Journal of Development and Agricultural Economics Vol. 4(12), pp. 311-321, October 2012
Available online at http://www.academicjournals.org/JDAE
DOI: 10.5897/JDAE11.112
ISSN 2006- 9774 ©2012 Academic Journals

Review

Climate change and food security in the developing world: Potential of maize and wheat research to expand options for adaptation and mitigation

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Accepted 16 August, 2012

Maize and wheat are two of the most important food crops worldwide. Together with rice, they provide 30% of the food calories to 4.5 billion people in almost 100 developing countries. Predictions suggest that climate change will reduce maize production globally by 3 to 10% by 2050 and wheat production in developing countries by 29 to 34%. This will coincide with a substantial increase in demand for maize and wheat due to rising populations. Maize and wheat research has a crucial role to play in enhancing adaptation to and mitigation of climate change while also enhancing food security. Crop varieties with increased tolerance to heat and drought stress and resistance to pests and diseases are critical for managing current climatic variability and for adaptation to progressive climate change. Furthermore, sustainable agronomic and resource management practices, such as conservation agriculture and improved nitrogen management can contribute to climate change mitigation. There is also a need for better policies and investments in infrastructure to facilitate technology adoption and adaptation. These include investments in irrigation, roads, storage facilities and improved access to markets. There is also a need for policy innovations for stabilizing prices, diversifying incomes, increasing farmer access to improved seeds and finance, and providing safety nets to enhance farmers' livelihood security. This review paper details the potential impacts of climate change on food security, and the key role of improved technologies and policy and institutional innovations for climate change adaptation and mitigation. The focus is on maize and wheat in sub-Saharan Africa and South Asia.

Key words: Maize, wheat, climate change, food security, germplasm, conservation agriculture.

INTRODUCTION

Farmers have a long record of adapting to the impacts of climate variability but predicted climate change represents an enormous challenge that will test farmers' ability to adapt and improve their livelihoods (Adger et al., 2007). Climate change is a threat to agriculture and food security and there is an urgent need to identify priorities for future research. The relationship between climate change, agriculture and food security, however, is a complex one that is also shaped by economic policies and political decisions. Appropriate climate change research, therefore, involves researchers from a broad spectrum of disciplines along with other stakeholders.

Maize and wheat are two of the most important cereal crops in the world and there is increasing concern about the impact of predicted climate change on the production and productivity of these key cereal crops. Maize and wheat research, therefore, has a critical role to play in stimulating adaptation to and mitigation of climate change. This review paper provides an overview of the potential impacts of climate change on food security and the crucial role of improved technologies and policy and

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institutional innovations for climate change adaptation and mitigation. The focus is on maize and wheat in sub-Saharan Africa and South Asia.

The authors are all agricultural researchers from the natural and social sciences and represent disciplines such as plant physiology, agricultural economics, agronomy, geography and geographical information systems (GIS). This review paper, by bridging the epistemological divide between the natural and social sciences, provides a holistic vision of an agenda for current and future research on maize and wheat. It also illustrates the type of participatory and inter-disciplinary research that is required to provide farmers, policy makers, donors and other stakeholders with the knowledge, tools and approaches required to meet the challenge of ensuring future food security.

The structure of this review paper is as follows: Subsequently, the importance of maize and wheat for food security is summarized, after which details of the impact of climate change on food security are given with an emphasis on maize and wheat. This is followed by a detailed account of the economic impact of climate change on these crops. This review paper provides details on key research and focuses on the development of maize and wheat varieties with increased resistance to heat and drought stress, and sustainable agronomic practices. Furthermore, this study considers policy issues such as the cost-effectiveness of improved germplasm, the need for effective extension provision, and farmers' diverse livelihood options, before it is concluded.

IMPORTANCE OF MAIZE AND WHEAT FOR FOOD SECURITY

Maize and wheat are vital for global food security and poverty reduction. Together with rice, maize and wheat jointly provide at least 30% of the food calories to more than 4.5 billion people in 100 developing countries. In Africa, maize is the most widely grown staple crop, and it is rapidly expanding in Asia. The current cultivated area in over 125 developing countries exceeds 100 million ha. About 67% of the total maize production comes from low and lower middle income countries, indicating the vital role the crop plays in the livelihoods of millions of poor farmers. Owing to the growing demand for feed and bio-energy, the demand for maize in the developing world is expected to double by 2050 and that for wheat to increase from 621 million tons during 2004 to 2006 to more than 900 million tons in 2050 (Rosegrant et al., 2007).

