2 Adaptation to Climate Change Impacts on Agriculture and Agricultural Water Management – A Review

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Abstract

This chapter reviews the global literature on impacts of climate change on agriculture and prospects for adaptation. Sensitivity of agriculture to climate change varies across the globe. Developing countries, where more than 800 million people are already undernourished, will be hardest hit. We review approaches for assessing the impact of climate change on agriculture and irrigation water requirements, and present recent progress in the assessment of adaptation measures. The challenges and constraints associated with climate change impact and adaptation research are critically discussed.

The review leads to the conclusion that warmer temperatures will tend to reduce the crop yields in many regions, mainly due to reduction of crop duration associated with water stress during the critical stages of crop development. Although efforts have been made to understand better the climate–crop relationships, there is still limited understanding of the interactions between and relative importance of factors such as elevated ozone and CO_2 levels, extreme weather conditions, weed variety, socio-economic changes and adaptation responses.

Evaluation of diverse adaptation options from farm to policy level, and covering a range of scales and issues, including availability of resources, constraints and associated uncertainties, are essential to address adequately the impacts of climate and other changes on agriculture. Most of the published studies on adaption focus on modification of existing management practices to improve crop yield, using process-based models. Trade-offs between crop production and resource availability, which influence the farmer's decision making and profitability, have not received substantial attention. More effort is required to incorporate constraints (such as social, financial, institutional, technical and resources) and adaptive responses into the model frameworks that most studies used.

2.1 Introduction

Global climate change is expected to have direct impacts on agricultural and food systems (Brown and Funk, 2008). Most staple crops are likely to experience yield reductions under various climate change scenarios, and the estimated reductions are generally larger in the developing countries (Nelson *et al.*, 2009). Increasing population

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and high rates of natural resource degradation will further increase the rates of poverty and food insecurity for Asia, sub-Saharan Africa and Latin America (Fischer *et al.*, 2002). As a consequence, the large population dependent on agriculture and living in the developing world, where more than 800 million people are already undernourished (UN Millennium Project, 2005), will live under increased food insecurity.

Agricultural systems have constituted one of the main subjects of analysis undertaken to understand the impact of both climate variability and climate change, as crop performance is strongly linked to the meteorological conditions of the growing season (Meza and Silva, 2009). Moreover, climatic conditions at critical stages of crop development, such as flowering and yield formation stages, have a pronounced impact on yield (Porter and Semenov, 2005). However, it is only partly understood to what extent the changed climate and variability will impact on agriculture.

This chapter reviews the current literature on impacts of climate change on crop production and possible adaptation measures to cope with the changing climate. There exist recent reviews on climate–crop modelling (e.g. Hansen *et al.*, 2006), ecosystem–hydrology–climate interaction (Betts *et al.*, 2006), agricultural contaminant fate (Boxall *et al.*, 2009), and impact of future hydrological changes on agricultural mitigation and adaptation options (Fallon and Betts, 2010). In this chapter, we particularly focus on the impacts of climate and socio-economic changes on agriculture and irrigation water requirement and the assessment of adaptation options, considering the limitations as well as challenges. Section 2.2 of this chapter presents some of the key issues related to the impact of variation in temperature, precipitation and CO_2 concentration on crop production. This section also presents the impact of climate and socio-economic developments on irrigation water requirements. In Section 2.3, we summarize some of the possible adaptation measures in agriculture and agricultural water managements that are deemed to be essential to offset the adverse impact of climate change. In Section 2.4, we present model-based evaluations of a range of adaptation measures across various geographical regions. In Section 2.5, some of the foremost challenges and constraints associated with the research on climate change impacts and adaptation are discussed, followed by some specific conclusions of the review in Section 2.6. While our review focuses on the developing countries, we make reference to other regions where appropriate.

2.2 Impact of Climate Change on Agriculture and Irrigation Water Requirement

2.2.1 Effects of elevated carbon dioxide

Plant development and crop production respond to rising atmospheric CO_2 concentration (one of the key indicators of human-induced global warming), higher temperature, altered precipitation regimes, increased frequency of extreme temperature and precipitation events (IPCC, 2007) as well as local factors, such as changes in water availability, agricultural practices and methods. However, the relative importance of these factors is a major topic for research.

A wide range of studies conducted in the last few decades have established that an increase in CO_2 concentration level enhances water-use efficiency and this tends to increase the plant biomass and yield for most agricultural plants (Tubiello *et al.*, 2007). Many experiments in controlled environments illustrate that the crop growth and biomass production increase up to $33 \pm 6\%$ for C3 crops (such as rice, wheat, soybean) under doubled CO_2 condition (e.g. Kimball, 1983; Porter, 1992; Ewert *et al.*, 1999; Hsiao and Jackson, 1999; Amthor, 2001), while for C4 (such as maize, sugarcane) crops the increase is in the range of 0–10% (e.g. Long *et al.*, 2004; Ainsworth and Long, 2005). Similarly, free air CO_2 enrichment (FACE) experiments in well-managed fields have confirmed these results (Kimball *et al.*, 2002). Overall, the sensitivity to atmospheric CO_2 and surface ozone is relatively higher for C3 crops, such as rice, wheat, soybean, than C4 crops, such as maize and sugarcane (e.g. Brown and Rosenberg, 1999; Gifford, 2004; Long *et al.*, 2004; Ainsworth and Long, 2005; Slingo *et al.*, 2005).

