts on a regional scale and estimate the impacts of the climate change on crop production [21]. Blenkinsop and Fowler [24] suggested that RCMs have some trouble when they are used to reproduce the observed duration of low sensitivity monthly rainfall amounts.

Climate models need to be integrated with other modelling approaches to predict climate vulnerability and climate parameters such as rainfall and temperature. Metzger et al. [25] provided an ATEAM (advanced terrestrial ecosystem analysis and modelling) framework to qualify the vulnerability of climate change using the GCM, HadCM3 (Hadley centre climate model 3) to predict climate change in 2080. Suppiah et al. [22] used the statistical method to select 15 best models to derive the annual and seasonal average projections of rainfall and temperature in the whole of Australia.

Khan [26] discussed climate variability and droughts in Australia according to historical climate data and suggested some possible policy approaches to deal with the extreme climate change variability, such as to adjust water allocations of surface and groundwater using prediction models, to improve water use efficiency in agriculture and to build a national legal framework to manage water resources in accordance with anticipated climate change impacts on water resources. Groves and Lempert [27] provided a new analytic method based on Robust Decision Making to quantify the SRES scenarios (Special Report on Emissions Scenarios) developed using the scenario-axes method for decision makers. Fowler et al. [28] studied the NSRP (Neyman–Scott Rectangular Pulse) rainfall scenario generation model to derive rainfall climate information using the stochastic simulation method. Xu et al. [29] used the PRECIS climate model to predict mean temperature and rainfall in China for 2080s under B2 scenarios, the results show that the mean temperature and rainfall will increase across China.

GCMs have been used to predict climate scenarios and impacts in many cases using the downscaling approach [30]. GCM data typically have a low resolution of several degrees, lack the spatial and temporal precision necessary for detailed regional analysis and in the many cases have errors to simulate even the present-day climate [31]. GCMs have uncertainties in predicting future climate data, while they can provide a reasonable accuracy about large-scale features and other variations due to climate forcing [32]. Since each climate model has its own uncertainty, more than one climate model will be better for dealing with the accurate projection problem [33]. Thus, further study on GCMs will be focused on how to improve the sensitivity of GCMs and to evaluate feedback of the factors influencing climate model projection results. Meanwhile, future climate models will consider more detailed factors and have higher precise latitude and longitude in order to reduce the spatial and temporal error for the accurate regional climate study.

3. Climate change impacts on water availability

It is known that water resources play a vital role in human prosperity and crop productivity. The world's agriculture, hydroelectric power and water supplies depend on different components of the hydrological cycle, including the natural replenishment of surface and groundwater resources [34]. Water availability issues include how much water can be diverted, when the water can be available and how much water can be stored in surface and ground-water reservoirs. Assessment of seasonal and long-term water availability is not only important for sustaining human life, biodiversity and the environment, but also helpful for water authorities and farmers to determine agricultural water management and water allocation. Climate change is one of the greatest pressures on the hydrological cycle along with population growth, pollution, land use changes and other factors [35]. Water availability is under threat from changing climate because of possible precipitation decrease in some regions of the world. In the light of the uncertainties of climate variability, water demand and socio-economic environmental effects, it is urgent to take some measures to use the limited water efficiently and develop some new water resources [34]. If the water resources are replenished by snow accumulation and the snowmelt process, the water system will be more vulnerable to climate changes [36].

Many studies have considered climate change impacts on streamflow as well as spatial distribution of water availability under different climate conditions across the world. Guo et al. [37] studied the climate change impacts on the runoff and water resources with the GIS (geographic information system) and GCMs in China and pointed out that runoff is more sensitive to precipitation variation than to temperature increase, and integrated water resources management can help mitigate climate change. Ma et al. [38] discussed climate variability impacts on annual streamflow through the *p*-test and *k*-test in the Shiyang River northwest of China, the results present that climate change can reduce 64% of mean annual streamflow owing to the decreased precipitation; meanwhile, precipitation is more sensitive for the catchment streamflow than potential evapotranspiration. Fujihara et al. [19] analyzed the water resources under present and future climate scenarios in the Seyhan River Basin with dynamical downscaling of GCMs and linked river basin hydrological models, the conclusion is that water scarcity will occur when water requirements increase, e.g. due to the expansion of irrigation; therefore, efficient water resources use is important in managing future water resource conditions. Wurbs et al. [39] provided a water availability modelling (WAM) system to assess the water supply capabilities and explore the climate impacts on hydrology and water availability for water users who depend on water supplies by the Brazos River Basin in Texas, and the key result is that future climate may decrease the mean streamflow, and its effects on water availability are various in different regions of the river basin. Quinn et al.

