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Crop models for assessing impact and adaptation options under climate change

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ABSTRACT

Increased amount of greenhouse gases (GHG) in the atmosphere will cause climate change that will adversely impact crop production especially in the arid and semi-arid regions of the developing countries. Development and implementation of field level adaptations measures to cope up with climate change are necessary to the farmers whose livelihood depends on crop-based income. Crop simulation models that incorporate soil-crop-climate processes of plant growth and that are sensitive to climate change factors can be used to quantify impact of climate change on crop production and evaluating and prioritizing adaptation measures at farm level. This paper analyses the impacts of climate change and plausible agronomic, land and water management and genetic adaptations options for the major crops of the semi-arid tropical region with examples from selected sites in India and other developing countries. The crop models need to be linked to the improved pest, disease and weed models to analyze and predict yield losses, especially those due to climate change. The simulation models also need to incorporate the impact of extreme weather events on crop production that is projected to increase with climate change.

Key words: Models as decision making tools, variability in climate change, impact on crops, adaptation strategies, sustainability

Increasing concentration of greenhouse gases (GHGs) in the atmosphere due to anthropogenic activities is warming the globe. According to the Intergovernmental Panel on Climate change (IPCC, 2021) concentrations of GHG have continued to increase in the atmosphere, reaching annual averages of 410 parts per million (ppm) for carbon dioxide (CO2), 1866 parts per billion (ppb) for methane (CH4), and 332 ppb for nitrous oxide (N2O) in 2019. The report also shows that emissions of GHGs from human activities are responsible for approximately 1.1°C of warming since 1850-1900, and finds that averaged over the next 20-year, global temperature is expected to reach or exceed 1.5°C of warming. For 1.5°C of global warming, there will be increasing heat waves, longer warm seasons and shorter cold seasons. At 2°C of global warming, heat extremes would more often reach critical tolerance thresholds for agriculture and health. Diverging effects of rising GHGs concentrations are: a) direct effects of climate change, b) indirect effects of climate change, and c) non-climatic impacts related to GHG emissions (Gornall *et al*., 2010). Direct effects include change in mean climate (higher temperatures, changing precipitation patterns) and increased climate variability and extremes (extreme temperatures and heat waves, drought, heavy rainfall and flooding, tropical or heavy storms). Indirect effects of climate change are change in water availability, change in length of growing season, climate induced high runoff and soil erosion, mean sea level rise and changed scenario of pests and diseases. The non-climate impacts related to GHG emissions are CO2 fertilization and effects of ozone on vegetation.

As climate is the primary determinant of agricultural productivity, agricultural production is most sensitive and vulnerable to climate change (Watson *et al*., 1996). With climate change in future, the productivity of crops, especially in the tropical regions, may be adversely affected thus threatening food security in these regions; while in some high latitude regions it may improve crop growth conditions for higher productivity. Agriculture is also contributing about one-third to total GHG emissions, mainly through livestock, rice production, nitrogen fertilization and tropical deforestation (Lotze-Campen, 2011). In developing countries about 70% of population lives in rural areas, where agriculture is the largest supporter of livelihoods. Most developing countries are located in the lower latitudes (tropical arid and semi-arid regions), which are

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already characterized by highly volatile climatic conditions. They will be strongly affected by climate impacts, and they have lower adaptive capacity. In many developing countries the economy is heavily depending on agriculture. The sector accounts for 28% of gross domestic product (GDP) in South Asia. However, in future, agriculture will have to compete for scarce land and water resources with growing urban areas and industrial production (Lotze-Campen, 2011). Non-climatic stresses such as population, poverty, unequal access to resources etc., increase vulnerability to climate change by reducing the adaptive capacity of the system. Creating more options for adapting to climate change and improving the adaptive capacity in the agricultural sector will be crucial for improving food security and preventing an increase in global inequality in living standards in the future (Lotze-Campen, 2011).

This paper is focused on the processes and impacts of projected climate change on crop production, regional and seasonal differences in climate change in South Asia, especially India, review of possible adaptation options at farm level, and use of crop models to evaluate adaptation measures that will most likely help in coping up with climate change with examples from India and elsewhere in developing countries.

HOW DOES CLIMATE CHANGE IMPACT CROP PRODUCTION?

High temperatures

High temperatures affect growth and development of crops, thus influencing potential yields. High temperatures drive shorter life cycles, resulting in less seasonal photosynthesis, shorter reproductive phase, and thus lower yield. In photoperiod-responsive plants, the timing of the reproductive stages is determined by an interactive response to temperature and photoperiod. Temperatures above the optimal range during reproductive stages have impacts beyond shortening of grain-filling duration. High-temperature stress has been shown to affect both pollen production and pollen viability. However, it is the pollen viability above the optimum temperature that affects the quantity and quality of yield via a range of mechanisms (Hedhly *et al.*, 2008). Within a permissive range, warming temperatures accelerate both the rate of pollen tube growth as well as stigma and ovule development, thus maintaining the male-female synchrony necessary for successful seed set. However, under high-temperature stress, this synchrony can be lost, leading to lower fertility and yield reduction (Hedhly *et al.*, 2008). Different crops show different sensitivities to warming. By fitting statistical relationships between growing season temperature, precipitation and global average yield for six major crops, Lobell and Field (2007) estimated that warming since 1981 has resulted in annual combined losses of 40 million tons or US$5 billion.

Extreme temperatures and heat waves

Meteorological records and future projections suggest that heat waves became more frequent over the twentieth century (IPCC, 2013). Changes in short-term temperature extremes can be critical, especially if they coincide with key stages of crop development. Only a few days of extreme temperature (greater than 32^{o}C) at the flowering stage of many crops can drastically reduce yield (Wheeler *et al*., 2000). Reviews of the literature (Porter and Gawith, 1999; Wheeler *et al.*, 2000) suggest that temperature thresholds are well defined and highly conserved between species, especially for processes such as anthesis and grain filling. Although groundnut is grown in semi-arid regions which regularly experience temperatures of 40^{o}C, if after flowering the plants are exposed to temperatures exceeding 42^{o}C, even for short periods, yield can be drastically reduced (Vara Prasad *et al*., 2003). Similarly, Increases in temperature above 29 ^{o}C for corn, 30 ^{o}C for soyabean and 32 ^{o}C for cotton negatively impacted the yields in the USA (Gornall *et al*., 2010).

Changes in precipitation

Water is vital to plant growth, so varying precipitation patterns have a significant impact on agriculture. As over 80 per cent of total agriculture is rain-fed, projections of future precipitation changes often influence the magnitude and direction of climate impacts on crop production (Tubiello *et al.,* 2002; Reilly *et al*., 2003). Precipitation is not the only influence on water availability. Increasing evaporative demand owing to rising temperatures and longer growing seasons at high latitudes could increase crop irrigation requirements globally by between 5 and 20 per cent, or possibly more, by the 2070s or 2080s, but with large regional variations. South-East Asian irrigation requirements could increase by 15 per cent (Döll, 2002).