However, it is still uncertain whether effects of CO_2 fertilization observed in controlled and FACE environments will be seen in the farmers' fields in the future (e.g. Tubiello and Ewert, 2002). On the other hand, the estimated benefits of elevated CO_2 may not be fully achieved due to many limiting factors such as increase in surface ozone level (Long *et al.*, 2005), water and nitrogen (Erda *et al.*, 2005), pests, weeds and air quality (Ainsworth and Long, 2005; Tubiello *et al.*, 2007), which are neither well understood nor well represented in the simulation models. Similarly, otherwise positive CO_2 effects on yield may be lowered by high temperature during the critical period of a crop (Caldwell *et al.*, 2005) and increased temperature during the growing season (e.g. Xiao *et al.*, 2005). Moreover, crop management practices such as irrigation and fertilization significantly influence the crop production under climate change (Tubiello *et al.*, 2002). For instance, water limitation enhances the positive benefits of CO_2 fertilization (Tubiello and Ewert, 2002). Further studies are required to understand the net effects of these interactions on crop production. Furthermore, as illustrated in Fig. 2.1, the possibility of more severe climate and saturated effect of CO_2 on plants after 2050 is likely to decrease significantly the yield and consequently the agricultural GDP (with reference to 1990 prices) in developing countries. This discrepancy between developed and developing countries is because of the dominancy of agriculture in the economy of the developing countries where a large fraction of population is employed on the farm. For example, in 2000 the GDP share of agriculture in developed countries was only 2.1% compared to 16% in the developing countries

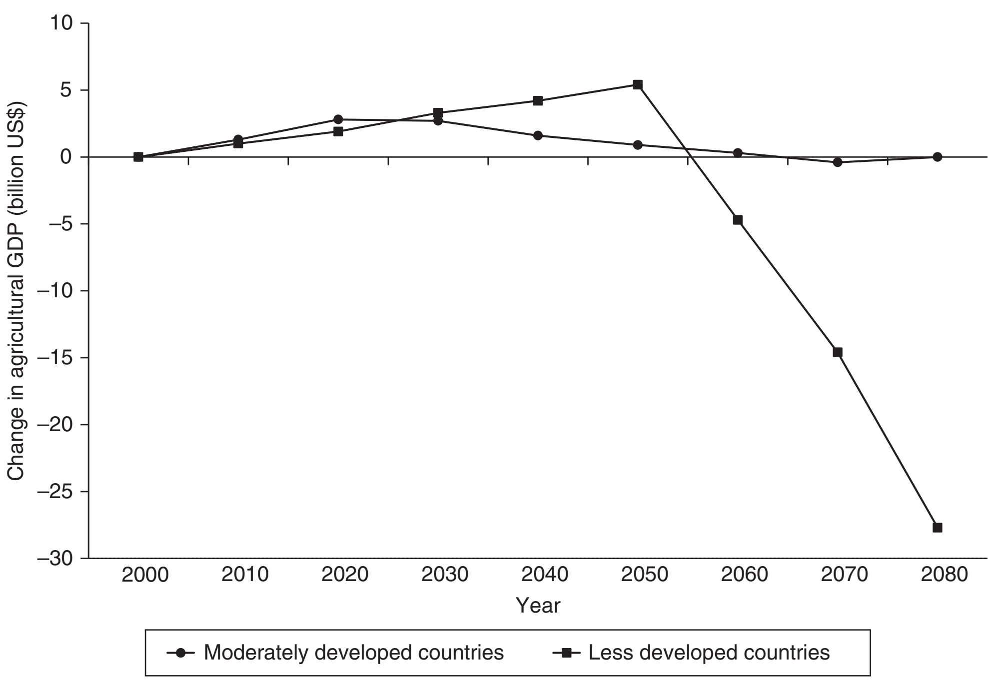

Fig. 2.1. Projected variation in agricultural GDP (billion US$, reference to 1990 price) due to climate change under A2r Hadley climate scenario. A2r is a revised Special Report on Emissions Scenarios (SRES), A2 scenario, with a revised population projection (see Riahi *et al.*, 2006) (from Tubiello and Fischer, 2007).

(Tubiello and Fischer, 2007). Additionally, lack of capital and technology for adaptation, warmer baseline climate, higher exposure to extreme events (Parry *et al.*, 2001) and reliance on weather-dependent natural resources make the developing countries more vulnerable to climate change than the developed countries.

2.2.2 Impact of temperature and precipitation

Temperature and precipitation are the major climatic variables in determining the crop yield. For instance, Kutcher *et al.* (2010) found that the number of days with maximum temperature (greater than 30°C) showed the strongest correlation with canola yield followed by the growing season total precipitation for Canada. Precipitation influences plant growth through altering soil moisture, humidity levels and general cloudiness (altering evaporation and surface level photosynthetically active radiation). The impact of warming on crop yield depends on the region and type of crops. In temperate regions, crop yields are expected to benefit slightly from moderate to medium increases in mean temperature (1–3°C) considering the effect of CO_2 fertilization and changing rainfall patterns (IPCC, 2007); yet large uncertainties remain (Easterling *et al.*, 2007). On the other hand, in semi-arid and tropical regions, this would decrease crop yield. Modelling studies have indicated that in low latitude regions a moderate temperature increase (1–2°C) is likely to have negative yield impacts for major cereals. Hence, for main cereal crops, climate change is expected to have negative impacts on crop productivity and yields in the tropics, while there may be some beneficial effects at high latitudes. This pattern is expected to be more pronounced as time progresses. However, the projected warming for the end of the 21st century is likely to have a negative impact on crop yield in all the regions (Tubiello *et al.*, 2007). Furthermore, increased evapotranspiration due to change in temperature could intensify drought stress (Tao *et al.*, 2003).

Existing literature also indicates the disparity in the climate-change-driven impacts on crop yield between the developed and developing countries, with mostly positive impacts in developed countries and negative impacts in developing countries. This discrepancy is estimated to be more pronounced for A1 and A2 Special Report on Emission Scenarios (SRES), based on the Basic Linked System (BLS) simulation for wheat, rice, maize and soybean, considering the beneficial effect of CO_2 fertilization (Fig. 2.2). The CO_2 level considered is maximum (810 ppm) for the scenario A1F1 (IPCC, 2000) and minimum (498 ppm) for the scenario S550 (see Arnell *et al.*, 2002). As crops are subjected to multiple stresses, the analysis of climate change alone provides only a partial view of the likely future yields. For a more vigorous assessment of impacts of climate change on agriculture, a range of drivers needs to be considered. However, if the climate-change effects dominate, crop yields are likely to be more negatively affected. Thus, we need to be prepared for the range of possible agriculture futures and search for ways to adapt to a more uncertain world in the coming decades (Parry *et al.*, 2004).