[40] discussed an integrated system to analyze the impacts of climate variability on water resources in the San Joaquin Basin, California, the conclusion is that this method can provide a reference for effective management strategies to assess climate vulnerability as a function of climate variability and extreme events. Qin et al. [41] explained the multi-criteria decision expert system to analyse water availability under climate change in the Gorgia Basin, Canada, the result shows that it is crucial to assess climate change impacts on socio-economic and environmental aspects. Alcamo et al. [42] evaluated climate impacts on water resources in Russia considering the changing frequency of extreme climate events, the conclusion is that average water availability will increase and high runoff events will occur frequently, which can be a threat to food production in Russia. Mirza [43] reported that climate change will increase the frequency of floods and droughts in South Africa. Hobbs [44] discussed the advantages of the Bayesian approach for analyzing the uncertainties of climate change impacts on water resources and found that Bayesian analysis is a practical and easy method to understand climate change uncertainty assessment. Cuculeanu et al. [33] used the VIDRA rainfall runoff model to discuss climate vulnerability impacts on water resources in 2075 in Romania, and the conclusion is that water requirements in the reference basin will exceed water availability. Westmacott and Burn [45] used the Mann-Kendall trend test and a regionalization procedure to quantify climate change severity impacts on the Churchill–Nelson River Basin in central Canada. Stone et al. [46] applied an ANOVA (analysis of variance) test to analyze the monthly, seasonal and annual climate change impacts on water resources in the Missouri River Basin, and the result shows that climate change increases the water yields significantly at different temporal scales.

Climate impacts on water resources are varied in different river basins. The frequency of droughts and floods will increase under future climate conditions. Runoff and streamflow are more sensitive to rainfall than to evapotranspiration. Efficient water use and integrated manage-

ment will be increasingly important for reducing the impacts on water scarcity and droughts. Although many water management approaches have been adapted to mitigate climate impacts, there is still a need to determine local solutions. It is necessary to know how much water can be used in each irrigation area and the river basin, when the water is available and how much water can be stored for use in the drought period, quantify variability of water resources over a long-term basis and associated links with energy and biodiversity.

4. Climate change impacts on crop yield

The changes in crop production related climatic variables will possibly have major influences on regional as well as global food production [47]. The likely impacts of climate change on crop yield can be determined either by experimental data or by crop growth simulation models. To predict future impacts on crop yields, crop models present valuable approaches. A number of crop simulation models, such as CERES-Maize (Crop Environment Resource Synthesis), CERES-Wheat, SWAP (soil–water–atmosphere–plant), and InFoCrop [6], have been widely used to evaluate the possible impacts of climate variability on crop production, especially to analyze crop yield–climate sensitivity under different climate scenarios. Table 2 shows a summary of the crop growth models used to study climate change impacts on crop yields in recent studies.

The studies about wheat production affected by climate change are mainly concerned with future CO₂ concentrations. Ortiz et al. [48] discussed how wheat can adapt to climate change in Indo-Gangetic Plains for 2050s and suggested that global warming is beneficial for wheat crop production in some regions, but may reduce productivity in critical temperature areas, so it is urgent to develop some heat-tolerant wheat germplasm to mitigate climate change. Anwar et al. [49] used CropSyst version-4 to predict climate change impacts on wheat yield in south-eastern Australia, and their results show that the elevated CO₂ level can

Table 2
Summary of crop models used for the study of climate change impacts.

Crop model	Objective crop	Predicted impacts	Reference(s)
CERES-Maize	Maize	Dry matter	[33]
	Maize	Sustainable production	[53]
	Maize	Planting date and different weather	[54]
	Maize	Precise and deficit irrigation	[55]
CERES-Wheat	Wheat	CO ₂ levels	[50]
	Wheat	CO ₂ levels	[51]
CropSyst	Wheat	Rainfall and warming temperature	[49]
CERES-Rice	Rice	CO ₂ levels	[60]
SWAP	Rice	CO ₂ levels	[58]
InFoCrop	Rice	Elevated CO ₂ and temperature	[59]
	Rice and wheat	Climate change	[6,7]
IBSNAT-ICASA	Cereal/soybean	Climate change	[61]
GLAM	Peanut	Climate uncertainty	[9]
GLYCIM	Soybean	Temperature rainfall and CO ₂ concentration	[18]
SWAT	Maize	Climate vulnerability	[63]

reduce the median wheat yield by about 25%. Eitzinger et al. [50] utilized the CERES-wheat model to assess climate change impacts on wheat production under four climate scenarios, and the results show that the CO₂ effect maintains a great responsibility for increasing crop yield in the research area. Luo et al. [51] discussed climate change impacts on wheat production with DSSAT 3.5 (Decision Support System for Agrotechnology Transfer) CERES-Wheat models under all CO₂ levels in Southern Australia for 2080s, and the result shows that wheat yield will increase under all CO₂ levels, and the drier sites are more suitable for wheat production but are likely to have lower wheat quality.

