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Economic Impacts of Climate Change on Agriculture: Adaptation and Vulnerability

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1. Introduction

It is well known that agriculture is vulnerable to climate change because agricultural industries are strongly affected by climate conditions (see the summary treatment in Intergovernmental Panel on Climate Change [IPCC], WGI, 2007). Production conditions are directly influenced by temperature, precipitation, storms, and droughts along with the plant growth stimulating effects of carbon dioxide (CO_2). They are also indirectly affected by climate induced alterations in market prices, incidence of pests and diseases, forest fire, and invasive species plus water supply.

Agricultural impacts have been found to vary by region. For example, at higher latitudes, crop productivity tends to increase when temperature increases in the range of crop heat tolerance and away from ranges where cold depresses production; however, in lower latitudes, temperature increases often have a negative effect on crop productivity (IPCC, WGII, 2007). Alterations in climate will further affect livestock production since it alters fecundity and appetite plus the changes in crop yields and forage growth rates directly influence feed availability.

It is extremely likely, in fact virtually inevitable that agriculture will need to adapt to climate change (IPCC, WGIII, 2007; Rose & McCarl, 2008). The momentum that society exhibits in terms of greenhouse gas emissions largely arising from the interrelationships of economic activity and energy use coupled with the lack of real progress on reducing emissions makes it likely that a substantial degree of climate change will be realized before greenhouse gas concentrations peak and begin to drop as indicated by table 3.5 in Chapter 3 of IPCC, WGIII (2007).

Given these motivations, in this chapter we review knowledge on agricultural climate change vulnerability and potential means to reduce sector vulnerability through adaptation.

2. Nature of agricultural vulnerability

Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC, WGII, 2007). In agriculture, vulnerability involves more than the biophysical impacts of altered temperature and precipitation. It also affects prices and markets for crops or livestock produced along with interregional comparative advantage and international trade patterns (Reilly et al., 2001; Wehbe et. al., 2005).

2.1 Production vulnerability

The production vulnerability of agriculture is related to a variety of interacting factors, including changes in temperature, rainfall regimes and water supply, frequency of occurrence of extreme weather events including droughts and storms, plant responses to CO_2 concentrations, climate induced changes in pest incidence, soil fertility, sea level induced inundation of lands, and adaptive adjustments in planting dates, crop mixes and other management factors. Some of these factors directly affect agricultural productivity, e.g., temperature, precipitation, droughts, rainfall and CO_2; while others influence the productivity indirectly, such as water supply, soil fertility and pests.

2.1.1 Factors causing vulnerability

The factors causing vulnerability as listed above are discussed in the subsections below.

2.1.1.1 Changing temperature

Changes in temperature can alter crop yields and water use. The effects vary across types of crops and locations. In general, rising temperature increases crop productivity at higher latitudes while the effect is negative at lower latitudes. In addition, some crops like cotton and sorghum are well adapted to warmer conditions and thus can gain in relative or absolute yield. This was found in the 2001 US national assessment (Reilly et al., 2001, 2002).

2.1.1.2 Precipitation and water supply

Agriculture is highly dependent on water. Irrigation uses an estimated 69% of global water with roughly 15-35% of irrigation withdrawals are unsustainable (World Business Council for Sustainable Development [WBCSD], 2009).

Climate change effects on water are projected to vary across the globe (IPCC, WGI, 2007). The IPCC shows a projection with a general mid-latitude drying coupled with a high-latitude wettening. Some countries, such as Africa, New Zealand, Australia, and Latin America, are expriencing reduced precipitation and increased evaporation raising water security problems. Changes in water seasonality are also expected where for example rising temperatures increase the proportion of winter precipitation received as rain and decrease the proportion arriving in the form of snow. This in turn decreases the amount of time that snow stores water and thus the hydrograph of runoff with less in the summer and more in winter/spring/fall (US Climate Change Science Program [USCCSP], 2008). The effect is regionally heterogenous where for example, Central and Eastern Europe will have a higher water stress because of the decrease of summer precipitation, while Asia might confront an increase flooding risk induced from glacier melt in the Himalayas (IPCC, WGII, 2007).