Many small-scale maize farmers in Africa, Asia and Latin America cannot afford irrigation even when it is available and, hence, grow maize under rain-fed conditions. The crop is, therefore, very vulnerable to climatic variability and change (Bänziger and Araus, 2007). Historical trends clearly show that maize yields fluctuate more widely from year-to-year than is the case for rice and wheat. The current probability of failed seasons in maize farming systems varies between 8 and 35% (Hyman et al., 2008). Production fluctuations often give rise to price fluctuations that can adversely affect both poor producers and consumers.

Although considered a temperate species, wheat is the most widely grown of any crop with around 220 million ha cultivated annually in environments ranging from very favourable in Western Europe to severely stressed in parts of Asia, Africa, and Australia (Braun et al., 2010). Wheat is one of the most susceptible crops to climate change and is especially sensitive to heat. Poor productivity growth or stagnation in the Green Revolution areas of South Asia and low yields in Africa, coupled with climate change, will make it more difficult to meet the growing demand for wheat (Rosegrant et al., 2009).

IMPACT OF CLIMATE CHANGE ON FOOD SECURITY

Climate change is likely to lead to increased water scarcity in the coming decades (Lobell et al., 2008; Hendrix and Glaser, 2007). Changes in precipitation patterns will lead to more short-term crop failures and long-term production declines. Water scarcity, due to a reduction in rainfall, is projected to become a more important determinant of food scarcity than land scarcity and the resulting decline in global per capita food production will threaten future food security (Brown and Funk, 2008; Gleditsch et al., 2006). In some regions, changes in rainfall distribution will result in temporary excessive soil moisture or water logging in maize production areas. Currently water logging regularly affects over 18% of the total maize production area in South and Southeast Asia.

Climate change is also likely to lead to an increase in temperature. Climate models show a high probability (>90%) that by the end of this century, growing season temperatures will exceed the most extreme seasonal temperatures recorded in the past century (Battisti and Naylor, 2009). In Sub-Saharan Africa, maximum temperatures are predicted to increase by an average of 2.6°C across maize mega-environments (Cairns et al., 2012). While an increase in temperature of a few degrees is likely to increase crop yields in temperate areas, in many tropical areas even minimal increases in temperature may be detrimental to food production.

High temperatures result in a reduction in crop yields by affecting an array of physiological, biochemical and molecular processes. Sensitivity to supra-optimum temperatures and mechanisms of tolerance depend on the severity, duration and timing of heat stress together with the developmental stage of the plant. The most significant factors associated with yield reduction under heat stress are increased sterility, shortened life cycle, reduced light interception and the perturbation of carbon assimilation processes (photosynthesis, transpiration, and respiration) (Reynolds et al., 2010). The effect of a combination of stresses such as heat and drought stress on crop yields will be greater than the effect of each stress individually.

Increasing temperatures and a higher frequency of droughts and flooding will also affect ecosystem resilience, increasing outbreaks of pests and diseases (Young and Lipton, 2006). Temperature influences insect development, survival and distribution. As temperatures increase, insect populations are likely to increase and diversify. Climate changes will also influence the development of maize and wheat diseases, with increasing temperatures and incidents of drought exacerbating plant stress and increasing plant susceptibility (Garrett et al., 2011; Savary et al., 2011). Climate represents the key agro-ecosystem driving force of fungal colonization and mycotoxin production (Paterson and Lima, 2010). If the temperature increases in cool or temperate climates, the relevant regions may become more susceptible to aflatoxins. Maize is particularly vulnerable particularly to climate change as exemplified by outbreaks of lethal aflatoxicoses in Kenya (Lewis et al., 2005).

The impact of climate change on agricultural production will be greatest in the tropics and subtropics, with Africa particularly vulnerable due to the range of projected impacts, multiple stresses and low adaptive capacity. Compared to the situation without climate change, climate change is projected to reduce maize production globally by 3 to 10% by 2050 (Rosegrant et al., 2009). A recent analysis of more than 20,000 historical maize trial yields in Africa over an eight-year period showed maize yields were reduced by 1 and 1.7% for every degree day above 30°C under optimal and drought conditions respectively (Lobell et al., 2011).

Jones and Thornton (2003) estimate that, due to increased temperatures and reduced rainfall, crop yields in Africa may fall by 10 to 20% by 2050. However, this figure masks variation. In some areas crop reductions will be greater (northern Uganda, southern Sudan, and the semi-arid areas of Kenya and Tanzania) while in other areas crops yields may increase (southern Ethiopia highlands, central and western highlands of Kenya and the Great Lakes Region) (Thornton et al., 2009). Analysis of climate risk identified maize in southern Africa as one of the most important crops in need of adaptation investments (Lobell et al., 2008). Climate change projections suggest that by 2030 maize yields in southern Africa will be 50% of the average yields achieved at the beginning of this century.