2.2.3 Impact of climate change on irrigation water requirement

Climate change also impacts agriculture and irrigation water requirements through the changes in local hydrology. Warmer temperature and change in precipitation (pattern and event characteristics) can cause significant changes in hydrological responses, e.g. evaporation, surface runoff, soil moisture, infiltration, percolation, base flow and groundwater recharge/discharge (Uhlenbrook, 2009). Existing studies have indicated an increase in irrigation water requirements both on global and regional scales, irrespective of the beneficial impact of increased CO_2 on crop water use efficiency. Considering the direct effect (without considering CO_2 effects) of climate change on crop evaporative demand, Döll

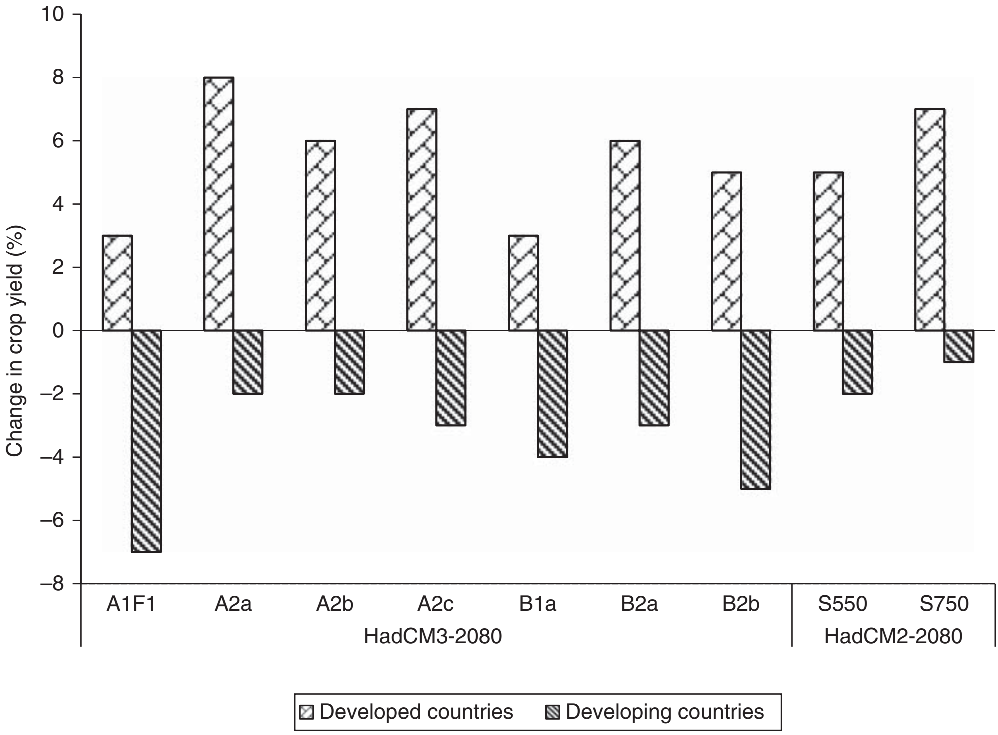

Fig. 2.2. Projected changes in crop yield (%) from baseline (1990) for various emission scenarios (Special Report on Emissions Scenarios) from HadCM3 and HadCM2 models in developed and developing countries (from Parry *et al*., 2004).

(2002) estimated an increase of net crop irrigation requirements by 3–5% until the 2020s and by 5–8% until the 2070s, with a large regional variation, e.g. +70% in Southeast Asia by the 2070s (Fig. 2.3). The increase in crop water requirement can be attributed to both direct (changes in temperature and precipitation) and indirect (changes in cropping pattern and growing season) impacts of climate change. Döll (2002) applied a raster-based Global Irrigation Model (Döll and Siebert, 2002) with a spatial resolution of 0.5° to explore the impact of climate change on net crop irrigation requirements for the areas across the globe that were equipped with irrigation until 1995. Recently, Fischer *et al.* (2007) projected an increase in global net irrigation requirements of 20% by the 2080s, considering positive effects of increased CO_2 on crop water use efficiency. About 65% of this increase in the net irrigation requirement was considered as a consequence of higher crop water demand and the remaining 35% was contributed by the extended crop calendar. They also reported about 40% reduction in the agricultural water requirement in the case of the climate scenario with and without mitigation for climate change. On the other hand, water stress (the ratio of irrigation withdrawal to renewable water resources) is projected to amplify in the Middle East and South-east Asia (Arnell, 2004; Fischer *et al.*, 2007). In the developing countries of Asia, water use is projected to increase by 40% in the next two decades to feed the growing population (see Sivakumar, 2006).

The influence of socio-economic developments (development paths as specified by IPCC SRES), with special reference to emission of greenhouse gases (GHGs) into the atmosphere on the irrigation water