Water supply and in turn the availability of irrigation water for agriculture could be affected by climate change in the following ways:

- Altered precipitation alters water runoff into surface water and infiltration into groundwater, thus affecting water stored behind dams or in aquifers;
- Higher temperatures and altered precipitation influence consumption by vegetation in watersheds altering run-off;
- Heat waves increase water demand by crops increasing respiration and evapotranspiration and irrigation requirements (Adams et al., 1999; McCarl, 2006; Adams & Peck, 2008);
- Climate change may alter vegetative mix in water sheds further influencing run-off;
- Higher temperatures increase evaporation loss from lakes, rivers, and reservoirs;

- Altered seasonal water availability will cause shifts in crop timing and species;
- Diminished supplies will mean less dilution and in turn cause pollutants and salts emitted into rivers and streams to be a greater problem rendering water less suitable for agriculture and putting greater pressure on agricultural water use and runoff (Thompson, 2005; IPCC, WGII, 2007);
- Precipitation alteration may contribute to yield variability. Campbell et al. (1997) argue that it is the cause of 90% of the variance in primary production of grassland systems.

Precipitation patterns are likely to shift in intensity. IPCC, WGI (2007) presented data showing that between 2001 and 2005 we observed an ever greater proportion of precipitation coming from the wettest days of a month. In addition, significant heavy-precipitation events have increased over the past several decades, and most intense precipitation usually occurs in warm regions (Easterling et al., 2000). This indicates a shift in precipitation shares from gentle frontal rains to more intense events which is a condition that is less suitable for agriculture. Several studies project increasing heavy precipitation events in the future over most regions (USCCSP, 2008, as cited in Kharin & Zwiers, 2005). Shifts in extreme precipitation events happen across regions within countries. For example, the incidence of heavy precipitation events has increased in north-eastern and south-eastern Australia as well as decreased in south-western Australia (Suppiah & Hennessy, 1998).

2.1.1.3 Increased frequency of extreme weather events

Projections indicate that climate change will cause extreme weather events to become more frequent, more widespread and/or more intense (IPCC, WGI, 2007). Altered frequencies and intensities of events like floods, droughts, heat waves, cold waves, tropical storms, hurricanes, and storms, are likely to have wide-ranging impacts on agricultural productivity. Besides, the hydrologic cycles are projected to intensify such that floods and droughts will become more severe in low- to mid-latitude regions and further alter seasonal water availability and the need for impoundments (McCarl & Reilly, 1999).

Extermes have been observed, for example,

- Europe suffered from a heat waves in 2003 with an estimated 14,800 excess deaths occurring (Haines et al., 2006) while the world had the warmest August in this period (National Oceanic and Atmospheric Administration [NOAA], 2003).
- Murray-Darling Basin in southeastern Australia, which supports 41% of Australian agriculture activities and 85% of the irrigation, has suffered from harsh droughts in the 2000s while, since the end of 2010, there have been large flood disasters in Queensland and Victoria induced by possible climate change forces along with tropical cyclone Tasha and a La Niña year (National Aeronautics and Space Administration [NASA], 2011).

Projections for future changes in extremes are as reviewed in the US Climate Change Science Program report (2008):

- In North America, droughts, floods or extreme heat are likely to become more frequent or severe in some regions to human-caused climate change.
- The intensity and frequency of hurricanes/typhoons are projected to increase by 1 to 8% and 6 to 18%, respectively. Some existing studies have attributed part of the increase to climate change (Mann & Emanuel, 2006; Trenberth & Shea, 2006; Anthes et al., 2006;

USCCSP, 2008). Hurricanes depress crop yields and reduce the total net welfare (Chen & McCarl, 2009).