As one of the main crops in the world, maize yield related with climate change is widely discussed in the world. Cuculeanu et al. [33] studied the rainfed maize yield by CERES-Maize using CCCM and GISS climate models, the conclusion of which is that the dry matter can increase 1.4–2.1 t ha⁻¹ with the CCCM model but 3.5–5.6 t ha⁻¹ by the GISS model. Conde et al. [52] presented some measures, such as greenhouse construction, compost usage and drip irrigation, to enhance adaptive capacities in farmers after analyzing rainfed maize with the CERES-Maize model in Mexico. Walker and Schulze [53] used the CERES-Maize model to predict crop sustainable production in smallholders with different climate scenarios by the Mann-Kendall non-parametric test in South Africa, and the result shows that increasing inorganic nitrogen and rainwater harvesting can increase crop yield for smallholders in the long run. Tojo Soler et al. [54] analyzed the impacts of planting dates and different weather on maize production in Brazil with CERES-Maize, and the result shows that a later planting date will decrease 55% on average yield under rainfed conditions and 21% under irrigated conditions, and an accurate yield forecast can be provided almost 45 d earlier than the harvest date. Popova and Kercheva [55] analyzed the maize yield under precise irrigation and deficit irrigation for a 30-year period in Sofia Bulgaria with CERES-Maize, and the result shows that average productivity under the dry growing season will be 60% lower than that under a sufficient soil moisture condition. Akpalu et al. [56] studied the climate impacts on maize yield in the Limpopo Basin of South Africa and showed that increased temperature and rainfall are positive for the crop yield, and the precipitation is more important for crop yield than the temperature. Eastering et al. [57] determined that the 1° × 1° resolution is the optimal spatial resolution to minimize the statistical error between the observed and simulated yield of wheat and maize in the central Great Plains of the United States.

The yield of rice and other cereals affected by climate change are presented in the following paragraphs. Droogers et al. [58] studied climate change impacts on rice yield in seven basins with the SWAP and HadCM3 climate model under A2 and B2 scenarios in the Volta Basin, and the result shows that rice yields are expected to increase by around 45% and 30% for A2 and B2 scenarios,

respectively. Krishnan et al. [59] analyzed the impacts of elevated CO₂ and temperature on irrigated rice yield in eastern India by ORYZAI and InFoCrop-rice models, and the result shows that increased CO₂ concentration can increase the rice yield, which is concerned with the sterility of rice spikelets at higher temperature, the sowing time and the selection of genotypes. Yao et al. [60] analysed CO₂ level impacts on rice yield with the CERES-Rice model in Chinese main rice production areas, which shows that rice yield will increase with CO₂ effect, otherwise it will decrease. Challinor and Wheeler [9] used the GLAM (general large-area model) to analyze climate uncertainty impacts on peanut yield, and the result is that the yield can rise by 10–30% with fixed-duration simulation. Parry et al. [61] used the IBSNAT-ICASA (International Benchmark Sites Network for Agrotechnology Transfer) dynamic crop model to estimate climate potential changes in the major grain cereals and soybean crop yield, the result of which is that climate change will increase yields at high and mid-latitudes and decrease yields at lower latitudes. Reddy and Pachepsky [18] validated soybean yield prediction based on the GCMs and soybean crop simulator, GLYCIM in Mississippi Delta, providing a practical method to derive the general relationship between crop yields and climate change including temperature, precipitation and CO₂ concentration. Challinor et al. [62] mainly discussed the temperature effect on the crop yield in India with the regional climate model PRECIS and the GLAM crop model under present (1961–1990) and future (2071–2100) climate conditions. The result shows that the mean and high temperature are not the main factors to decide the crop yield, but extreme temperature has a negative effect on crop yield when irrigation water is available for the extended growing period. Xie and Eheart [63] used the SWAT (soil and water assessment tool) model to predict the vulnerability of crop yield to climate change in the Mackinaw watershed USA under different future climate scenarios.

Climate change impacts on crop yield are different in various areas, in some regions it will increase, in others it will decrease which is concerned with the latitude of the area and irrigation application. The crop yield can be increased with irrigation application and precipitation increase during the crop growth; meanwhile, crop yield is more sensitive to the precipitation than temperature. If water availability is reduced in the future, soil of high water holding capacity will be better to reduce the frequency of drought and improve the crop yield [55]. With climate change, the growing period will reduce, and the planting date also needs to change for higher crop production. Climate change can decrease the crop rotation period, so farmers need to consider crop varieties, sowing dates, crop densities and fertilization levels when planting crops [33]. The positive effects of climate change on agriculture are concerned with the CO₂ concentration augment, crop growth period increases in higher latitudes and montane ecosystems; the negative effects include the increasing inci-

dence of pests and diseases, and soil degradation owing to temperature change [1]. This has urged scientists to develop more crop varieties suiting the changing climate and degrading soil in order to obtain sufficient yield for the increasing population. Quantification of climate uncertainty is an important indicator for crop yield variation in future climate scenarios.