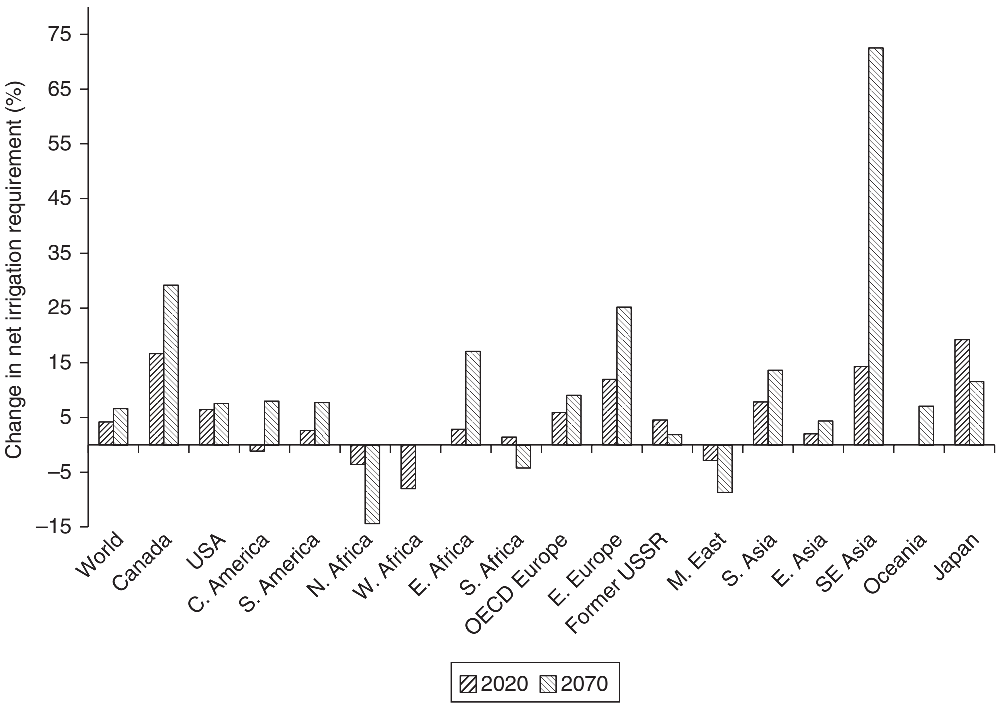

Fig. 2.3. Change in net irrigation water requirement (IRnet) for the 2020s (2020–2029) and the 2070s (2070–2079) of the world regions equipped with irrigation in 1995 (change in IRnet projected from ECHAM4 and HadCM3 climate change scenarios were averaged; data from Döll, 2002).

requirement, may vary significantly across the region and much remains to be done in predicting the irrigation demand resulting from the interaction of socio-economic and climate change scenarios. For developing countries, the increase in net irrigation water requirement from socio-economic developments (A2r scenario, i.e. SRES A2 scenario with revised population projection) is higher than the increase from climate change (HadCM3). However, the reverse is the case for developed countries (Fig. 2.4). Fischer *et al.* (2007) assumed that the BLS projected an increase in irrigation water requirement from socio-economic developments (A2r scenario), which is proportional to the estimated additional irrigated land. Hence, the large proportion of the projected additional irrigated area from the developing countries (112 million ha (Mha) out of 122 Mha for 2080) will result in a significant increase in the irrigation water demand under socio-economic development.

2.3 Adaptation Options in Agriculture and Agricultural Water Management

Adapting agriculture and agricultural practices (including agricultural water management) to climate change is a complex, multi-dimensional and multi-scale process (Bryant *et al.*, 2000). Climate change is expected to increase the variability in climate by shifting and intensifying extreme weather events and introducing higher uncertainty in the quality and quantity of water supply. Thus, adaptation strategies should incorporate both traditional and new technologies to cope with climate change and variability as well as the changes in agronomic practices. Moreover, water resources management options implemented to cope with current climate variability will also assist to better prepare for increased variability expected in the future. Furthermore, the social and technological aspects of vulnerability, such as obtainable

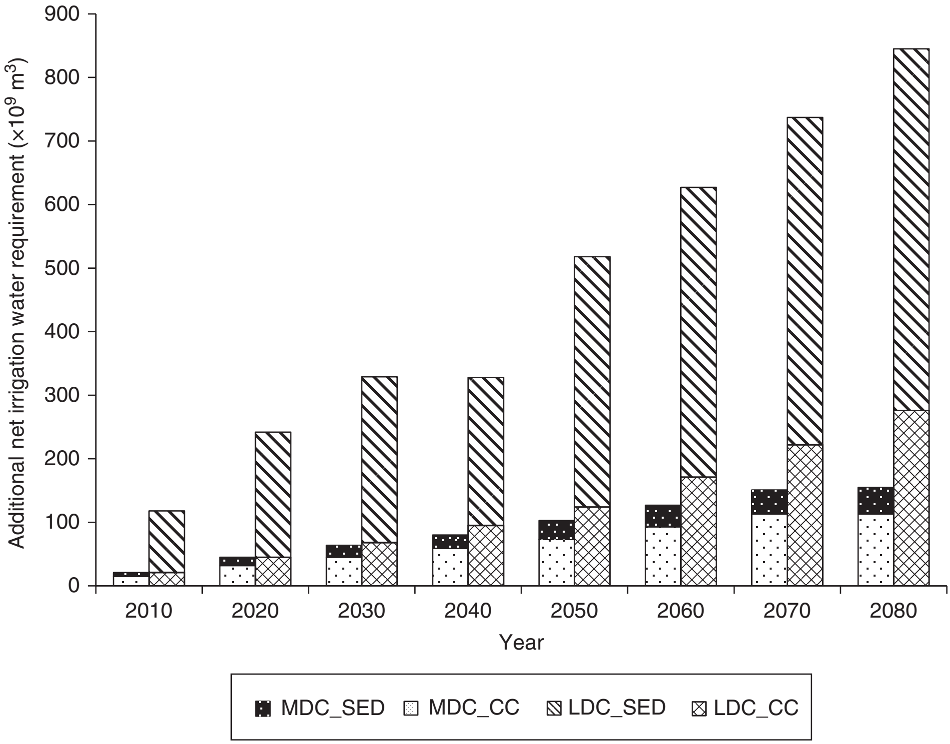

Fig. 2.4. Agro-ecological zone (AEZ) projected an additional net irrigation water requirement (with reference to irrigation water requirement in 2000) from socio-economic development (SED) and climate change (CC) (Hadley) for MDC and LDC under the A2r scenario (from Fischer *et al.*, 2007).

adaptive capacity in a region and the complexity of adaptation for specific crops, should be incorporated while developing adaptation strategies (Lobell *et al.*, 2008). More importantly, such adaptation options must be easily available to the farmers.