Increased frequency of drought

Globally, the areas sown for the major crops of barley, maize, rice, sorghum, soyabean and wheat have all seen an increase in the percentage of area affected by drought (IPCC, 2007). Li *et al*. (2009) defined a yield reduction rate (YRR) for a crop as the ratio of actual reduced yield due to climate variability to the long-term trend yield. Using national-scale data for the four major grains (barley, maize, rice and wheat), Li *et al.* (2009) suggested that 60–75% of observed YRRs can be explained by a linear relationship between YRR and a drought risk index based on the Palmer Drought Severity Index (Palmer, 1965). By assuming the linear relationship between the drought risk index and YRR holds into the future, Li *et al*. (2009) estimated that drought related yield reductions would increase by more than 50 per cent by 2050 and almost 90% by 2100 for the major crops.

Heavy rainfall and flooding

Heavy rainfall events leading to flooding can wipe out entire crops over wide areas, and excess water can also lead to other impacts including soil water logging, anaerobic conditions and reduced plant growth and grain quality. Indirect impacts include delayed farming operations. The proportion of total rain falling in heavy rainfall events appears to be increasing, and this trend is expected to continue as the climate continues to warm. Using daily rainfall data from 1951 to 2000, Goswami *et al.* (2006) also showed significant rising trend in the frequency and magnitude of extreme rainfall events over central India during the monsoon season, suggesting enhanced risks associated with extreme rainfall over India in the coming decades.

Tropical or heavy storms

Tropical cyclone frequency is likely to decrease or remain unchanged over the 21st century, while intensity (i.e. maximum wind speed and rainfall rates) is likely to increase (IPCC, 2013). Both societal and economic implications of tropical cyclones can be high, particularly in developing countries with high population growth rates in vulnerable tropical and subtropical regions.

Heavy rains, droughts and high temperatures also cause high runoff and soil erosion and loss of nutrients from the soils. Nutrient conservation is affected by warmer temperatures because high temperatures are likely to increase natural decomposition of organic matter because of a stimulation of microbial activity. If mineralization exceeds uptake, nutrient leaching will be the consequence (Niklaus, 2007). Increased frequency of droughts further intensifies erosive losses as plant biomass and its positive effects on soils are reduced (Nearing *et al*., 2004; Niklaus, 2007).

Change in length of growing season

Length of growing season (LGP) at any location is an important indicator of the yield potential of that location and determines the suitability of contrasting management practices and maturity length of crop types and cultivars. Based on the global analysis of LGP with and without climate change, Cooper *et al.* (2009) estimated that the net semi-arid tropical area (SAT) would increase with climate change. They also expected that the greater the aridity and warming in the climate change scenarios, more pronounced is the impact on changes in the distribution of the SAT. The changes in the distribution of SAT will affect many millions of families world-wide who rely on rainfed agriculture for their livelihoods. This will have major effect on the current farming systems of the SAT region in future with climate change. In a similar study Kesava Rao *et al.* (2013) estimated 3.45 million hectare increase in SAT area in India with climate change from 1971-90 to 1991-2004.

Pests and diseases

Temperature rise and elevated CO2 concentration could increase plant damage from pests in future decades, although only a few quantitative analyses exist to date (Easterling *et al.,* 2007; Ziska and Runion, 2007). Pests such as aphids (Newman, 2004) and weevil larvae (Staley and Johnson, 2008), respond positively to elevated CO2. Increased temperatures also reduced the overwintering mortality of aphids enabling earlier and potentially more wide-spread dispersion (Zhou *et al*., 1995). Pathogens and disease may also be affected by a changing climate. This may be through impacts of warming or drought on the resistance of crops to specific diseases and through the increased pathogenicity of organisms by mutation induced by environmental stress (Gregory *et al.,* 2009). Over the next 10–20 years, disease affecting oilseed rape could increase in severity within its existing range as well as spread to more northern regions where at present it is not observed (Evans *et al.,* 2008). Changes in climate variability may also be significant, affecting the predictability and amplitude of outbreaks (Gornall *et al.,* 2010).

Increase in atmospheric carbon dioxide

Increasing atmospheric carbon dioxide (CO2) concentrations can directly affect plant physiological processes of photosynthesis and transpiration (Field *et al.,* 1995). Experiments under idealized conditions show that a doubling of atmospheric CO2 concentration increases photosynthesis by 30–50% in C3 plant species and 10–25% in C4 species (Ainsworth and Long, 2005). Crop yield increase is lower than the photosynthetic response; increases of atmospheric CO2 to 550 ppm would on average increase C3 crop yields by 10–20% and C4 crop yields by 0–10% (Long *et al*., 2004; Ainsworth and Long, 2005). Despite the potential positive effects on yield quantities, elevated CO2 may, however, be detrimental to yield quality of certain crops. For example, elevated CO2 is detrimental to wheat flour quality through reductions in protein content (Sinclair *et al.,* 2000). In fact without CO2 fertilization all global regions are projected to experience a loss in productivity owing to climate change by 2050 (Parry *et al.,* 2004; Nelson *et al*., 2009). However, estimates suggest that stabilizing CO2 concentrations at 550 ppm would significantly reduce production losses by the end of the century (Arnell et al., 2002; Tubiello and Fisher, 2006). For all species higher water-use efficiencies and greater root densities under elevated CO2 in field systems may, in some cases, alleviate drought pressures, yet their large-scale implications are not well understood (Wullschleger *et al*., 2002; Centritto, 2005). This could offset some of the expected warming-induced increase in evaporative demand, thus easing the pressure for more irrigation water (Gornall *et al.,* 2010).

Ozone

Ozone is a major secondary air-pollutant, which at current concentrations has been shown to have significant negative impacts on crop yields (Van Dingenen *et al.,* 2009). Higher ozone concentration reduces photosynthetic rates and other important physiological functions, which in turn reduces on final yield and yield quality (Mills *et al.,* 2009; Ainsworth and McGrath, 2010). The interactive effects of ozone with other environmental factors such as CO2, temperature, moisture and light, are important but not well understood.

REGIONAL AND SEASONAL DIFFERENCES IN CLIMATE CHANGE

Warming is observed over the entire globe, but with significant regional and seasonal variations. In Asia, warming is likely to be well above the global mean in eastern Asia and South Asia, and similar to the global mean in Southeast Asia. Precipitation in winter is likely to increase in eastern Asia and the southern parts of Southeast Asia. Precipitation in summer is likely to increase in East Asia, South Asia and most of Southeast Asia. It is very likely that heat waves/hot spells in summer will be of longer duration, more intense and more frequent in East Asia. Fewer very cold days are very likely in East Asia and South Asia. There is very likely to be an increase in the frequency of intense precipitation events in parts of South Asia, and in East Asia. Extreme rainfall and winds associated with tropical cyclones are likely to increase in East Asia, Southeast Asia and South Asia.

Table 1: Regional MMD-A1B model projections for climate change in Asia by the end of the 21st century. The data presented are annual values of minimum, maximum, 25%, 50% (median), and 75% quartile values among the 21 models (IPCC, 2007).