The effects of climate change on wheat production will vary greatly depending on region. While future climate scenarios may be beneficial for the wheat crop in high latitudes, global warming will reduce productivity in zones where favorable temperatures already exist, for example in the Indo-Gangetic Plains (IGP) of South Asia. The IGP, currently part of the favorable, high potential, irrigated, low rainfall mega-environment, accounts for 15% of global wheat production. By 2050 and due to climate change, 51% of the region might suffer from a significant reduction in wheat yields unless farmers adopt appropriate cultivars and crop management practices (Ortiz et al., 2008).

The effect of warming on wheat yield depends on changes in minimum (tmin) daily and maximum (tmax) daily temperature. Using an empirical regression model and a process model (CERES), Lobell and Ortiz-Monasterio (2007) show that the effects of higher temperatures on wheat yields were consistently negative. Modeled sensitivities for symmetric warming ranged from -10% per degree Celsius in the warmest site (Yaqui Valley of Mexico) to -7% per degree Celsius at the coolest sites (Imperial Valley California). However, non-symmetric increases in tmin (night temperature) seem to generate the greatest effect on wheat productivity in tropical growing regions.

In the Yaqui Valley, increases in tmin by 2°C led to a 17% decline in yields in the empirical model and 11.7% decline in the CERES model. Comparable changes in tmax however showed -4% in the empirical model compared to -12% in the CERES model, indicating lesser sensitivity to increases in daytime temperature. Maintaining current yields in the face of predicted warming of 1 to 3°C expected over the next 50 years will therefore represent a considerable challenge. Increased research for developing less sensitive and more adapted germplasm to heat will therefore be a key strategy for the warmer and perhaps drier future.

Global warming is likely to increase productivity and open up new cropping opportunities at high latitudes in areas of Canada and Russia, but is projected to reduce wheat production in developing countries by 29 to 34% (Rosegrant et al., 2009). Predicted climate change will, hence, negatively affect agricultural production and impede the ability of many regions to achieve the necessary gains for future food security (Lobell et al., 2008). Under current agriculture production systems in Africa, a 2°C increase in temperature could result in 12 million people at risk of hunger as a result of crop failure by 2050 (Nkomo et al., 2006). Temperature increases of 3.3 and 3.4°C may put 60 and 70 million people at risk, respectively.

ECONOMIC IMPACT OF CLIMATE CHANGE ON MAIZE AND WHEAT

Research by the International Food Policy Research Institute (IFPRI) (Nelson et al., 2009) combines for the first time modeling of crop growth under climate change with insights from a detailed global agriculture model. The research provides detailed estimates of the impacts of climate change on agricultural production (including maize and wheat), consumption, prices, and trade, and the costs of adaptation. It uses a global agricultural

Table 1. Climate change effects on crop production, no CO_2 fertilization (adapted from Nelson et al., 2009).

Agricultural product	South Asia	East Asia and Pacific	Europe and Central Asia	Latin America and Caribbean	Middle East and North Africa	Sub-Saharan Africa	Developed countries	Developing countries	World
Wheat									
2000 (mmt)	96.7	102.1	127.5	23.5	23.6	4.5	205.2	377.9	583.1
2050 No CC (mmt)	191.3	104.3	252.6	42.1	62	11.4	253.7	663.6	917.4
2050 No CC (% change)	97.8	2.2	98.1	79.1	162.7	153.3	23.6	75.6	57.3
CSIRO (% change)	-43.7	1.8	-43.4	11.4	-5.1	-33.5	-7.6	-29.2	-23.2
NCAR (% change)	-48.8	1.8	-51.0	17.4	-8.7	-35.8	-11.2	-33.5	-27.4
Maize									
2000 (mmt)	16.2	141.9	38	80.1	8.2	37.1	297.9	321.3	619.2
2050 No CC (mmt)	18.7	264.7	62.7	143.1	13.1	53.9	505.1	556.2	1061.3
2050 No CC (% change)	15.4	86.5	65	78.7	59.8	45.3	69.6	73.1	71.4
CSIRO (% change)	-18.5	-12.7	-19.0	-0.3	-6.8	-9.6	11.5	-10.0	0.2
NCAR (% change)	-8.9	8.9	-38.3	-4.0	-9.8	-7.1	1.8	-2.3	-0.4

Note: The rows labeled 2050 No CC (%) indicate the percent change between production in 2000 and 2050 with no climate change. The rows labeled CSIRO (%) and NCAR (%) indicate the relative percent change (compared to no climate change) in production in 2050 due to climate change. For example, Sub-Saharan Africa maize production was 37.1 mmt in 2000. With no climate change, Sub-Saharan Africa maize production is predicted to increase to 53.9 mmt, an increase of 45.3%. With the CSIRO scenario in 2050 Sub-Saharan Africa maize production is 9.6% lower than with no climate change.

supply-and-demand projection model (IMPACT, 2009) linked to a biophysical crop model (DSSAT) of the impact of climate change. The researchers used two climate models to stimulate future climate: the National Center for Atmospheric Research, US (NCAR) model and the Commonwealth Scientific and Industrial Research Organization, Australia (CSIRO) model.