There exists a large array of possible adaptation options in response to diversity of agricultural practices depending on the range of climate, cultural, economic and environmental variables (Howden *et al.*, 2007). However, the response of a particular cropping system to a specific adaptation strategy can vary significantly depending on the location and climate scenario. Changing crop varieties, efficient water use, and altering the timing or location of cropping activities are some of the widely suggested adaptation strategies. The full list of the options suggested in the literature is large. For ease in discussion, we classified them into a number of groups that range from water and crop management options to technology developments and government programmes. These adaptation options together with their pros and cons are listed in Table 2.1. Although fully implemented simple adaptation options like shifting planting date and switching to existing cultivars can reduce the negative impacts (Mendelsohn and Dinar, 1999), the pronounced benefit will likely result from more costly measures such as developing new crop varieties and expanding irrigation (Rosenzweig and Parry, 1994). The fact is that, whether we like it or not, most of the widely effective measures require substantial investment from the farmers, development organizations, governments and scientists. Such strategies are also time-consuming (developing new varieties may take up to decades) and may be constrained by other sectors

Table 2.1. Adaptation options in agriculture and agricultural water management (from LEISA, 2000; Desjardins *et al.*, 2002; Kurukulasuriya and Rosenthal, 2003; Verchot *et al.*, 2007).

Adaptation options	Examples	Pros (P) and cons (C)
1. Water management		
Water access (increasing water supply and ecosystem services)	Water transfer schemes Storage reservoirs Rainwater harvesting Groundwater extraction (wells) Reuse of wastewater	P: Addresses the uncertainty associated with natural precipitation regime and assists to cope with increased climate variability. C: High implementation cost and is applicable only in regions without physical scarcity.
Water demand (decreasing water demand and increasing use efficiency)	Remove invasive non-native vegetation Use of drought-resistant crops Maintenance of irrigation infrastructure Change in irrigation techniques Crop management (change in cropping pattern and timing of farm operations)	P: Efficient use of available water resources, which is relatively cheaper than supply management. P: Increases the tolerance and suitability of plants to temperature, moisture and other relevant climatic conditions. C: May not have pronounced benefits in all conditions.
2. Information systems		
Weather and climate information systems and knowledge management	Implement systems to use daily and seasonal weather forecasts	P: Improves efficiency of agricultural management by providing information early enough to adjust the critical decision. C: The information may not be always achieved in time and scale relevant to farmers.
3. Socio-economic		
Agricultural subsidy and support	Subsidy/support programmes to influence farm-level production	P: Reduces the risk of climate-related income loss and can motivate for positive change in farm-level management. C: Limited by the government subsidy and support programme.
Insurance	Insurance schemes to address crop damage from climate-related events, e.g. drought	P: Reduces vulnerability at the farm level. C: Limited by the government subsidy and support programme.
4. Farm production practices		
Land use	Change in location of crop production Change from rainfed to irrigated agriculture Use of alternate fallow and tillage practices	P: Conserve moisture and nutrients. C: Cost of the support system and infrastructure will be high for change in location and shift to irrigated agriculture.
Land topography	Change land topography (land contouring and terracing)	P: Reduces erosion, improves the retention of moisture and nutrient and improves water uptake.
5. Diversifying production system	Agroforestry	P: Maintains production during both wetter and drier years and acts as a buffer against income risks associated with climate variability. C: Government help is required to smallholder farmers mainly during the initial years.
6. Traditional knowledge and indigenous practices	Traditional water-harvesting technologies, grass-mulching, etc.	P: More likely to be accepted by the community and feasible to be adopted without external help.

(e.g. the inter-sectoral competition for resources may constrain expansion of irrigation).

2.4 Modelling-based Assessment of Adaptation Options

A continuous assessment of the impacts, particularly concerning the impact of higher temperature, change in precipitation patterns (Watanabe and Kume, 2009) and climate variability including short-term extreme events constitute the basis for developing a sound adaptation strategy for sustainable crop production. The nature of the stimuli and allied vulnerability establish the relevancy of adaptation options (Pittock and Jones, 2000). It is imperative to recognize the climate variables to which a particular adaptation option is the most suitable and to take into account the role of non-climatic factors that influence the sensitivity of agriculture to climate change. Typically, adaptation options are evaluated using a crop growth simulation model, with or without a coupled hydrological model, forced with climate projections from one or more global climate models. The use of a hydrological model to couple with the crop growth models is not very common. Only a few studies reported the coupling with the Variable Infiltration Capacity (VIC) hydrological model. When a hydrological model is integrated with a crop model for the impact analysis on crop yield, the crop model benefits from the dynamic input of available water on the temporal scale to which the hydrological model works, typically daily. On the other hand, changes in crop characteristics may also modify the hydrological impacts of climate change such as the risk of drought and flooding (Betts, 2005) on a much smaller scale than the climate models allow. Table 2.2 summarizes the recent literature on model-based evaluation of various adaption measures indicating the study region, types of crops analysed, models used for climate projections and crop growth simulations, types of adaptation options evaluated and climatic variables considered for assessing the adaptation measures. Key results and conclusions reported in the literature are also summarized. The literature covers a wide geographic range and crop types. CERES (Ritchie *et al.*, 1998), DSSAT (Jones *et al.*, 1998) and CropSys (Stöckle *et al.*, 2003) are the most commonly used crop growth models or modelling systems in these studies. The commonly assessed adaptation options reported in these studies are the following:

- sowing dates;
- crop varieties (hybrids, slow maturing, etc.);
- level of fertilizer application;
- crop density, different crop rotations and double-cropping;
- expansion of irrigation and soil moisture conservation;
- improvement in agricultural technology; and
- land use and water allocation policies, etc.