	Temperature responses (°C)					Rainfall response (%)				
Region	Min	25%	50%	75%	Max	Min	25%	50%	75%	Max
East Asia	2.3	2.8	3.3	4.1	4.9	2	4	9	14	20
South Asia	2.0	2.7	3.3	3.6	4.7	-15	4	11	15	20
Southeast Asia	1.5	2.2	2.5	3.0	3.7	-2	3	7	8	15

In South Asia, the MMD-A1B model projections show a median increase of 3.3°C (Table 1) in annual mean temperature by the end of the 21st century. Studies based on earlier AOGCM simulations (Douville *et al*., 2000; Lal and Harasawa, 2001; Lal *et al*., 2001; Rupa Kumar and Ashrit, 2001; Ashrit *et al*., 2003; May, 2004) support this picture. Downscaled projections using the Hadley Centre Regional Model (HadRM2) indicate future increases in extreme daily maximum and minimum temperatures throughout South Asia due to the increase in greenhouse gas concentrations. This projected increase is of the order of 2°C to 4°C in the mid-21st century under the IPCC Scenario IS92a in both minimum and maximum temperatures (Krishna Kumar *et al.*, 2003).

Most of the MMD-A1B models project a decrease in precipitation in DJF (December, January and February-the dry season), and an increase during the rest of the year. The median change is 11% by the end of the 21st century (Table 1), and seasonally is –5% in DJF and 11% in JJA (June, July and August), with a large inter-model spread. This qualitative agreement on increasing precipitation for most of the year is also supported by the AOGCM simulations. The HadRM2 RCM shows an overall decrease by up to 15 days in the annual number of rainy days over a large part of South Asia, under the IS92a scenario in the 2050s, but with an increase in the precipitation intensity as well as extreme precipitation (Krishna Kumar *et al*., 2003).

Results from a more recent RCM, PRECIS, under scenarios of increasing greenhouse gas concentrations and sulphate aerosols indicate marked increase in both rainfall and temperature towards the end of the 21st century. The warming is monotonously widespread over the country, but there are substantial spatial differences in the projected rainfall changes. West central India shows maximum expected increase in rainfall. Extremes in maximum and minimum temperatures are also expected to increase into the future, but the night temperatures are increasing faster than the day temperatures, with the implication that cold extremes are very likely to be less severe in the future. Extreme precipitation shows substantial increases over a large area, and particularly over the west coast of India and west central India (Rupa Kumar *et al.,* 2006).

Based on regional HadRM2 simulations, Unnikrishnan *et al*. (2006) reported increases in the frequency as well as intensities of tropical cyclones in the 2050s under the IS92a scenario in the Bay of Bengal, which will cause more heavy precipitation in the surrounding coastal regions of South Asia, during both southwest and northeast monsoon seasons. Rao (2007) analyzed the rainfall data of 1140 meteorological stations in India, which showed a negative trend in rainfall among the stations situated in the southern states of India, southern peninsular areas, central India, and parts of the north and northeastern regions. Positive trends in rainfall were observed for Gujarat, Maharashtra, coastal Andhra Pradesh, and Odisha. However, the parts of the country covering eastern Uttar Pradesh, eastern Madhya Pradesh, the west coast, and greater parts of northwest India did not show any changes. Among the rainfed districts, 40% of the stations showed a negative trend, 48% showed a positive trend, and 12% showed no changes in rainfall.

Using the all-India mean surface air temperature for 1901–2000 from a network of 31 well-distributed, representative stations, the trends in mean annual temperatures across the country were determined by Rupa Kumar *et al*. (2002). Warming trends were observed during four seasons (winter, pre-monsoon, monsoon, and post-monsoon) with a higher rate of temperature increase during winter (0.04 C per decade)and post-monsoon seasons (0.05 C per decade) compared with the pre-monsoon (0.02 C per decade) and monsoon seasons (0.01 C per decade). The warming across the Indian subcontinent was mainly contributed by the post-monsoon and winter seasons. The monsoon temperatures did not show a significant trend in most parts of India, except for a significant negative trend across northwest India (De and Mukhopadhyay, 1998). The diurnal temperature range has also decreased, with nighttime temperature increasing at twice the rate of the daytime maximum temperature (Sen Roy and Balling, 2005). Prabhjyot-Kaur and Hundal (2010) reported gradual increases in minimum temperature across a recent 30-year period, however, the maximum temperature showed no significant trend at most locations in the state. Similarly, annual rainfall either decreased/increased or had no significant trend in its variability at various sites in Punjab. Because of the large spatial and temporal variability in weather factors in a region, the availability of more detailed scenarios for different agro-climatic zones is desirable.

CROP SIMULATION MODELS

Plant growth simulation models which integrate various physical and physiological processes of plant growth and development can be used to assess growth and yield of different crop cultivars in different environments by using environment-specific weather, soil and agronomic management data (Boote *et al.*, 2001, Boote *et al.*, 2003). The major components of the crop models are vegetative and reproductive development, carbon balance, water balance and nitrogen balance. The crop growth and development is simulated using a daily time step from sowing to maturity and ultimately predicts yield. Genotypic differences in growth, development and yield of crop cultivars are affected through genetic coefficients (cultivar-specific parameters) that are input to the model in addition to the crop-specific coefficients that are considered less changeable or more conservative in nature across crop cultivars. The physiological processes that are simulated describe crop response to major weather factors, including temperature, precipitation and solar radiation and include the effect of soil characteristics on water availability for crop growth. In the model, high temperature influences growth and development and reduces allocation of assimilates to the reproductive organs through decreased pod/seed set and pod/seed growth rate. Changes in rainfall characteristics influence soil water balance and thus the pattern of water availability to the crop during its life cycle. Increased CO2 concentrations in the atmosphere increase crop growth through increased radiation use efficiency (RUE) or increased leaf-level photosynthesis, which responds to CO2 concentration using simplified rubisco kinetics similar to Farquhar and von Caemmerer (1982). Increased CO2 concentration reduces transpiration from the crop canopy via an empirical relationship between canopy conductance and CO2 concentration. Thus crop models have the potential to simulate crop growth and development under climate change conditions, such as high air temperatures, variability in rainfall and increased CO2 concentrations in the atmosphere, and their interaction with genetic traits of the crop that ultimately result in final crop yields at maturity. The crop models need to be linked to the improved pest, disease and weed models to analyze and predict yield losses, including those due to climate change is still a challenge for the scientific community. Key research questions not only involve the assessment of the potential effects of climate change on known pathosystems, but also on new pathogens which could alter the impacts of pests and diseases on agricultural systems. The simulation models also need to incorporate the impact of extreme weather events on crop production that is projected to increase with climate change.