The report assesses climate-change effects on food security and human well-being using two indicators: per capita calorie consumption and child malnutrition numbers. The impacts of climate change on agriculture and human well-being include: 1) the biological effects on crop yields; 2) the resulting impacts on outcomes including prices, production, and consumption; and 3) the impacts on per capita calorie consumption and child malnutrition. The biophysical effects of climate change on agriculture induce changes in production and prices, which play out through the economic system as farmers and other market participants adjust autonomously, altering crop mix, input use, production, food demand, food consumption, and trade.

Research by Nelson et al. (2009) suggests that climate change will have a negative impact on agriculture and human well-being. Crop yields will decline, crop and meat prices will increase, and consumption of cereals will fall, leading to reduced calorie intake and increased child malnutrition. The negative effects of climate change on crop production are very pronounced in Sub-Saharan Africa and South Asia (Table 1). In South Asia, the climate scenario results in a production decline of 14% in rice production relative to the no–climate-change scenario, 44 to 49% in wheat, and 9 to 19% in maize. In Sub-Saharan Africa, wheat and maize yield declines with climate change are 34 and 10%, respectively.

With no climate change, world prices for the most important agricultural crops- rice, wheat, maize, and soybeans - will increase between 2000 and 2050, driven by population and income growth and demand for bio-fuels.

Even with no climate change, the price of rice would rise by 62%, maize by 63%, soybeans by 72%, and wheat by 39%. Climate change results in additional price increases: 32 to 37% for rice, 52 to 55% for maize, 94 to 111% for wheat, and 11 to 14% for soybeans. The overall predicted impact of climate change on the total number of malnourished children is stark (Table 2).

The aforementioned IFPRI research on climate change does not factor in the costs of climate change in terms of potential displacement, environmental refugees and conflict. If these costs are included then the economic impact of climate change will be even greater. There are gloomy predictions of how environmental crises will affect global security (Paskal, 2010). Through direct effects on livelihoods and indirect effects on state functions, climate change may in certain circumstances increase the risk of violent conflict. The environmental problems associated with climate change could, in turn, play a role in stimulate greater migration leading to conflict in receiving areas: the arrival of “environmental migrants” can burden the economic and resource base of the receiving area,

Table 2. Total number of malnourished children in 2000 and 2050 (million children under five years of age) (adapted from Nelson et al., 2009).

Region		2050	
	2000	No climate change	Climate change
South Asia	76	52	59
East Asia and Pacific	24	10	14.5
Europe and Central Asia	4	3	4
Latin America and Caribbean	8	5	6
Middle East and North Africa	3	1	2
Sub-Saharan Africa	33	42	52
All developing countries	148	113	138

promoting native-migrant contest over resources such as cropland and freshwater (Raleigh and Urdal, 2007; Warner, 2010).

CLIMATE CHANGE ADAPTATION AND MITIGATION RESEARCH OPTIONS

Germplasm technology

Climate change poses huge challenges to food security and the livelihood security of millions. Any activity that supports agricultural adaptation also enhances food security. Agriculture adaptation must, however, be addressed at both the policy and management level at the country and international level. The development and dissemination of improved germplasm and risk-reducing management options have the potential to offset some of the yield losses linked to climate change. Communities may adapt in different ways, including switching to water-efficient or drought and heat tolerant crops better suited to a warmer and drier climate (Lobell et al., 2008) and/or diversifying livelihood strategies across crops and livestock (Seo, 2010).

Food security in an era of climate change may be possible if farmers transform agricultural systems via the use of improved seed and fertilizer along with improved governance (Brown and Funk, 2008). Models of the global food economy suggest that trade will also represent an important but not complete buffer against climate change induced yield effects (Rosenzweig and Parry, 1994). Nelson et al. (2009) assessed the costs of productivity-enhancing investments in agricultural research, rural roads, and irrigation infrastructure and efficiency that could help farmers adapt to climate change, and concluded that there is a need for increased agricultural productivity investments of US$7 billion per year. As part of this increased investment, research is needed to develop stress tolerant and widely adapted maize and wheat varieties (and other crops and livestock).