The adaptation responses are commonly evaluated with respect to the improvement in the crop yields alone. In practice, some of these adaptation options may not be always feasible either due to the constraints from other sectors (e.g. competition for resources, socio-economic, institutional, technical constraints) or due to high underlying cost. These modelling-based methods constitute what is commonly known as the 'impact approach'. Although less commonly reported in the literature, adaptation options for agriculture are also evaluated using the 'capacity approach' in which the existing capacities and vulnerabilities of socio-economic groups are the basis for developing politically and economically feasible adaptation options given the plausible future climate projections (Vermeulen *et al.*, 2013). To bridge the gap between science and policy and planning long-term adaptation, integration of impact and capacity approaches is essential. Although the uncertainty due to climate scenarios and selection of General Circulation Models (GCMs) are normally considered in most of the climate-change adaptation studies, the uncertainty (input data, model structure and parameters) of the impact (crop and hydrological) model and

Table 2.2. Development and evaluation of adaption options.

Study region, crops and source	Climate model and scenarios	Adaptation options evaluated and climatic variables considered	Key results and conclusion
South-eastern USA Maize, wheat, soybean and groundnut Alexandrov and Hoogenboom (2000)	CMS: Geophysical Fluid Dynamics Laboratory (GFDL-R15), Canadian Centre for Climate Modelling and Analysis (CGCM1), Max-Planck Institute for Meteorology (ECHAM4), UK Hadley Center for Climate Prediction and Research (HadCM2) and Australian Commonwealth Scientific and Industrial Research Organization (CSIRO-Mk2b) (Mitchell *et al.*, 1995; Hirst *et al.*, 1996; Haywood *et al.*, 1997; Johns *et al.*, 1997; Bacher *et al.*, 1998; Flato *et al.*, 1999). CGM: CERES (Ritchie *et al.*, 1998) and CROPGROW (Boote *et al.*, 1998).	Changing sowing dates, hybrids and cultivar and fertilization. Temperature, precipitation, solar radiation and CO_2 levels.	Increased temperature projected a shorter vegetative and reproductive growing season for maize for 2020. Assuming the direct benefits of elevated CO_2 level, simulations indicated an increase in soybean and groundnut yield under all GCM climate change scenarios for 2020. Alteration of sowing dates, cultivars and fertilization could minimize the negative impact of future warming.
Northern Thailand Rice Babel *et al.* (2011)	CMS: ECMWF atmospheric general circulation model coupled with the University of Hamburg's ocean circulation model (ECHAM4) A2 (Roeckner *et al.*, 1996), providing regional climates for impact studies (PRECIS). CGM: CERES (Ritchie *et al.*, 1998).	Changing sowing dates, nitrogen application, tillage practices and cultivars. Temperature and CO_2 levels.	Under future climate, duration between anthesis and maturity was reduced resulting in reduced yield. Delayed sowing avoids high temperature during the grain-filling phase. However, the alteration of sowing date is limited by water availability. Modification of fertilizer application schedule and use of cultivars having longer maturity duration, lower photoperiod sensitivity and higher temperature tolerance has a positive impact on yield under future climatic condition.

Romania Winter wheat and rain-fed maize Cuculeanu *et al.* (1999)	CMS: Canadian Climate Centre model (CCCM) (McFarlane *et al.*, 1992) and Goddard Institute for Space Studies (GISS) (Hansen *et al.*, 1988). CGM: CERES (Godwin *et al.*, 1989; Ritchie *et al.*, 1998).	Changing crop varieties, sowing dates, crop density, and level of fertilization. Temperature, precipitation and CO_2 levels.	Winter wheat and rain-fed maize benefit from the climate change but irrigated maize shows negative response to climate change. The negative impact on maize was reduced by the use of longer-maturing hybrids, change in sowing date and plant density and increasing fertilization level. The effect of doubling CO_2 on photosynthesis and water use varies according to the plant species, which is still an important research question.
Keith, South Australia Wheat Luo *et al.* (2009)	CMS: CSIRO-conformal cubic atmospheric model (C-CAM) for 2080 (Sadourny, 1972). CGM: Agricultural Production Systems sI Mulator (APSIM)-Wheat (Keating *et al.*, 2003).	Early sowing, changing fertilizer application rate and use of different cultivars. Mean rainfall, temperature, solar radiation, wet spells, dry spells and temperature variability.	Early sowing is effective in dealing with the adverse effect of climate change. In drier conditions, the early sowing needs to be supplemented by other adaptation options such as irrigation. Changing N application rate and wheat cultivars is not adequate to fully offset the negative impact of climate change.
Asia Rice Matthews *et al.* (1997)	CMS: GFDL, GISS and United Kingdom Meteorological Office (UKMO) (Wilson and Mitchell, 1987). CGM: ORYZA1 (Kropff *et al.*, 1994) and SIMRIW (Horie, 1987).	Modification of sowing/planting dates, use of varieties with a higher tolerance of spikelet fertility to temperature. Temperature and CO_2 levels.	The average production in the region will decline but the magnitude of the impact varies with climate scenarios, regions and crop simulation models. At high altitudes where warmer temperature allowed a longer-growing season, modification of sowing date may permit double-cropping. Similarly, in case of a longer growing season, shifting of planting date will avoid high temperature at the critical stage of development.
Chile Maize (irrigated) Meza *et al.* (2008); Meza and Silva (2009)	CMS: HadCM3 for A1F1 and B2B scenario. CGM: Decision Support System for Agrotechnology Transfer (DSSAT) (Jones *et al.*, 2003).	Changing sowing dates, nitrogen fertilizer doses, plant densities and double-cropping. Temperature and precipitation.	Showed yield reduction from 10 to 30%, depending on change scenarios and hybrid used. Early sowing and N management can minimize the adverse impact of climate change. In case of a longer growing season, double-cropping outperformed other adaptation options, such as new cultivars.

Continued

Table 2.2. Continued.