The minimum data set required to simulate a crop for a site are described by Jones *et al*. (2003). Briefly, it includes site characteristics (latitude and elevation), daily weather data (solar radiation, maximum and minimum air temperatures and precipitation), basic soil profile characteristics by layer (saturation limit, drained upper limit and lower limit of water availability, bulk density, organic carbon, pH, root growth factor, runoff and drainage coefficients) and management data (cultivar, sowing date, plant population, row spacing, sowing depth and dates and amounts of irrigation and fertilizers applied). The cultivar data include the genetic coefficients or the cultivar-specific parameters (quantified traits) which distinguish one cultivar from the other in terms of crop development, growth and partitioning to vegetative and reproductive organs and seed quality (Boote *et al*., 2001).

IMPACT ON TROPICAL CROPS

Long-term impacts of climate change on agricultural productivity are not expected to be geographically uniform. While small increase in yields and production could occur with climate change in certain high latitude locations, there is serious threat to crop productivity in the tropical regions that are already food insecure. Some of these regions are South Asia or Sub-Saharan Africa where most of the population increase will take place in future (Sultan, 2012). For example, it is estimated that by 2050 food needs will more than double in Asia and more than quintuple in Africa (Collomb, 1999). Therefore, the potential impact of climate change on crop productivity is an additional strain on the global food system which is already facing the difficult challenge of increasing food production to feed a projected 9 billion people by 2050 with changing consumption patterns and growing scarcity of water and land (Beddington, 2010).

Better knowledge of climate change impacts on crop productivity in the vulnerable regions is crucial to support adaptation strategies and inform policies and that may counteract the adverse effects (Sultan, 2012). There have been several studies in the past in Asia and Africa to assess the impact of climate change on crop production. Most of the studies have been conducted on major food crops like rice, wheat and maize with much less work on the rainfed crops like sorghum, millets, groundnut and other grain legumes of the semi-arid tropics. Lobell *et al.* (2008) estimated the probability distribution of percent yield change among major crops across most of Africa and South and South East Asia compared with the baseline (1980-2000) and projections for 2020-2040, assuming an increase of 1^{o}C in temperature between 1980-2000 and 2020-2040 across most regions. They predicted significant negative impacts of climate change on food security that could occur as early as 2030 for several crops in these regions. Although there is a growing literature on the impact of climate change on crop productivity in tropical regions, it is difficult to provide a consistent assessment of future yield changes because of large uncertainties in regional climate change projections, in the response of crops to environmental change (rainfall, temperature, CO2 concentration), in the coupling between climate models and crop productivity functions, and in the adaptation of agricultural systems to progressive climate change (Roudier *et al.*, 2011; Challinor *et al.*, 2007). A rigorous multi-ensembles approach, with varying climate models, emissions scenarios, crop models, and downscaling techniques, as recommended by Challinor *et al.*, (2007), would enable a move towards a more complete sampling of uncertainty in crop yield projections. In that sense, coordinated modeling experiments such as the ones conducted throughout the Agricultural Model Inter-comparison and Improvement Project (AgMIP; www.agmip.org/) are likely to improve substantially the characterization of the threat of crop yield losses and food insecurity due to climate change (Sultan, 2012). A study by Knox *et al.* (2012) is among the first to provide robust evidence of how climate change will impact productivity of major crops in South Asia and Africa. The analysis was conducted for eight food and commodity crops (rice, wheat, maize, sorghum, millet, cassava, yam and sugarcane) which collectively account for over 80% of total crop production in Africa and South Asia (FAO, 2010). Using a meta-analysis of different independent published studies, Knox *et al.* (2012) show a consistent yield loss by the 2050s of major crops (wheat, maize, sorghum and millet) in both regions. They estimate that mean yield change for all crops is -8% by the 2050s with strong variations among crops and regions. Across Africa, mean yield changes of -17% (wheat), -5% (maize), -15% (sorghum) and -10% (millet) and across South Asia of -16% (maize) and -11% (sorghum) were estimated. No mean change in yield was detected for rice. Evidence of crop yield impact in Africa and South Asia was robust for wheat, maize, sorghum and millet, and either inconclusive, absent or contradictory for rice, cassava and sugarcane. Such robust evidence of future yield change in Africa and South Asia can be surprising in regards to the diverging projections in a warmer climate of summer monsoon rainfall, the primary driver for rainfed crop productivity in the region, especially in West Africa where some studies make projections of wetter conditions and some predict more frequent droughts (Druyan, 2011). This is because of the adverse role of higher temperatures in shortening the crop cycle duration and increasing evapotranspiration demand and thus reducing crop yields, irrespective of rainfall changes (Berg *et al*., 2012; Roudier *et al*., 2011; Schlenker and Lobell, 2010). Potential wetter conditions or elevated CO2 concentrations hardly counteract the adverse effect of higher temperatures (Sultan, 2012). In spite of the threat of crop yield losses in a warmer climate, developing countries in the tropics have the potential to more than offset such adverse impacts by implementing more intensive agricultural practices and adapting agriculture to climate and environmental change (Berg *et al.,* 2012). Indeed Africa and in a lesser extend South Asia are among the only regions of the world where there is an untapped potential for raising agricultural productivity since poor soil fertility and low input levels, combined with extensive agricultural practices, contributed to a large gap between actual and potential yields (Licker *et al.,* 2010; Sultan, 2012).

ADAPTATION MEASURES

The pervasiveness of climate impacts on food security and production means that some level of adaptation of food systems to climate change will be necessary. Adaptation response can be autonomous or planned. Autonomous adaptations are those that take place without the directed intervention of a public agency and assuming efficient markets (Smit and Pilisova, 2001). According to Howden *et al*., (2010), autonomous adaptations are incremental changes in the existing system including the ongoing implementation of extant knowledge and technology in response to the changes in climate experienced. They include coping responses and are reactive in nature. Planned or policy driven adaptation is the result of a deliberate policy decision by public agency based on an awareness that conditions are about to change or have changed and that action is required to minimize the losses or benefit from opportunities (Pittock and Jones, 2000). Planned adaptations are proactive and can either adjust the broader system or transform it. Adaptations can occur at a range of scales from field to policy. There is an increasing recognition in the literature that whilst many adaptation actions are local and build on past climate risk management experience, effective adaptation will often require changes in institutional arrangements and policies to strengthen the conditions favorable for effective adaptation including investment in new technologies, infrastructure, information and engagement processes.

Adaptation strategies often contain both social and technical elements that sometimes act independent of each other and at other times interact. Among social adaptation strategies are maximization of family labor use, including generating remittances by temporary or permanent migration; diversification into nonagricultural enterprise; development of social protection and employment schemes; crop and livestock insurance; and realization of collective action and community-based empowerment effort. Resilience, in the context of social elements mentioned above, is strongly associated with diversification of income-generating opportunities that reduce exposure to livelihood shocks from climatic and non-climatic factors. In this review we have primarily focused on the field level adaptation measures, although other types of adaptation measures are also important to the farming community to adapt to the climate change. Field level adaptation measures include agronomic, land and water management and genetic improvement measures to enhance and sustain crop yields under climate change conditions.