Based on climate change predictions to 2050 in Sub-Saharan Africa, Burke et al. (2009) reported that the majority of African countries are likely be faced with 'new' climates over at least half of their current crop area by 2050. In the case of 75% of these countries, the new climates will be similar to already existing climates in other Sub-Saharan countries. This suggests that there may exist already crop germplasm that is appropriate for the predicted 2050 climates. In these cases, a key challenge will be to ensure that there is a policy environment that facilitates the international movement of germplasm from areas where it currently exists to areas where it will be needed for future climate change adaptation. A greater challenge is in the hotter Sahelian region. In this case, appropriate germplasm does not currently exist for the predicted future climates. This poses a serious challenge in terms of the need to develop appropriate crop varieties for these drastically changed agro-climates for which appropriate germplasm does not already exist. Similar analysis of projected future climates and current analogues is needed at higher levels of resolution to guide and inform policy choices.

The International Wheat and Maize Improvement Center (CIMMYT) together with international and national agricultural research institutes are working to develop maize and wheat technologies for climate vulnerable countries. Work on maize in Africa is coordinated with the International Institute of Tropical Agriculture (IITA) while that on wheat in the West Asia and North Africa (WANA) region is coordinated with the International Center for Agricultural Research in the Dry Areas (ICARDA).

Maize

The development of climate-adapted germplasm is possible through a combination of conventional, molecular and transgenic breeding approaches. In conventional breeding for tropical maize, the application of proven drought breeding methodologies in managed stress screening has resulted in significant grain yield increases under drought stress (Bänziger et al., 2006). Hybrids developed through CIMMYT's stress tolerance breeding program have a yield advantage of up to 20% compared to commercially available hybrids (Bänziger et al., 2006). However, further yields gains will be required to offset the potential effects of climate change on maize.

Emerging molecular breeding technology and phenotyping offers new high-throughput approaches to developing germplasm for future climates (Cabrera-Bosquet et al., 2012). In maize, donors with increased tolerance to drought stress have been identified and are being incorporated into the breeding pipeline. Furthermore, novel alleles associated with drought, heat and water logging tolerance, and stress combinations have also been identified using the latest advances in whole genome sequencing. Together these developments should speed up the development of climate adapted maize germplasm.

Within the primary maize and wild relatives gene pool there exists unexploited genetic diversity for novel traits and alleles (Ortiz et al., 2009) that can be used for breeding new high yielding and stress tolerant cultivars using conventional approaches. Where limited genetic variation in maize exists for biotic and abiotic stress tolerance, transgenes will provide the opportunity to increase genetic variation into breeding programs (Juma, 2011).

Relatively little research on heat stress has been conducted in maize compared to other abiotic stresses. On-going research at CIMMYT suggests that large genetic variation exists within tropical maize for adaptation to heat stress and that a breeding program can take advantage of this. More research is needed on the interaction of heat and drought stress in cereals (Barnabás et al., 2008). Heyne and Brunson (1940) showed the combined effect of heat and drought stress in maize was greater than the effect of each stress separately. Research is required into the identification of traits associated with combined heat and drought tolerance, and the development of improved germplasm for high temperature, water-limited environments.

Wheat

Wheat yields decline at supra-optimal temperatures (Wardlaw et al., 1989; Reynolds et al., 1994) and significant breeding effort will be required to maintain productivity in regions closer to the equator. Nonetheless, wheat is relatively well adapted to water deficits and is grown widely in semi-arid regions such as Central Asia, Australia, and throughout the Mediterranean region. In regions that become progressively more arid, wheat may become more competitive than crops, such as maize, that are currently grown. Wheat breeding has had considerable impact in marginal environments as well as temperate ones. For example, analysis of CIMMYT international nursery data shows clear and steady progress in the performance of both bread and durum wheat under drought (Trethowan et al., 2002; Braun et al., 2010). Analysis up to the present shows genetic gains of 0.5 to 1.0% per annum depending on the region (Lopes et al., 2012; Manès et al., 2012; Sharma et al., 2012). Recent effort has focused on breeding for earlier maturing cultivars that escape terminal heat stress and encompass resistance to diseases associated with warm humid environments (Joshi et al., 2007) as well as the highly virulent Ug99 stem rust strain.

One of the most effective research strategies for wheat has been, and will continue to be, to change the phenological pattern of the crop so that critical growth stages do not coincide with stressful conditions or simply to finish the life cycle early before severe stress conditions occur. Another is to minimize the occurrence of stress through development of a good root system that, in the case of drought, permits water to be accessed deeper in the soil and, in the case of heat, permits transpiration rates that better match evaporative demand, thereby permitting maximal carbon fixation with the added benefit of cooler plants (Reynolds et al., 2010).