5. Climate change impacts on crop water productivity

In the 21st century, global agriculture has met the new challenge, namely, to increase food production for the growing population under increasing scarce water resources [64], which can be achieved by improving crop water productivity [64–66]. Water productivity is a concept to express the value or benefit derived from the use of water and includes essential aspects of water management such as production for arid and semi-arid regions [67]. Increasing water productivity means either to produce the same yield with less water resources or to obtain higher crop yields with the same water resources [68]. While Bouman [64] suggested that just “increasing water productivity” may not solve the dual challenge, so it is necessary to understand the latent mechanism of increased water productivity. The existing studies show that climate is the single most important determinant of agricultural productivity, basically through its effects on temperature and water regimes [1,69]. Climate change impacts on crop water productivity are affected by many uncertain factors [70], of which one of the most important factors is the uncertainty in global climate model predictions, especially regarding climate variability. The other factors include soil characteristics such as soil water storage [71], long-term condition in soil fertility [72], climate variables and enhanced atmospheric CO₂ levels [73] and the uncertainty of the crop growth model, which is connected with biophysical interactions. All of these factors will affect the estimation of climate change impacts on crop productivity. As long as the researchers reduce the effects of uncertain aspects, it is possible to obtain more accurate predictions about climate change impacts on crop productivity.

Van de Geijn and Goudriaan [74] found that positive climate effects on crop growth can be adjusted by effective rooting depth and nutrients; meanwhile, it can improve water productivity by 20–40%. Howden and Jones [75] found that changing planting dates and varieties are good measures to increase crop benefit, and the median benefit is projected to be US\$158 million/year but within a range of US\$70 million to over US\$350 million/year. ABARE (Australian Bureau of Agricultural and Resource Economics) [76] reported that the main agricultural income of commercial productions in Australia will decline 9–10% by 2030 and 13–19% by 2050. Meanwhile, it is urgent to maintain strong productivity and supply some new adaptations and mitigation technologies so as to deal with potential climate impacts. Kijine et al. [66] reported that water productivity can be improved by increasing investments in

agricultural infrastructure and research rather than investments in the irrigation system. Khan et al. [77] presented an approach, combining GIS with groundwater modelling MODFLOW (Modular Three-dimensional Finite-difference Ground-water Flow Model) to enhance water productivity in the Liuyuankou Irrigation Area, China and concluded that the reduction in non-beneficial evapotranspiration can make the extra water be used in other areas, thus improving water productivity. Li and Barker [78] found that the AWD (alternate wetting and drying) irrigation technique can increase water productivity for paddy irrigation in China.

Water productivity concerned with water saving irrigation is dependent on the groundwater level and evapotranspiration [79]. Crop water productivity is an important index to evaluate water saving and water investments for farmers and scientists. Meanwhile, it is inversely related with vapor pressure [68]. Crop water productivity can be increased significantly if irrigation is reduced and the crop water deficit is widely induced. Climate change will influence temperature and rainfall. In the decreased precipitation regions, the irrigation amount will increase for optimal crop growth and production, but this may decrease crop water productivity. Therefore, it will be a big challenge to increase crop water productivity at all levels [66].

6. Climate change impacts on soil water balance

Soil water balance is important for the water management and water use strategy. Climate change will make the temperature and rainfall fluctuate, consequently, influencing soil evaporation and plant transpiration. IPCC AR4 (Intergovernmental Panel on Climate Change Fourth Assessment Report) [80] projected that mean annual precipitation will increase in the tropical regions and at high northern latitudes, and decrease in the subtropics. Meanwhile, precipitation may increase in one season, while it may decrease in another one. Over most parts of the globe, the mean annual runoff will increase; however, there are still some significant areas where runoff will decrease such as Middle-East Europe, northern Africa, Central America, Southern Africa, major parts of southern and western Australia, and various areas of South America. All of these may influence the regional soil water balance under various climatic conditions.

Soil water balance is reliable evidence to calculate crop water requirements and water use efficiency. Fischer [81] analyzed the climate change impacts on irrigation requirements based on daily water balance with the FAO (Food and Agriculture Organization)-IIASA Agro-ecological Zone model and concluded that mitigated climate can reduce by about 40% impacts on agricultural water requirements in comparison to unmitigated climate. De Silva et al. [82] studied climate change impacts on irrigation water requirements and the water balance of paddy rice with HadCM3 and GIS mapping for 2050s A2 and B2 climate scenarios in Sri Lanka, and the conclusion is that average

paddy irrigation requirements will increase by 23% (A2) and 13% (B2). Thomas [30] discussed the water balance calculation in China with high-resolution gridded climatic data sets and the FAO agro-ecological model, and the result shows that the interannual climatic variability has great effects on future cropping conditions. Eitzinger et al. [50] used the CERES-wheat model to assess climate change impacts on soil water balance under four climate scenarios, and the results show that the factors which affect the soil water balance also have influences on sustainable crop production and water resources in agriculture. Holden and Brereton [83] reported that although higher levels of irrigation can obtain higher yields, farmers need to prevent higher irrigation led high runoff for some of the heavier soil.

Climate change impacts on water balance will present changes in soil water storage, groundwater level, soil moisture status and can provide some information about irrigation quantity. The water balance will change with precipitation and evapotranspiration, and the resultant fluctuations in soil moisture status [82].