Study region, crops and source	Climate model and scenarios	Adaptation options evaluated and climatic variables considered	Key results and conclusion
India Sorghum Srivastava *et al.* (2010)	CMS: HadCM3 for A2a scenarios. CGM: InfoCrop-SORGHUM (Aggarwal *et al.*, 2006a, b).	Changing crop varieties, planting dates and a combination of both. Temperature, precipitation, CO_2 levels.	More impacts were observed on winter crops in the central and south-central zone, and on monsoonal crops in the south-western zone. Simple strategies such as shifting sowing time and changing varieties can reduce vulnerability. Although better management strategies can reduce vulnerability, low-cost adaptation options must be explored for benefit in resource-constrainted situations.
North China Plain Maize Tao and Zhang (2010)	CMS: SuperEPPS using ten climate scenarios from 5 GCMs (HadCM3, PCM, CGCM2, CSIRO2 and ECHAM4) and two emission scenarios (A1F1, B1). CGM: Model to Capture the Crop–Weather relationship over a Large Area (MCWLA) (Tao *et al.*, 2009).	Early planting, late planting, fixing crop-growing duration and use of different varieties. Temperature and precipitation.	Without adaptation the maize yield could reduce by 13–19% during the 2050s. Different adaptation options (changing planting dates and fixing growing duration) showed marginal (<5%) to significant (>30%) increase in yield. The benefits are sensitive to the crop varieties. The highest benefit was obtained from the high-temperature-tolerant variety.
Switzerland (alpine region) Maize, wheat, canola Torriani *et al.* (2007)	CMS: HIRHAM4 (Christensen *et al.*, 1998) driven by HadAM3H (SRES A2 scenario). CGM: Cropping Systems Simulation Model (CropSyst) (Stöckle *et al.*, 2003).	Slow maturing variety, shifting planting date and expansion of irrigation. Temperature, precipitation, solar radiation, relative humidity and CO_2 levels.	Shifting the sowing date resulted in positive yield on maize and negative yield on wheat and canola. Slow-maturing cultivars showed a positive impact on average yield on all three crops. Adaptation responses are crop specific and difficult to generalize.
Czech Republic Barley Trnka *et al.* (2004)	CMS: ECHAM4, HadCM2, NCAR-DOE and scenario averaged over 7 GCMs. CGM: CERES-Barley (Otter-Nacke *et al.*, 1991).	Early sowing, change of cultivars, change in N-fertilizer and soil moisture conservation. Temperature, precipitation and CO_2 levels.	Simulations showed generally positive impacts on yield, considering the effect of doubled CO_2 concentration. Early planting and use of cultivars with longer growing season will further increase the yield under doubled CO_2 concentration. Soil water conservation is important for sustainable production mainly in the low rainfall areas.

Modena and Foggia (Italy) Maize, wheat, soybean, barley, sorghum, sunflower (in rotations) Tubiello *et al.* (2000)	CMS: GISS (Hansen *et al.*, 1988) and Geophysical Fluid Dynamics Laboratory (GFDL) (Manabe and Weatherland, 1987). CGM: Cropping Systems Simulation Model CropSyst (Stöckle *et al.*, 2003).	Early planting, use of slow-maturing variety and expansion of irrigation. Temperature and precipitation.	Warmer temperature showed crop yield reduction by 10–40%. Combination of early planting for spring–summer crops and slower-maturing winter cereal cultivars is able to maintain yield. High temperature increases evaporative demand and reduces irrigation water use efficiency. For irrigated crops, 60–90% more irrigation water was required to maintain yield.
USA Wheat, potato, maize, citrus Tubiello *et al.* (2002)	CMS: CCGS and HCGS (CC: Canadian Centre Model; HC: Hadley Centre Model; GS: greenhouse gases with sulfate aerosols). CGM: DSSAT.	Changing planting dates and cultivars. Temperature, precipitation and CO_2 levels.	Yield response to climate change varied significantly in magnitude and even direction for the climate change scenarios considered, due to difference in projected precipitation. For all the crops simulated, precipitation and elevated CO_2 each contributed about half of the yield increase.
China Rice, maize, wheat Wei *et al.* (2009)	CMS: PRECIS (Jones *et al.*, 2004) based on SRES A2 and B2. CGM: CERES (Ritchie *et al.*, 1989). HM: Variable Infiltration Capacity VIC (Liang *et al.*, 1994, 1996).	Improvement in agricultural technology, land-use change policy and water allocation policy. Temperature, precipitation, solar radiation, CO_2 levels.	The absolute effects of climate change are relatively modest, but climate scenarios combined with socio-economic developments lead to a decrease in total production. Policy options related to land, water and agricultural technology can offset the negative impact and the combination of these policy options presents a better result.

CMS, Climate Model and Scenario; CGM, Crop Growth Model; HM, Hydrological Model.

socio-economic uncertainty (price fluctuation, international trade) is mostly neglected. Therefore, a more comprehensive study should prioritize the adaptation strategies giving due attention to the availability of resources, financial and social constraints, responses of stakeholders and farmers and associated uncertainties under the changed environment. Moreover, such adaptation measures should be cost effective and easily available to the farmers.

Adaptation success is closely linked with the alternatives available to the farmers. Integration of two or more feasible adaptation measures is generally expected to give higher benefits (e.g. Srivastava *et al.*, 2010). The impact on crop yield may also come from secondary factors such as higher weed and pest infestations (e.g. Hossain *et al.*, 2003), which are more likely under higher exposure to warm temperatures (Tubiello *et al.*, 2000). Such indirect consequences of climate change are normally not considered in most models used in adaptation studies. Thus, it is likely that the estimated benefits of some of these adaptation measures may not be achieved in the farmers' fields. Moreover, adaptation assessment studies should not just consider the level of crop yield but need to evaluate the trade-offs between crop production and resources availability that considerably influence farmers' decision making and profitability.

The existing simulation studies signify the progress in our understanding of how adaptation measures can be useful to curtail the likely effect of future climate on crop yields in different geographic and climatic regions. However, it is still poorly understood how variation in crop production and water availability, as a consequence of climate change, will interact with other socio-economic pressures. Moreover, the estimated impact of climate change on crop production and significance of adaptation can depend largely on the crop model used, particularly the approach used for simulating the impact of extreme events (Tao and Zhang, 2010). Thus, evaluation of adaptation responses using two or more crop models might help to minimize the uncertainty due to the crop model structure.