Agronomic measures

Changing planting dates is a frequently identified as an option for cereals and oilseeds provided there is not an increase in drought at the end of the growing season. This may be necessitated owing to high temperatures and/or low rainfall with climate change during early part of the growing season in the semi-arid areas or the possibility of extended growing seasons because of higher temperatures increasing growth in cooler months (Travasso *et al.,* 2009; Tingem and Rivington, 2009; Laux *et al.,* 2010; Van de Geisen *et al*., 2010; Tao and Zhang, 2010). Aggregated across studies, changing planting dates may increase yields by a median of 3-17% but with substantial variation. Optimization of crop varieties and planting schedules appears to be effective adaptations, increasing yields by up to 23% compared with current management when aggregated across studies. This flexibility in planting dates and varieties according to seasonal conditions could be increasingly important with ongoing climate change (Deressa *et al*., 2009) and especially in dealing with projections of increased climate variability. Changing plant population and nutrient management; crop substitution to less water intensive crops in response to changes in rainfall and LGP, increased rainfall variability and drought (Howden *et al*., 2007); site-specific cropping systems and patterns and their management (Butt *et al.*,2005); and greater diversity of crops and cultivars in response to increases in rainfall variability, drought, soil salinity or water logging, and increased severity of pests and diseases (Cooper *et al*.,2009; Ebi *et al*., 2011; Butt *et al*., 2005) could also optimize crop yields and farmer's income. Integrated pest, disease and weed management in response to increased severity of pests and diseases (Aggarwal, 2008; Howden *et al*., 2007); shelter belts for microclimate modification (Aggarwal, 2008) and climate forecasts also help to reduce production risks (Howden *et al.*, 2007; Cooper *et al*., 2009; Baethgen, 2010) under variable and changing climate.

Diversification of activities is another climate adaptation option for cropping systems (Lioubimtseva and Henebry, 2009; Thornton *et al*., 2010). Diversification of activities often incorporates higher value activities or those that increase efficiency of a limited resource such as through increased water use efficiency (Thomas, 2008) or to reduce risk (Seo, 2010). In some cases, increased diversification outside of agriculture may be favored (Mary and Majule, 2009; Mertz *et al.*, 2009). The above adaptations, either singly or in combination, could significantly reduce negative impacts of climate change or take advantage of positive changes.

Land and water management measures

Soil and water conservation measures and prevention of water logging (Aggarwal, 2008; Howden *et al*., 2007; Thomas, 2008); Cooper *et al.*, 2009; Ebi *et al*., 2011); more effective water harvesting, improved irrigation technologies and judicious use of water such as drip and deficit irrigation (Aggarwal, 2008; Howden *et al.*, 2007; Deryng *et al*., 2011; Thomas, 2008); conservation agriculture such as application of surface crop residues, minimum tillage, no till, crop rotations and agro-forestry (Ebi *et al*., 2011; Lioubimtseva and Henebry 2009) that increase soil carbon are amongst many other possible adaptations. Crop adaptations can lead to moderate yield benefits (mean of 10 to 20%) under persistently drier conditions (Deryng *et al.,* 2011) and that irrigation optimization for changed climate can increase yields by a median of 3.2% as well as having a range of other beneficial effects.

Genetic measures

Major effect of increase in GHGs in the atmosphere is the increase in ambient temperature that would result in increase or decrease in rainfall and its variability especially in the semi-arid tropical areas. Rise in sea level and increased evaporation will cause increase in soil salinity especially in the coastal areas. As the length of growing season would change due to change in rainfall and temperature, the different agricultural regions would require either short or longer duration cultivar (Aggarwal, 2008; Howden *et al*., 2007; Thomas, 2008) Improving cultivar tolerance to high temperature is a frequently identified adaptation for almost all crops and environments worldwide as high temperatures are known to reduce both yield and quality (Challinor *et al.,* 2007, 2009; Butt *et al.* 2005; Ebi *et al*. 2011; Luo *et al.,* 2009). Similarly, the prospect of increasing drought and salinity conditions in many cropping regions of the world raises the need for breeding additional drought-tolerant (Mutekwa, 2009; Tao and Zhang, 2011) and salinity tolerant cultivars (Reddy *et al*., 2010.).

Noting that a new cultivar usually takes between eight and 20 years to deliver and so it is important to be selecting cultivars for expected future climate and atmospheric conditions (Ziska *et al.*, 2012). Improving gene conservation and access to extensive gene banks could facilitate the development of cultivars with appropriate thermal time and thermal tolerance characteristics (Mercer *et al*., 2008) as well as to take advantage of increasing atmospheric CO2 concentrations (Ziska *et al.*, 2012) and respond to changing pest, disease and weed threats with these developments needing to be integrated with *in situ* conservation of local varieties (IAASTD, 2009).

Some autonomous adaptations, such as shifting planting dates, modifying crop rotations or the uptake of pre-existing crop varieties will help offset some negative impacts of climate change. However, it is reported that the greatest benefits in food insecure regions are likely to arise from more expensive adaptation measures including the development of new crop varieties and uptake of new technologies including, for example, the expansion of irrigation infrastructure (Lobell *et al.*, 2008). These will require substantial investments by farmers, governments and development agencies. It is thus vital that any policy decisions to support their implementation, particularly aid investments, are informed by a synthesis of the best available evidence, and not distorted by single studies. Prioritization of farm level adaptations to climate change will also need to account for the different crops grown within a target region, local farmer attitudes to risk and the time horizons over which investments are made (Lobell *et al.*, 2008).

To quantify the benefits of adaptation, a meta-analysis of crop adaptation studies has been undertaken for wheat, rice and maize (IPPC, 2013, Working Group II, AR5, Chapter 7). The analysis indicated that the average benefit (the yield difference between the adapted and non-adapted cases) of adapting crop management is equivalent to about 15 to 18% of current yields. This response is, however, extremely variable, ranging from negligible benefit from adaptation to very substantial. The responses are dissimilar between wheat, maize and rice with temperate wheat and tropical rice showing greater benefits of adaptation. The responses also differ markedly between adaptation management options. For example, when aggregated over studies, cultivar adaptation (23%) and altering planting date in combination with other adaptations (3 to 17%) provide on average more benefit than optimizing irrigation (3.2%) or fertilization (1%) to the new climatic conditions. These limits to yield improvements from agronomic adaptation and the increasingly overall negative crop yield impact with ongoing climate change mean a substantial challenge in ensuring increases in crop production of 14% per decade given a population of nine billion people in 2050. This could be especially so for tropical wheat and maize where impacts from increases in temperature of more than 3^{o}C may more than offset benefits from agronomic adaptations. Indigenous knowledge is an important resource in climate risk management and is important for food security in many parts of the world. Climate changes may be reducing reliance on indigenous knowledge in some locations but also some policies and regulation may be limiting the contribution that indigenous knowledge can make to effective climate adaptation. Forthcoming studies should examine the impact of proposed adaptations when employed in the current climate. In this way management changes that are beneficial in a range of environments can be separated from management changes that are specifically targeted at climate change.