7. Climate change impacts on food security

Food security is defined by the Food and Agriculture Organization (FAO) [84] as a “situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life”. The definition involves four aspects of food security, namely, food availability, food stability, food access and food utilization [85]. However, the existing studies are focused on the climate change impacts on food availability, scarcely referring to the impacts of potential increase in climate variability, frequency and intensity of extreme events on food stability. The FAO [86] mentioned that biotechnology can be an approach to improve food security and reduce the environmental pressure. Meanwhile, modified crop varieties, resisting drought, waterlogging, salinity and extreme climate, can expand the crop planting area such as in the degraded soils, consequently, to increase food availability in the future.

Climate change will affect the food quality because of the increasing temperature and decreasing crop growth period. Droogers [87] analysed the climate change impacts on food security with the HadCM3, SWAP and water-salinity basin model to simulate the evapotranspiration and available water in field scale thus to decide the relationship between the irrigation depth, crop area and food quality. The result is that in order to increase total grain production, there is a need to extend the crop area otherwise, it would decrease the food security. Alcamoa et al. [42] evaluated present and future climate scenario impacts on food security and water availability in 2020 and 2070s and provided some measures to enlarge potential crop production such as diversifying crops and expanding the rain-fed and irrigated agriculture areas. Droogers and Aerts [88]

analyzed climate change impacts on food quantity and security with ADAPT and SWAP models and pointed out that increasing crop area can improve food quantity but will degrade food security, while reducing water allocation for irrigation and decreasing the crop area can improve environmental quantity and security. Luo et al. [51] combined Global Climate Models with DSSAT 3.5 CERES-Wheat to discover the potential effects of climate change on South Australian Wheat with different CO₂ concentration levels, and the result showed that climate change can degrade the wheat quality at drier sites, while the drier sites can benefit more than the wetter sites under climate change scenarios. Khan et al. [89] reviewed water management and crop production for food security in China, who pointed out that it is necessary to integrate climate, energy, food, environment and population together to discuss future food security in China, and in the world as well. This is because climate change has many uncertainties in water management and other water-related issues.

Food security is increasingly important for human beings all over the world. Food availability and food quality still are the big challenges for scientists due to changing climate. Food security is always studied with CO₂ effects under changing climate scenarios. Further research on food security needs to integrate population, crop production, climate change and water availability, consequently, to evaluate food security completely and systematically.

8. Conclusion

This paper summarizes the use of climate models and climate scenarios, climate change impacts on water availability, crop yield, crop water productivity and food security. Many climate models have been developed to predict climate change impacts with higher spatial resolution climate models being helpful to provide more accurate predictions for future climate scenarios. Future climate projections show that temperature will increase but the precipitation may increase or decrease depending on the location of the research area.

Climate change impacts on crop yield are often integrated with its effects on water productivity and soil water balance. Global warming will influence temperature and rainfall, which will directly have effects on the soil moisture status and groundwater level. Crop yield is constrained to crop varieties and planting areas, soil degradation, growing climate and water availability during the crop growth period. With temperature increasing and precipitation fluctuating, water availability and crop production will decrease in the future. If the irrigated areas are expanded, the total crop yield will increase; however, food and environmental quality may degrade. Soil evaporation and plant transpiration will be changed with climate change; thus, water use efficiency may decrease in the future. Improving water productivity and keeping stable relations with global food suppliers will be vital for food security.