Given the time lag between technology development, deployment and on-farm adoption of new varieties, current research also needs to focus on institutional innovations and policy options that facilitate farmers' access to existing and new germplasm. Socio-economic and spatial agro-climatic research is also needed to understand and map the climate hotspots, vulnerability of livelihoods, current adaptation options and the institutional and policy mechanisms that promote adoption of new technologies and enhance local adaptive capacity to climate change.

Conservation agriculture

Climate change will be especially detrimental to crop production in cropping systems where soils have degraded to an extent that they no longer provide sufficient buffer (for example, adequate water-holding capacity) against drought and heat stress. These affects will be most severe if irrigation is not available to compensate for decreased rainfall or to mitigate the effects of higher temperature. Improving genetic adaptation to heat or drought stress alone will not address these problems; there is also a need for complementary agronomic interventions (Hobbs and Govaerts, 2010). In short, the benefits from investment in genetic technology are more likely to be realized if crops are grown in well-managed soils that maximize expression of genetic potential and buffer the crop against weather fluctuations.

Scientists are developing improved cropping systems and management practices known as conservation agriculture. Conservation agriculture involves significant reductions in tillage, enhanced surface retention of adequate crop residues, and diversified, economically viable crop rotations. This has contributed to productivity growth, reduced burning of crop residues, and efficient utilization of water, soil nutrients, as well as savings in cost of fuel and labor. Conservation agriculture is particularly important in rain-fed areas where it helps in retaining water and improving yields. Conversely, during years of more intensive rains, conservation agriculture reduces soil loss through wind and water erosion (Hobbs and Govaerts, 2010). Conservation agriculture also enhance soil carbon sequestration and cuts CO_2 emissions by reducing tillage (and hence use of fossil fuels) and by reducing or eliminating the burning of crop residues.

There is on-going work in developing countries with the use of precision agriculture tools that allow a more efficient use of nitrogen. This results in a significant reduction in the emission of nitrous oxide, a powerful greenhouse gas that has close to 300 times the global warming potential of CO_2. Currently, more than 70% of all nitrogen fertilizer is applied in the developing world. The Yaqui Valley of Mexico is an area with intensive agriculture that has an agro-ecosystem typical of about 40% of all the wheat-producing areas in the developing world. In the Yaqui Valley, the use of precision agriculture tools, together with improved timing of nitrogen application, has reduced emissions of nitric and nitrous oxide by 50% compared to farmers' practices, while improving farm income. The result, hence, benefits both farmers and the environment (Matson et al., 1998).

Conservation agriculture can also facilitate sequestration of carbon. One way of mitigating CO_2 concentration in the atmosphere is through carbon sequestration in the above ground biomass and in the soils, hence directly contributing to climate change mitigation. Given the low cost of carbon sequestration in developing countries, farmers could benefit by selling the sequestered carbon to those countries that are required to cutback emissions as allowed under the Clean Development Mechanism of the Kyoto protocol. However, there is a need to facilitate farmers' access to such markets for C-sequestration services and to reduce the prevailing high transaction cost associated with measurement and verification of C-sequestration. Payments for environmental services could serve as the often-lacking incentive for farmers to adopt conservation agriculture on fragile lands.

TOWARDS AN ENABLING POLICY ENVIRONMENT

Does investment in technology development pay off?

The arguments for increased investment in agricultural research are more convincing if there is evidence that it has a beneficial economic impact. La Rovere et al. (2010) evaluated the potential impacts by year 2016 of investing in drought tolerant maize (DTM) in 13 countries of East, Southern and West Africa. The study explored where the greatest economic and poverty reduction returns can be achieved. Yield variance reduction has been a priority for crop improvement programs (Gollin, 2006) and La Rovere et al. (2010) focused on the impact of DTM on variance of maize yields. The approach is relevant for climate change scenarios as it considers not only the conventional mean yield gains, but also the additional benefits from yield stability gains, or equivalently the climate or rainfall risk reduction.

The benefits from investment in DTM for Africa were estimated in terms of economic gains from the increase in average maize yields and economic benefits from reduction in yield variability. The study forecast the largest gains to be in lower drought risk zones. With a potential full replacement of improved varieties with DTM by 2016, there would be economic gains of US$ 907 million over all 13 countries, assuming conservative yield gains, and US$ 1,535 million, assuming optimistic yield gains. Kenya, Malawi, Zambia, Zimbabwe, as well as Nigeria and Ethiopia would expect the greatest benefits in terms of production gains and poverty reduction. More than four million people- both producers and consumers- would experience a significant reduction in poverty in all 13 countries by 2016.

Institutional and policy options for adaptation

Extension services

Farmers will not be able to benefit from existing and future technology options if they are unable to access the improved seed and other technological innovations. There will be a need, hence, to address multiple market and government failures in the delivery of technologies, inputs and services (Cooper et al., 2008). This requires new institutional arrangements and policy instruments to enhance local capacity and stimulate the adoption of improved technologies for adaptation, managing risks and protection of vulnerable livelihoods.