EVALUATING ADAPTATION OPTIONDS USING CROP MODELS

The semi-arid tropics of the world have varied agro-climatic conditions in terms of soils and climate. Although temperature in projected to increase in all the production environments, the direction and magnitude of changes in rainfall will vary from region to region. Thus in future the impact of climate change on the productivity of the production systems will vary from region to region and would require different adaptation strategies to cope up with climate change. The strategies at the farm level would include different agronomic, land and water management and genetic improvement measures for the small holder farmers to adopt. Before these measures are successfully adopted by the farmers, these must be evaluated for their potential contribution to enhance yields and farmer’s income. Crop simulation models that are sensitive to climate change factors and natural resources management provide this opportunity to meet these objectives.

Here some examples are given of evaluating various agronomic, land and water management and genetic improvement technologies in terms of their contribution to enhance crop yields under both current and future climates of the selected sites mostly in South Asia and Africa, just to highlight that a number of technologies must be evaluated and prioritized before they are recommended for adoption at any site.

Sorghum

Mohammed and Misganaw (2022) used CERES-sorghum model to evaluate the impact of climate change on sorghum production and to identify best crop management strategies that can sustain sorghum production in semi-arid Amhara Region of Ethiopia. The result of impact analysis showed that sorghum grain yields were adversely affected by 2030s and 2050s under both RCP4.5 and RCP8.5 scenarios. However, the result of management scenarios showed that sorghum yield may be substantially increased through use of optimum nitrogen fertilizer, application of supplemental irrigation and by early sowing, individually or in combination.

Maize

Tao and Zhang (2010) applied a super-ensemble-based probabilistic projection system (SuperEPPS) to project maize productivity during 2050s in the North China Plain to examine the relative contributions of adaptation options. Based on a large number of simulation outputs from the super-ensemble-based projection, the results showed that without adaptation maize yield could decrease on average by 13.2–19.1% during 2050s, relative to 1961–1990. In comparison with the experiment without adaptation, using high-temperature sensitive varieties, maize yield could on average increase by 1.0–6.0%, 9.9–15.2%, and 4.1–5.6%, by adopting adaptation options of early planting, fixing variety growing duration, and late planting, respectively. In contrast, using high-temperature tolerant varieties, maize yield could on average increase by −2.4% to −1.4%, 34.7–45.6%, and 5.7–6.1%, respectively. They concluded that biggest benefits will result from the development of new crop varieties that are high-temperature tolerant and have high thermal requirements. They also showed that, depending on the climate and variety, the spatial patterns of relative contributions of adaptation options can be geographically quite different.

Gummadi *et al.* (2020) simulated adaptation strategies to offset potential impacts of climate variability and change on maize yields in five different agro-ecological zones (AEZs) of Embu County, Kenya, using projections by 20 CMIP5 (Coupled Model Inter-comparison Project—Phase 5) climate models under RCP4.5 and RCP8.5. Two widely used crop simulation models - APSIM (Agricultural Production Systems Simulator) and DSSAT (Decision Support System for Agro-technology Transfer) - were used to simulate the potential impacts of climate change on maize yield. Among the management practices, impacts of cultivar, soil fertility and plant population were found to be quite important. Under climate change, yields increased with increasing plant population in all AEZs. Soil fertility management also contributed significantly to the productivity of maize. Highest increase in yield was observed in fertile soils with high organic carbon content under low doses of fertilizer application. Similar increase in sorghum yields under low input systems was also reported by Turner and Rao (2013). This was attributed to the greater availability of nitrogen with increased mineralization under warmer and wetter future climatic conditions.

Rice

Khaliq *et al.* (2020) using APSIM-ORYZA model assessed the climate change impacts and adaptation strategies for rice production in Punjab, Pakistan. Climate change scenarios were developed for selected locations through statistical downscaling by selecting five general circulation models under RCP8.5 for mid-century (2039-2069).The impact of climate change was studied by calculating the difference of baseline (1980-2010) and future yield. Model simulated results indicated that the rise in temperature will reduce the rice yield by 7.3%. To overcome this decrease in rice yield, suitable adaptation strategies were tested for mid-century. The developed adaptations, i.e., increased in plant population, nitrogen amount, and early transplanting, improved the rice yield by 8.7% under RCP8.5 for mid-century scenarios. Overall, this study provided better understanding of the adaptation processes for sustainable rice yield under anticipated future climate change.

Debnath *et al.* (2021) evaluated the effectiveness of agronomic adaptation options on the rainfed rice yield gap for the baseline period (1981–2005) and two future periods (2016–2040 and 2026–2050) for India using bias-corrected RegCM4 output and the Decision Support System for Agro-technology Transfer (DSSAT) model. Results suggested that a combined adjustment of transplanting time (advancing by fortnight), crop spacing (10 x 10 cm) and N-fertilizer application (140 kg/ha) was the best strategy as compared to the single adaptation option to close the yield gap under the climate change scenario. The strategy improved rice yield by 37.5–168.0% and reduced the average attainable yield gap among the cultivars from 0.74 to 0.16 t/ha under future climate projection. This study provided agronomic indications to rice growers and laid the basis for an economic analysis to support policy-makers in charge of promoting the sustainability of the rainfed rice-growing systems.

Groundnut

Singh *et al.* (2014d) used the CROPGRO-Groundnut model to assess the potential of various agronomic technologies for adapting groundnut to climate change by 2050 at two sites in Andhra Pradesh (Anantapur and Mahbhoobnagar) and one site in Gujarat (Junagadh), where groundnut is predominantly grown by farmers in India. They first evaluated the effect of sowing date on the productivity of groundnut and later evaluated its combined effect with other agronomic management practices. At Anantapur the maximum yield increase was simulated with supplemental irrigation, followed by delay in sowing and growing a longer maturity variety. At Mahboobnagar, the maximum yield gain was with delayed sowing, followed by growing a longer maturity variety, supplemental irrigation and application of crop residues. At Junagadh, the yield increase was the maximum with normal sowing date, followed by supplemental irrigation and application of crop residues. Thus the relative contribution of agronomic practices to increase groundnut yield under climate change varied with the region.

Kadiyala *et al* (2015) analyzed the spatial variability of climate change impacts on groundnut yields in the Anantapur district of India. The climate change projections of five GCMs (MPI-ESM-MR, MIROC5, CCSM4, HadGEM2-ES and GFDL-ESM2M) relative to the 1980–2010 baseline for Anantapur district indicated an increase in rainfall activity to the tune of 10.6 to 25% and warming exceeding 1.4 to 2.4 °C during Mid-century period

(2040–69) with RCP8.5. The spatial crop responses to the projected climate indicated a decrease in groundnut yields with all GCMs, except the GFDL-ESM2M where a contrasting 6.3% increase in yield was observed. Simulations using CROPGRO-Peanut model revealed that groundnut yields can be increased on average by 1.0%, 5.0%, 14.4%, and 20.2%, by adopting heat tolerant cultivar, drought tolerant cultivar, supplemental irrigation and a combination of drought tolerance cultivar and supplemental irrigation, respectively. The spatial patterns of relative benefits of adaptation options were geographically different and the greatest benefits could be achieved by adopting new cultivars having drought tolerance and with one supplemental irrigation at 60 days after sowing.