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References

- [1] Lal R. Climate change, soil carbon dynamics, and global food security. In: Lal R, Stewart B, Uphoff N, et al., editors. *Climate change and global food security*. Boca Raton (FL): CRC Press; 2005. p. 113–43.
- [2] Magadza CHD. Climate change impacts and human settlements in Africa: prospects for adaptation. *Environ Monit Assess* 2000;61:193–205.
- [3] Howden SM, O'Leary GJ. Evaluating options to reduce greenhouse gas emissions from an Australian temperate wheat cropping system. *Environ Modell Software* 1997;12:169–76.
- [4] Hoogenboom G. Contribution of agrometeorology to the simulation of crop production and its applications. *Agric Forest Meteorol* 2000;103:137–57.
- [5] Gbetibouo G, Hassan R. Economic impact of climate change on major South African field crops: A Ricardian approach. *Glob Planet Change* 2005;47:143–52.
- [6] Aggarwal PK, Kalra N, Chander S, et al. InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. I. Model description. *Agric Syst* 2006;89:1–25.
- [7] Aggarwal PK, Banerjee B, Daryaei MG, et al. InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments II. Performance of the model. *Agric Syst* 2006;89:47–67.
- [8] Dhungana P, Eskridge KM, Weiss A, et al. Designing crop technology for a future climate: an example using response surface methodology and the CERES-Wheat model. *Agric Syst* 2006;87:63–79.
- [9] Challinor AJ, Wheeler TR. Crop yield reduction in the tropics under climate change: processes and uncertainties. *Agric Forest Meteorol* 2008;148:343–56.
- [10] Chang H, Knight CG, Staneva MP, et al. Water resource impacts of climate change in southwestern Bulgaria. *Geol J* 2002;57:159–68.
- [11] Wilby RL. Uncertainty in water resource model parameters used for climate change impact assessment. *Hydrol Process* 2005;19:3201–19.
- [12] Wilby RL, Whitehead PG, Wade AJ, et al. Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *J Hydrol* 2006;330:204–20.
- [13] Herrera-Pantoja M, Hiscock KM. The effects of climate change on potential groundwater recharge in Great Britain. *Hydrol Process* 2008;22:73–86.
- [14] Lexer MJ, Honninger K, Scheifinger H, et al. The sensitivity of Austrian forests to scenarios of climatic change: a large-scale risk assessment based on a modified gap model and forest inventory data. *For Ecol Manage* 2002;162:53–72.
- [15] Harle KJ, Howden SM, Hunt LP. The potential impact of climate change on the Australian wool industry by 2030. *Agric Syst* 2007;93:61–89.
- [16] Dockerty T, Lovett A, Sunnenberg G. Visualising the potential impacts of climate change on rural landscapes. *Comput Environ Urban Syst* 2005;29:297–320.
- [17] Dockerty T, Lovett A, Appleton K, et al. Developing scenarios and visualisations to illustrate potential policy and climatic influences on future agricultural landscapes. *Agric Ecosyst Environ* 2006;114:103–20.
- [18] Reddy VR, Pachepsky YA. Predicting crop yields under climate change conditions from monthly GCM weather projections. *Environ Modell Software* 2000;15:79–86.
- [19] Fujihara Y, Tanaka K, Watanabe T. Assessing the impacts of climate change on the water resources of the Seyhan River Basin in Turkey: use of dynamically downscaled data for hydrologic simulations. *J Hydrol* 2008;353:33–48.
- [20] IPCC. Appendix I: glossary. In: Parry ML, Canziani OF, Palutikof JP, et al., editors. *Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press; 2007. p. 79–131.
- [21] Mearns LO. Climate change and variability. In: Reddy KR, Hodges HF, editors. *Climate change and global crop productivity*. New York: CABI Publishing; 2000. p. 7–35.
- [22] Suppiah R, Hennessy KJ, Whetton PH, et al. Australian climate change projections derived from simulations performed for the IPCC 4th assessment report. *Aust Meteorol Mag* 2007;56:131–52.
- [23] IPCC. Summary for policymakers. In: Solomon S, Qin D, Manning M, et al., editors. *Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press; 2007. p. 1–18.
- [24] Blenkinsop S, Fowler HJ. Changes in European drought characteristics projected by the PRUDENCE regional climate models. *Int J Climatol* 2007;27:1595–610.
- [25] Metzger MJ, Leemans R, Schroter D. A multidisciplinary multi-scale framework for assessing vulnerabilities to global change. *Int J Appl Earth Observ Geoinform* 2005;7:253–67.
- [26] Khan S. Managing climate risks in Australia: options for water policy and irrigation management. *Aust J Exp Agric* 2008;48:265–73.
- [27] Groves D, Lempert R. A new analytic method for finding policy-relevant scenarios. *Global Environ Change* 2007;17:73–85.
- [28] Fowler HJ, Kilsby CG, O'Connell PE, et al. A weather-type conditioned multi-site stochastic rainfall model for the generation of scenarios of climatic variability and change. *J Hydrol* 2005;308:50–66.
- [29] Xu Y, Zhang Y, Lin E, et al. Analyses on the climate change responses over China under SRES B2 scenario using PRECIS. *Chin Sci Bull* 2006;51(18):2260–7.
- [30] Thomas A. Agricultural irrigation demand under present and future climate scenarios in China. *Glob Planet Change* 2008;60:306–26.
- [31] Bonan GB, Oleson KW, Vertenstein M, et al. The land surface climatology of the community land model coupled to the NCAR community climate model. *J Clim* 2002;15:3123–49.
- [32] Salinger MJ, Stigter CJ, Das HP. Agrometeorological adaptation strategies to increasing climate variability and climate change. *Agric Forest Meteorol* 2000;103:167–84.
- [33] Cuculeanu V, Tuinea P, Balteanu D. Climate change impacts in Romania: vulnerability and adaptation options. *Geol J* 2002;57:203–9.
- [34] ACE (Atmosphere, Climate and Environment). Climate change fact sheet series for key stage 4 and A-level. Buchdahl; 2002. p. 1–171.
- [35] Aerts J, Droogers P. Climate change in contrasting river basins: adaptation strategies for water, food, and environment. The Netherlands: CABI Publishing; 2004. p. 1–264.
- [36] Dracup JA, Vicuna S. An overview of hydrology and water resources studies on climate change: the California experience. Copyright ASCE 2005; 1–12.
- [37] Guo S, Wang J, Xiong L, et al. A macro-scale and semi-distributed monthly water balance model to predict climate change impacts in China. *J Hydrol* 2002;268:1–15.
- [38] Ma Z, Kang S, Zhang L, et al. Analysis of impacts of climate variability and human activity on streamflow for a river basin in arid region of northwest China. *J Hydrol* 2008;352:239–49.
- [39] Wurbs RA, Asce M, Muttiah RS, et al. Incorporation of climate change in water availability modeling. *J Hydrol Eng* 2005;5:375–85.
- [40] Quinn NWT, Miller NL, Dracup JA, et al. An integrated modeling system for environmental impact analysis of climate variability and extreme weather events in the San Joaquin Basin, California. *Adv Environ Res* 2001;5:309–17.