Public- and private-supported extension programs can play a key role in information sharing by transferring technology, facilitating interaction, building capacity among farmers, and encouraging farmers to form their own networks. Extension services that specifically address climate-change adaptation include disseminating local cultivars of drought-resistant crop varieties; teaching improved management systems; and gathering information to facilitate national research work. The breeding and agronomic research work needs to be supported by other factors including complementary investments in climate-responsive information and input delivery systems; and strengthening of institutions to coordinate grain marketing with seed, fertilizer and credit delivery. The development of reliable seasonal weather forecast, record of reliable weather, and strengthening of early warning system are also crucial for facilitation of adaption to climate change.

The above can best be achieved via a judicious mix of public and private service provision in the agricultural sector.

Risk management options

Climate change is likely to lead to unpredictable extreme events and erratic rainfall and along with declining groundwater tables and scarcity of water for irrigation, this will cause volatility of supply (and hence market prices) and amplify production and market risks for the poor. Protecting the livelihoods of the poor under risky environments will require developing institutional innovations to provide new opportunities for ex-ante and ex-post risk management. Typically, poor households in developing countries are not well equipped to cope with such risks due to the absence of well-functioning insurance and credit markets. The welfare loss resulting from weather shocks, risk aversion and lack of appropriate ex-ante and ex-post risk management strategies can be significant even under current climates (Dercon, 2008). The ex-post impacts of climatic shocks include the direct production loss due to the shock and the subsequent disinvestment of assets that follows such shocks.

The ex-ante impacts of climatic risk are no less serious. The fear of falling into extreme consumption shortfall in years of climatic shock means that poor farm households tend to become excessively risk averse. The result is that farmers often avoid risky production technologies even though these could significantly increase productivity in good years. An adoption study in Malawi shows that risk aversion towards fertilizer use explains farmers' low adoption rate of hybrid maize (Simtowe et al., 2006). Even worse is the fact that creditors avoid lending to poor farm households for fear of excessive default rate when the covariate catastrophic event such as drought occurs, resulting in poorer households being rationed out of the credit markets (Dercon and Christiansen, 2010).

Traditional insurance mechanisms mediated through reciprocity and social networking within extended families are either insufficient to manage correlated risks or impose excessive transaction costs, making them less suitable for managing climate-induced shocks and agricultural risks. Access to credit for both production inputs (seeds and fertilizer) and consumption smoothing will be critical to allow ex-ante and ex-post adjustments for managing risk. In some cases, such credit can be linked with insurance schemes although problems of covariate risk, adverse selection and moral hazard have historically led to rationing and imperfections in rural financial markets. There is growing interest in weather index based insurance mechanisms as a means to overcome the prohibitive transaction costs associated with performance based insurance (Barnett and Mahul, 2007).

Index based insurance is an innovative financial product that pays out indemnities in events that are triggered by easy-to- measure weather variables such as rainfall. Reducing risk exposure by transferring the climate risk to insurance companies is expected to encourage more risk-taking and facilitate adoption of improved crop varieties. The design of such insurance schemes however requires more research, field level piloting and innovations in measuring losses for alternative crops, for example, using crop modeling work so as to better represent the relationship between weather variables and crop yield at the required spatial scale.

Investment in market infrastructure and strategic reserves

Marketing costs in Sub-Saharan Africa (SSA) are estimated to reach up to 70% of retail price of marketed output, with transportation taking the biggest share (Gabre-Madhin, 2001; Fafchamps and Gabre-Madhin, 2006). High marketing costs have hindered the adoption of improved farming practices, preventing poor farmers from taking advantage of available improved agricultural technologies. Increased investment in rural roads is a decisive climate adaptation strategy (Rosegrant et al., 2009). Several studies have shown a significant reduction in poverty and improvement in income due to investment in rural infrastructure in developing countries (Dercon et al., 2009; Fan et al., 2000; Fan and Chan-Kang, 2005). Most of these studies demonstrate that investment in rural roads ranks first or second among public investments in reducing rural poverty and improving incomes.

Improved rural infrastructure such as roads reduces the costs of marketing thereby increasing the farm-gate price of the agricultural output. It also reduces the cost of delivering inputs to the farmers. Linking farmers to domestic and regional markets is, therefore, an important adaptive strategy so that farmers can respond to changing market opportunities.

This needs to be complemented by national and regional strategic reserves for major staples that can be used for stabilizing food prices and buffer food production shortfalls in vulnerable countries. Such policies for price stabilization for agricultural commodities need to be implemented carefully as many governments in Africa and Asia have increasingly adopted discretionary policies implemented through powerful grain marketing parastatals.