2.5 Challenges in Climate Change Impact and Adaptation Research

The impacts of climate change on crops (vegetation), catchment hydrology and water management systems underline the need for integrative studies. However, the issue of scale and uncertainty is a challenge for such integration (Betts, 2005). The difference in temporal as well as spatial scales between climate and crop models is one of the major difficulties of integration, which is also discussed by Osborne *et al.* (2006).The integrated climate-crop models if used appropriately can play an important role to identify potential adaptation strategies. However, their role may be limited to support agricultural climate risk management (Hansen, 2005). Although parameterization of some components of hydrological models can be uncertain due to inadequate data, the relationship between climate, human activities and water resources can be investigated with the hydrological models (Jothityangkoon *et al.*, 2001) forced with the climate model results (predictions), normally with downscaling of the climatic variables.

The climate scenarios used can alter the magnitude and even the direction of the impact on crop yield irrespective of the location and type of crops studied (e.g. see Reilly *et al.*, 2003) due to the variation of the projected change in climatic variables, especially precipitation. A large part of this ambiguity in precipitation is due to the coarse resolution of the GCM, as it does not sufficiently represent specific regional land features (such as mountains and lakes). Such regional or local features can significantly influence the local climates (Hu *et al.*, 2013a, b). A widely recognized approach to address the uncertainty related to the choice of GCMs is to employ an ensemble of a range of models, but obviously it adds complexity in modelling and analysis. Managing the present risk and building capacity to deal with unpredictable future events is key for the adaptation to climate change. Moreover, the relative importance of the uncertainty associated with climate change may vary spatially and temporally. Vermeulen *et al.* (2013) presented a framework for prioritizing adaptation approaches with particular reference to uncertainty linked to the time frames considered. They illustrated the importance of timescale in applying a suitable approach: impact approach or capacity approach or a combination of the two.

Scale and geography are also important for determining the crop yield. The balance between the generality and specificity in region and scale is yet another challenge to predict the response of crops to climate change (Challinor *et al.*, 2009). Variation in commodity prices, trade agreements, resources use rights and government subsidies and support programmes may obscure the adaptation process (Smit *et al.*, 1996). Generally, social and technical constraints in developing countries may restrict sustainable production in the long run (Parry *et al.*, 1999). In certain circumstances, such socio-economic complexity may even outweigh the climatic uncertainty in evaluating the feasible adaptation measures (Eakin, 2005; Vincent, 2007). On the other hand, the adaptation capability is low in developing countries due to limited access to market for crop inputs or outputs and lack of appropriate infrastructure (Reilly and Hohmann, 1993). In order to address these challenges, an adaptation framework needs to equitably involve farmers, agribusiness and policy makers (Howden *et al.*, 2007) and cover a range of scales and issues which should be integrated with a comprehensive and dynamic policy approach.

2.6 Conclusions and Recommendations

Sensitivity of agriculture to climate change varies across the globe. Warmer temperatures tend to reduce the crop yields in many regions, mainly due to reduction of crop duration associated with water stress during the critical stages of crop development. Developing countries, where more than 800 million people are already undernourished, will be hardest hit. Hence, adaptation in the agriculture sector is essential in order to feed the world's growing population. Even without climate change, inherent climate variability and socio-economic development mean that transformation of agricultural systems is inevitable, but the urgency of timely adaptation has been amplified due to climate change.

Crop growth and production and water resources distribution will be affected by the interaction between increasing atmospheric CO_2 concentration, higher temperature, varying patterns of precipitation, altered frequency and severity of extreme events, land-use change and regional socio-economic development. Although efforts have been made to understand better the climate–crop relationship, the interactions that are still not fully described include: (i) field response of crop to higher CO_2 concentration; (ii) response to increased extreme events under climate change; (iii) influences of local/regional socio-economic drivers on the climate crop relationship; (iv) economics of adaptation at the regional/local scale; and (v) significance of the uncertainty of the impact model.

To fully understand the resulting impacts of these interactions requires an integrated approach that incorporates the physics of climate change with the biology of crop development and socio-economic dimension of the region. Furthermore, the resulting impacts are highly dependent on regional variability of biophysical conditions (Tan and Shibasaki, 2003). Limited knowledge of this variability constrains our capacity to determine optimal responses for adaptation. Therefore, future adaptation studies should consider, among other things, the influence of extreme temperature at the critical stages of crop development, regional socio-economic development and significance of the uncertainty of the impact model. Similarly, there is a need to expand the number of field experiments to understand the influence of increased CO_2 concentration on a range of crops.

Integrated technical and policy adaptation measures including no-regret options based on both traditional and new technologies are deemed to be favourable to cope with climate and other global changes. Any adaptation options proposed must be easily available and economically acceptable to the farmers. Thus, there is a need to expand the number of studies that focus on the acceptability of adaptation options in terms of factors important to all stakeholders. Furthermore, the social and technological aspects of vulnerability, such as obtainable adaptive capacity in a region and the complexity of adaptation for specific crops, should be incorporated while developing adaptation strategies (Lobell *et al*., 2008).

Most of the adaptation studies reported in the literature have focused on the modification of existing practices (such as shifting planting dates, using existing cultivars, application of irrigation, etc.) to improve crop yield. Such studies should be extended to evaluate and prioritize a range of other possible management and policy options, taking into account social, technical, financial, institutional and resource constraints in the modelling framework. Trade-offs between crop production and resource availability, which influence the farmers' decision making and profitability, have not received substantial attention so far. To adequately address the impacts of climate and other changes on agriculture, evaluation of diverse adaptation options is needed, covering a range of scales from farm to policy level and with consideration of the availability of resources, constraints and associated uncertainties. Interaction with the farmers and stakeholders is also essential to evaluate the employability of any adaptation options and to understand the dynamics of traditional practices to cope with the changing environment.

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