- [41] Qin XS, Huang GH, Chakma A, et al. A MCDM-based expert system for climate-change impact assessment and adaptation planning – a case study for the Georgia Basin, Canada. *Expert Syst Appl* 2008;34:2164–79.
- [42] Alcamo J, Droninb N, Endejana M, et al. A new assessment of climate change impacts on food production shortfalls and water availability in Russia. *Global Environ Change* 2007;17:429–44.
- [43] Mirza M. Climate change, adaptation and adaptive governance in water sector in South Asia. *Phys Sci Basis* 2007;1–19.
- [44] Hobbs BF. Bayesian methods for analysing climate change and water resource uncertainties. *J Environ Manage* 1997;49:53–72.
- [45] Westmacott JR, Burn DH. Climate change effects on the hydrologic regime within the Churchill–Nelson River Basin. *J Hydrol* 1997;202:263–79.
- [46] Stone MC, Hotchkiss RH, Stone AB. Climate change impacts on Missouri River Basin water yields: the influence of temporal scales. *ASCE* 2005;1–10.
- [47] Abrahams MG, Savage MJ. Potential impacts of climate change on the grain yield of maize for the midlands of KwaZulu-Natal, South Africa. *Agric Ecosyst Environ* 2006;115:150–60.
- [48] Ortiz R, Sayre KD, Govaerts B, et al. Climate change: can wheat beat the heat? *Agric Ecosyst Environ* 2008;126:46–58.
- [49] Anwar MR, O’Leary G, McNeil D, et al. Climate change impact on rainfed wheat in south-eastern Australia. *Field Crops Res* 2007;104:139–47.
- [50] Eitzinger J, Stastna M, Zalud Z, et al. A simulation study of the effect of soil water balance and water stress on winter wheat production under different climate change scenarios. *Agric Water Manage* 2003;61:195–217.
- [51] Luo Q, Williams M, Bellotti W, et al. Quantitative and visual assessments of climate change impacts on South Australian wheat production. *Agric Syst* 2003;77:173–86.
- [52] Conde C, Ferrer R, Orozco S. Climate change and climate variability impacts on rainfed agricultural activities and possible adaptation measures: a Mexican case study. *Atmosfera* 2006;19(3):181–94.
- [53] Walker NJ, Schulze RE. An assessment of sustainable maize production under different management and climate scenarios for smallholder agro-ecosystems in KwaZulu-Natal, South Africa. *Phys Chem Earth* 2006;31:995–1002.
- [54] Tojo Soler CM, Sentelhas PC, Hoogenboom G. Application of the CSM-CERES-Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment. *Eur J Agron* 2007;27:165–77.
- [55] Popova Z, Kercheva M. CERES model application for increasing preparedness to climate variability in agricultural planning-risk analyses. *Phys Chem Earth* 2005;30:117–24.
- [56] Akpalu W, Hassan RM, Ringler C. Climate variability and maize yield in South Africa: results from GME and MELE methods. Environment and production technology division IFPRI discussion paper; 2008. p. 1–12.
- [57] Eastering W, Weiss A, Hays C, et al. Spatial scale of climate information for simulating wheat and maize productivity: the case of the US Great Plains. *Agric Forest Meteorol* 1998;90:51–63.
- [58] Droogers P, van Dam J, Hoogeveen J, et al. Adaptation strategies to climate change to sustain food security. In: Aerts J, Droogers P, editors. *Climate change in contrasting river basins: adaptation strategies for water, food and environment*. The Netherlands: CABI Publishing; 2004. p. 49–73.
- [59] Krishnan P, Swain DK, Bhaskar BC, et al. Impact of elevated CO₂ and temperature on rice yield and methods of adaptation as evaluated by crop simulation studies. *Agric Ecosyst Environ* 2007;122:233–42.
- [60] Yao F, Xu Y, Lin E, et al. Assessing the impacts of climate change on rice yields in the main rice areas of China. *Clim Change* 2007;80:395–409.
- [61] Parry M, Rosenzweig C, Iglesias A, et al. Climate change and world food security: a new assessment. *Global Environ Change* 1999;9:S51–67.
- [62] Challinor AJ, Wheeler TR, Craufurd PQ, et al. Adaptation of crops to climate change through genotypic responses to mean and extreme temperatures. *Agric Ecosyst Environ* 2007;119:190–204.
- [63] Xie H, Eheart JW. Assessing vulnerability of water resources to climate change in midwest. Copyright ASCE 2004; 1–10.
- [64] Bouman BAM. A conceptual framework for the improvement of crop water productivity at different spatial scales. *Agric Syst* 2007;93:43–60.
- [65] Kijne JW, Barker R, Molden D. Water productivity in agriculture: limits and opportunities for improvement. Wallingford UK: CABI Publishing; 2003. p. 332.