Livelihood diversification

Proposed investments in agriculture are justified but it is also important to note that agriculture alone may not offer an effective livelihood strategy to adapt to climate change. Based on Dixon et al. (2001), there are a number of livelihood diversification strategies available to farmers in the face of climate change.

Farmers can expand into new or existing production channels in order to increase income, decrease income variability, and diversity income sources. This may include the cultivation of new varieties, crop-livestock integration, on-farm processing, and switching to more heat- and drought-tolerant crops such as sorghum and millet (Burke et al., 2009).

Farmers are able to secure part of their income from off-farm sources. This has historically been important as many farmers in low potential areas already seek seasonal or long-term off-farm employment. The income generated may be used to smooth consumption, enhance agricultural investments and/or facilitate farmers moving away from agriculture altogether.

Farmers can pursue non-agricultural livelihood strategies. Migration and employment opportunities in the formal and informal non-agricultural sectors would play an important role for climate change adaptation (Adger et al., 2007). Declining land productivity due to soil nutrient depletion or depletion of surface and ground water may also trigger such responses.

Diverse livelihood strategies do not undermine the argument for increased investment in agriculture, they illustrate that other avenues need to be explored with agriculture-based alternatives for adapting to and mitigating the impacts of climate change.

CONCLUSIONS

Maize and wheat are among the three most important crops for global food security. Climate change will have variable impacts of supply and demand patterns for these crops. While wheat production may expand in high latitude temperate regions, global warming will reduce production in low rainfall tropical growing regions. Maize production in the developing countries will suffer significantly from climate change. Climate change will therefore undermine food and livelihood security and complicate efforts to fight poverty, hunger and environmental degradation. Adaptation options include the following;

1. Technological strategies (investment in research and development of stress tolerant and widely adapted crop varieties, irrigation and natural resource management options).
2. Policy options (finance, weather index insurance, strategic food reserves, etc.)
3. Capacity building (institutional plus physical infrastructure including water storage, irrigation systems, food storage, processing, forecasting and disaster preparedness).
4. Income diversification (within and outside of agriculture).

Despite some uncertainties on the spatially differentiated impact of climate change on agricultural production, there is little doubt that new germplasm, more suited to future climates, is critical along with improved agronomic and crop management practices. There is an urgent need to develop climate-adaptable crop varieties with improved tolerance to heat stress, and combined heat and drought stress. In some cases, climate change may create new biotic stresses brought by new conditions conducive to pest and disease infestations. Decision support systems (crop modelling) may help project any likely effects of climate change on the outbreak and spread of disease and pest epidemics. This may require proper forecasting and early warning systems.

The development and dissemination of climate-responsive germplasm may take several years because the process consists of several steps including breeding, on-farm testing, release of varieties and germplasm dissemination. It is very important to facilitate farmers' adoption of these technologies. Such an effort has often been the missing link and has prevented farmers fully benefiting from investment in agricultural research. In addition to enhancing adaptation and reducing vulnerabilities, improved agricultural innovations such as conservation agriculture may also contribute towards mitigating global warming and climate change. Furthermore, the adoption of precision agriculture technologies in intensive agricultural systems can significantly reduce emissions of nitrous oxide by about 50% while maintaining yields and improving farm income.

The performance of agricultural systems coupled with the introduction of climate change adaptable varieties is determined by the complex interaction of agro-ecosystems and human activity. Climate variability does not only affect the yield of crops but also contributes to risk avoidance on the part of farmers. Programs such as better credit and insurance schemes in areas where imperfect capital and financial markets prevent farmers from accessing such services are important in realizing the potential benefit of such improved germplasm. Due to variation in the biophysical and socioeconomic environments, it is important to model the vulnerabilities as well as the impact of proposed technological and policy interventions at spatially disaggregated scales. Such analysis, coupled with economic analysis, would enhance the ability to measure the impact of climate change on human wellbeing as well as the potential of alternative response options for climate change adaptation and mitigation.

Along with investments and policy options to increase and diversify income sources both within and outside agriculture, policy support is required for building local capacity, establishing institutions that enhance access to information, seeds and services, insurance mechanisms to buffer market and production risks, and safety nets that help resilience and recovery from climate-induced shocks. The success of adaptation options would depend on the availability of resources and ability to mix technological and institutional innovations to address location specific challenges that adversely affect agriculture and livelihood systems.

ACKNOWLEDGEMENTS

The authors would like to thank our colleagues who contributed to the ideas for this paper, especially George Mahuku, Gary Atlin and BM Prasanna. We are very grateful to an anonymous reviewer for invaluable comments on an earlier version of this paper.

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