Chickpea

Mohammed *et al*. (2017) used the CROPGRO-chickpea model to assess the impacts of projected climate change on grain yield of chickpea by 2030s (2020–2049) and 2050s (2040–2069) periods under all the RCPs with and without CO2 fertilization to identify crop management options that increase productivity of the crop. Different varieties of chickpea, supplemental irrigation and change in planting dates were been evaluated. The result of climate change impact analysis on chickpea showed that grain yield is predicted to significantly increase both by 2030s and 2050s under CO2 fertilization across all the RCPs as compared to baseline grain yield (1961–1990). However, simulation without CO2 showed that grain yield will not significantly increase by 2030s and 2050s across all the scenarios. Based on the prediction result it can be generalized that chickpea will be benefited from the projected climate changes in northeastern Ethiopia. Two supplemental irrigations (flower initiation and pod setting stages) and early sowing significantly ($P < 0.05$) increased grain yield of chickpea in northeastern Ethiopia under the present and future climate conditions. Selection of appropriate cultivars based on the agro-ecology of the area has paramount importance to increase chickpea productivity under the present and future climate condition.

Adapting cropping systems to ENSO phase

In southern India, the ENSO condition to some degree determines the potential of the ensuing rainy season in terms of amount of summer monsoon rainfall that is likely to be received in the region. Singh *et al.* (2008), using crop simulation models and long-term weather records (1961 to 2006), assessed the productivity and net income of three sequential and three intercrop systems for the three ENSO phases for Nandyal situated in the Kurnool district of Andhra Pradesh. The simulation analysis showed that during the La and Niña years groundnut-chickpea sequential, groundnut/pigeonpea and soybean/pigeonpea intercrop systems; while during the El Niño years maize/pigeonpea and groundnut/pigeonpea intercrop systems gave higher net income at low risk among the cropping systems studied. During Neutral years, groundnut/pigeonpea intercrop systems was the most promising in terms of net income. Thus the farmers can minimize climatic risks and maximize incomes by adapting the more efficient cropping systems to the ENSO condition of the ensuing seasons.

Genetic improvement

Singh *et al.* (2014a, 2014b, 2014c and 2017) evaluated the potential benefits of genetic improvement technologies (crop maturity duration, enhanced yield potential, drought and heat tolerance traits and their combinations) for sorghum, groundnut, chickpea and pearl millet for adapting to current and future climates by 2050 of the target sites in South Asia and Africa where these crops are predominantly grown. The approach used was virtual crop modeling using the current and future (projected) weather data of the sites along with soils and management data required to simulate crop yields.

For rainy season sorghum CERES-sorghum model was used. The selected sites were Akola and Indore in India and Samanko and Cinzana in Mali (Singh *et al*., 2014a). The commonly grown sorghum cultivars used in the simulation were CSV 15 at both Akola and Indore, CSM 335 at Samanko and CSM 63E at Cinzana. Decreasing crop life cycle duration of each cultivars by 10% decreased yields at the respective sites under both current and future climates. In contrast, increasing crop life cycle duration by 10% increased yields up to 10% at Akola, 9% at Indore, 7% at Samanko and 31% at Cinzana. Enhancing yield potential traits (radiation use efficiency, relative leaf size and partitioning of assimilates to the panicle each increased by 10%) in the longer cycle cultivars increased the yields by 11–26% at Akola, 18-23% at Indore, 10–11% at Samanko and 14–36% at Cinzana across virtual cultivars under current climates of the sites. The relative benefits due to yield potential traits were even larger under climate change. Except for the Samanko site, yield gains were larger by incorporating drought tolerance than heat tolerance under the current climate. However, under future climates of the sites the yield gains were higher by incorporating heat tolerance at Akola, Samanko and Cinzana, but not at Indore. Net benefits of incorporating both drought and heat tolerance increased yield up to 17% at Akola, 9% at Indore, 7% at Samanko and 15% at Cinzana under climate change.

For pearl millet the modified CSM-CERES-Pearl millet model was used for six locations in arid (Hisar, Jodhpur, Bikaner) and semi-arid (Jaipur, Aurangabad and Bijapur) tropical India and two locations in semi-arid tropical West Africa (Sadore in Niamey and Cinzana in Mali) (Singh *et al*., 2017). In all the study locations the yields decreased when crop maturity duration was decreased by 10% both in current and future climate conditions; however, 10% increase in crop maturity significantly ($p < 0.05$) increased yields at Aurangabad and Bijapur, but not at other locations. Increasing yield potential traits by 10% increased yields under both the climate situations in India and West Africa. Drought tolerance imparted the lowest yield gain at Aurangabad (6%), the highest at Sadore (30%) and intermediate at the other locations under current climate. Under climate change the contribution of drought tolerance to the yield of cultivars either increased or decreased depending upon changes in rainfall of the locations. Yield benefits of heat tolerance substantially increased under climate change at most locations, having the greatest effects at Bikaner (17%) in India and Sadore (13%) in West Africa. Aurangabad and Bijapur locations had no yield advantage from heat tolerance due to their low temperature regimes. Thus drought and heat tolerance in pearl millet increased yields under climate change in both the arid and semi-arid tropical climates with greater benefit in relatively hotter environments. This study will assists the plant breeders in evaluating new promising plant traits of pearl millet for adapting to climate change at the selected locations and other similar environments.

For groundnut the CROPGRO-peanut model was used and the selected sites were Anantapur and Jungadh in India, Samanko in Mali and Sadore in Niger (Singh *et al.*, 2014b). In case of groundnut, increasing crop maturity by 10 % increased yields up to 15 % at Anantapur, 23 % at Samanko and 7% at Sadore and sustained the yields at Junagadh under baseline climate, however, under climate change the yield benefits were somewhat less. Increasing yield potential of the crop by increasing leaf photosynthesis rate, partitioning to pods and seed-filling duration each by 10 % increased pod yield by 9 to 13 % under baseline climate and 11 to 14% under climate change relative to the baseline yields across the four sites. Under current climates of Anantapur, Junagadh and Sadore, the yield gains were larger by incorporating drought tolerance than heat tolerance. However, under climate change the relative contribution of heat tolerance increased for the three sites. Under climate change the yield gains from incorporating both drought and heat tolerance increased up to 13 % at Anantapur, 12 % at Junagadh and 31 % at Sadore. At the Samanko site, the yield gains from drought or heat tolerance were negligible. It was concluded from the above studies that different combinations of plant traits will be needed to increase and sustain productivity of sorghum, groundnut and chickpea in current and future climates at the target sites. However, the model findings of these studies need to be field tested before adoption by plant breeders or farmers.