- [66] Kijne JW, Barker R, Molden D. Improving water productivity in agriculture: editors’ overview. In: Kijne JW, Barker R, Molden D, editors. *Water productivity in agriculture: limits and opportunities for improvement*. Wallingford UK: CABI Publishing; 2003. p. xi–xix.
- [67] Singh R, van Dam JC, Feddes RA. Water productivity analysis of irrigated crops in Sirsa district, India. *Agric Water Manage* 2006;82:253–78.
- [68] Zwart SJ, Bastiaanssen WGM. Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agric Water Manage* 2004;69:115–33.
- [69] Oram PA. Views on the new global context for agricultural research: implications for policy. In: *Climate and food security*. Manila: International Rice Research Institute; 1989. p. 3–23.
- [70] Carter TR, Hulme M, Viner D. Representing uncertainty in climate change scenarios and impact studies. ECLAT-2 report no. 1. In: *Proceedings of the Helsinki workshop*, Norwich, UK, April 14–16; 1999. p. 130.
- [71] Eitzinger J, Zalud Z, Alexandrov V, et al. A local simulation study on the impact of climate change on winter wheat production in northeastern Austria. *Ecol Econ* 2001;52:199–212.
- [72] Sirotenko OD, Abashina HV, Pavlova VN. Sensitivity of Russian agriculture to changes in climate, CO₂ and tropospheric ozone concentrations and soil fertility. *Clim Change* 1997;36:217–32.
- [73] Amthor JS. Effects of atmospheric CO₂ concentration on wheat yield: review of results from experiments using various approaches to control CO₂ concentration. *Field Crops Res* 2001;73:1–34.
- [74] van de Geijn SC, Goudriaan J. The effects of elevated CO₂ and temperature change on transpiration and crop water use. In: Bazzaz F, Sombroek WG, editors. *Global climate change and agriculture production*. Chichester (UK): Wiley; 1996. p. 1–21.
- [75] Howden M, Jones RN. Risk assessment of climate change impacts on Australia’s wheat industry. In: *New directions for a diverse planet: proceedings of the 4th international crop science congress*, Brisbane, Australia, Sept. 26 – Oct. 1; 2004. p. 1848.
- [76] ABARE (Australian Bureau of Agricultural and Resources Economics). Climate change impacts on Australian agriculture. *Aust Commodities* 2007;14(4):657–76.
- [77] Khan S, Hafeez MM, Rana T, et al. Enhancing water productivity at the irrigation system level: a geospatial hydrology application in the Yellow River Basin. *J Arid Environ* 2008;72:1046–63.
- [78] Li Y, Barker R. Increasing water productivity for paddy irrigation in China. *Paddy Water Environ* 2004;2:187–93.
- [79] Govindarajan S, Ambujam NK, Karunakaran K. Estimation of paddy water productivity (WP) using hydrological model: an experimental study. *Paddy Water Environ* 2008;6:327–39.
- [80] Meehl GA, Stocker TF, Collins WD, et al. Global climate projections. In: Solomon S, Qin D, Manning M, et al., editors. *Climate change 2007: the physical science basis*. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge: Cambridge University Press; 2007. p. 749–844.
- [81] Fischer G, Tubiello F, van Velthuisen H, et al. Climate change impacts on irrigation water requirements: effects of mitigation, 1990–2080. *Technol Forecast Soc Change* 2007;74:1080–107.
- [82] De Silva CS, Weatherhead EK, Knox JW, et al. Predicting the impacts of climate change – a case study of paddy irrigation water requirements in Sri Lanka. *Agric Water Manage* 2007;93:19–29.
- [83] Holden NM, Brereton AJ. Adaptation of water and nitrogen management of spring barley and potato as a response to possible climate change in Ireland. *Agric Water Manage* 2006;82:297–317.
- [84] FAO. The state of food insecurity in the world 2001. Food and Agriculture Organization, Rome; 2002.

- [85] Schmidhuber J, Tubiello FN. Global food security under climate change. *Proc Natl Acad Sci USA* 2007;104:19703–8.
- [86] FAO. World agriculture: towards 2015/2030 summary report. Food and Agriculture Organization, Rome; 2002.
- [87] Droogers P. Adaptation to climate change to enhance food security and preserve environmental quality: example for southern Sri Lanka. *Agric Water Manage* 2004;66:15–33.
- [88] Droogers P, Aerts J. Adaptation strategies to climate change and climate variability: a comparative study between seven contrasting river basins. *Phys Chem Earth* 2005;30:339–46.
- [89] Khan S, Hanjra MA, Mu J. Water management and crop production for food security in China: a review. *Agric Water Manage* 2009;96:349–60.