For chickpea the CROPGRO-chickpea model was used and the selected sites in South Asia were Hisar, Indore and Nandhyal in India and Zaloke in Myanmar and for East Africa the sites were Debre Zeit in Ethiopia, Kabete in Kenya and Ukiriguru in Tanzania (Singh *et al*., 2014c). In case of chickpea, the crop response to life-cycle duration was variable across sites under baseline climate, however under climate change, the 10% shorter duration cultivars gave higher yield than the longer duration cultivars, except for Nandhyal and Zaloke. Drought tolerance is a priority trait for increasing yields at Indore and Zaloke; whereas at Nandhyal both heat tolerance and yield potential are the priority traits. At Zaloke and Debre Zeit, heat tolerance is not a priority trait under climate change as compared to drought tolerance or yield potential traits. At Ukiriguru adjusting the crop life cycle will be sufficient to increase the yield of chickpea; whereas at Kabete the use of baseline cultivar with some degree of drought tolerance will be required for higher yields. At Hisar, a short duration cultivar along with some degree of drought and heat tolerance and yield potential traits will be needed to increase yields under climate change.

Rosegrant *et al*. (2014) assessed the future scenarios of the potential impact and benefits of alternative agricultural technologies in terms of future yield and production growth, food security, demand and trade. To achieve these goals, they used the DSSAT crop models to simulate changes in yields for rice, maize, and wheat following the adoption of different technologies, agricultural practices, improved varieties, or a combination of these, compared to a business-as-usual baseline. Across the three crops, the largest yield gains, in percentage terms, are in Africa, South Asia, and parts of Latin America and the Caribbean. Their analysis found wide heterogeneity in yield response, making it important to target specific technologies to specific regions and countries. Heat-tolerant varieties, no-till, nitrogen-use efficiency, and precision agriculture are technologies with particularly great potential for yield improvement in large parts of the world. Moving these technologies forward will require institutional, policy, and investment advances in many areas.

In the Sub-Saharan Africa (SSA) region, among the three crops studied, maize is most important for SSA. The DSSAT results indicated that no-till was the most yield-increasing technology (30% yield boost for maize) for this region because of its soil-protection and water-enhancing properties under both climate change scenarios (Rosegrant *et al*., 2014). Although maize is largely rainfed in the region at this point, irrigation development is growing rapidly, and both maize and rice will increasingly benefit from irrigation. Improved nitrogen use efficiency (NUE) in maize and rice also showed largest benefits for SSA with more than 10 percent yield improvement by 2050 under rainfed conditions for both crops and up to 96 percent improvement for irrigated maize and a 50 percent yield increase for irrigated rice by 2050 under the CSIRO A1B scenario. This positive result again underlines the strong demand for enhanced nutrient—in particular, nitrogen—availability for cereal crops in the region. Integrated soil fertility management (ISFM) also showed large yield-enhancing benefits for maize in SSA compared to the DSSAT baseline scenario, with yields growing 21 percent under rainfed and 16 percent under irrigated conditions. High ISFM impacts are likely due to the low levels of nutrients available in African soils, generally considered the key yield constraints in this region. Moreover, drought tolerance showed major benefits in low rainfall environments of East Africa under the CSIRO A1B scenario (17 percent yield improvement) and still resulted in 7 percent improvement under the MIROC A1B scenario. Also, in higher-rainfall environments (rainfall greater than 500 mm per season), drought-tolerant crops do best in West and East Africa under both climate change scenarios. Crop protection for rainfed maize would have the largest ex ante yield impacts for SSA, with yield improvements in the range of 12–20 percent, depending on the cropping system and climate change scenario. For disease and insect control, only South Asia has similarly high yield benefits. Among the combined technologies assessed, SSA showed high beneficial yield impacts of combined no-till and heat-tolerant varieties, with ex ante yield increases of more than 40 percent for rainfed and more than 100 percent for irrigated conditions under both climate change scenarios.

Similar to SSA, yield gains in South Asia were particularly high for no-till for both wheat and maize; for ISFM for rice and wheat; for precision agriculture for wheat; drought tolerance for wheat across all rainfall regimes; and NUE across all three cereals (Rosegrant *et al.*, 2014). South Asia also displayed substantial benefits from advanced irrigation technologies for wheat, most likely due to the severe water shortages that the region already faces and that will be compounded as a result of climate change. Heat tolerance is another technology with high potential in South Asia, particularly for maize and wheat. Irrigated maize yields were 66 percent higher with heat tolerance, and irrigated wheat yields were 33 percent higher under the MIROC climate change scenario. Yield improvements were lower but still substantial under the CSIRO climate change scenario. Crop protection also resulted in higher yields ex ante, with largest benefits for maize through weed and insect control. In contrast, impacts for disease are roughly equally distributed across the three cereals, with yield improvements ranging from 1 to 33 percent. Given that South Asia's wheat yields are under particular threat of adverse climate change effects, a range of technologies can make major inroads in reducing these adverse effects for this key staple and breadbasket region.

The above described examples show that the potential of agro-technologies to increase crop yields vary from region to region under both current and future climates. These technologies must be evaluated and prioritized in terms of productivity enhancements, social and economic benefits to the rural populations at large before they are promoted for achieving food security under conditions of climate change in future.

SUMMARY

With climate change in future, the productivity of crops, especially in the tropical regions, will be adversely affected thus threatening food security in these regions. In South Asia, model projections show a median increase of 3.3°C in annual mean temperature by the end of the 21st century. The tendency of the warming to be more pronounced in winter is also a conspicuous feature of the observed temperature trends over India. Most models project a decrease in precipitation in December, January and February (DJF) and an increase during the rest of the year. There are both direct and indirect effects of climate change on crop production. Direct effects include change in mean climate and increased climate variability and extremes. Indirect effect of climate change are change in water availability, change in the length of growing season, climate induced high runoff and soil erosion, mean sea level rise and changed scenario of pests and diseases. The non-climate impacts related to GHG emissions are CO2 fertilization and effects of ozone on vegetation. Until now, most studies have focused more on the direct effects of changes in mean climate state on crops and did not consider changes in extremes or in indirect effects of climate change such as pests and diseases or sea level rise. In spite of the threat of crop yield losses in a warmer climate, developing countries in the tropics have the potential to more than offset such adverse impacts by implementing more intensive agricultural practices and adapting agriculture to climate and environmental change. This paper is primarily focused on the field level adaptation measures, although other types of adaptation measures are also important to the farming community to adapt to the climate change. Field level adaptation measures include agronomic, land and water management and genetic improvement measures to enhance and sustain crop yields under climate change conditions. it is also reported that the greatest benefits in food insecure regions are likely to arise from more expensive policy driven adaptation measures that include the development of new crop varieties and uptake of new technologies such as the expansion of irrigation infrastructure. These will require substantial investments by farmers, governments and development agencies.

The adaptation studies, using climate change sensitive crop models, should examine the impact of proposed adaptations when employed in both the current and future climates. The potential of adaptation technologies in terms of yield response may vary from region to region under both current and future climates. These technologies must be evaluated and prioritized in terms of productivity enhancements, social and economic benefits to the rural populations at large before they are promoted for achieving food security under conditions of climate change in future.

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