- More intense and frequent El Niño-Southern Oscillation (ENSO) events and other large-scale climate circulation patterns such as the Pacific Decadal Oscillation (PDO), and the Northern Annular Mode (NAM) have occurred since the late 1970s and appear to influence climate extremes. Timmermann et al. (1999) forecasted increased intensities and frequencies of the cold and hot ENSO phases which in turn would likely increase the intensity and frequency of extreme events.

More information about the impacts of climate change due to extreme events can be found in Table 1.

2.1.1.4 Changing CO_2 concentrations

Since the mid-20th century most of the observed increase in global average temperatures is very likely (>90%) owing to the observed increase in anthropogenic greenhouse gas (GHG) concentrations (IPCC, WGI, 2007). CO_2 is one of the most important anthropogenic GHGs. CO_2 concentrations are not only one of the drivers of climate change but also a growth simulating factor. Analyses in Adams et al. (1990) show that this is a key item to consider as ignoring it leads to impact estimates that are substantially more damaging.

2.1.1.5 Soil fertility and water holding

Soil fertility and soil water holding capacity is affected by climate change. Temperature increases combined with precipitation increases will likely reduce the water-holding capacity and organic matter content of soils, leading to erosion and consequently to an increase in the magnitude of soil nutrient losses and water stresses. Given a constant water supply increases in temperature decreases soil moisture at a nonlinear rate and would need to be offset by precipitation increases and/or expansions in irrigation. In addition, organic matter can be negatively affected as microbial decomposition is stimulated by warmer temperatures. In turn this lessens orgainc matter which is key to the ability of the soil to retain nutrients and moisture. Soil managment may in part overcome this as Luers et al. (2003) indicate better managed soils are less vulnerable to changing climate, irrespective of the soil type.

2.1.1.6 Pest incidence

Climate conditions are likely to exacerbate pest problems, such as expanding pest ranges and management costs (Chen & McCarl, 2001; Gan, 2004; IPCC, WGII, 2007). For instance, more than 1.2 Mha of pinyon pine mortality occurred due to extreme drought, coupled with a beetle outbreak in the southwest of US (Breshears et al., 2005). Chen and McCarl (2001) indicate that US pesticide use is projected to increase for most crops in most states under the climate scenarios although non chemical means such as host resistance, tillage, IPM and other items may increase as well and possibly substitute. Increased pesticide use could cause some substantial water quality and other environmental problems.

2.1.1.7 Animal and crop diseases

Animal and crop diseases are likely to increase with earlier springs and warmer winters, which create favorable conditions for higher survival rates of pathogens and parasites. Owing to climate change, previously rare diseases may become more prevalent. For example, Mu (2009) finds that spread of Avian Influenza, is positively correlated with increased temperatures while Egbendewe-Mondzozo et al. (2011) find that malaria spread is

Phenomenon and direction of trend (Likelihood of future trends)	Examples of major projected impacts by sector			
	Agriculture, forestry and ecosystems	Water resources	Human health	Industry, settlement and society
Over most land areas, warmer and fewer cold days and nights, warmer and more frequent hot days and nights (Virtually certain)	Increased yields in colder environments; decreased yields in warmer environments; increased insect outbreaks	Effects on water resources relying on snow melt; effects on some water supplies	Reduced human mortality from decreased cold exposure	Reduced energy demand for heating; increased demand for cooling; declining air quality in cities; reduced disruption to transport due to snow, ice; effects on winter tourism
Warm spells/heat waves. Frequency increases over most land areas (Very likely)	Reduced yields in warmer regions due to heat stress; increased danger of wildfire	Increased water demand; water quality problems, e.g., algal blooms	Increased risk of heat-related mortality, especially for the elderly, chronically sick, very young and socially-isolated	Reduction in quality of life for people in warm areas without appropriate housing; impacts on the elderly, very young and poor
Heavy precipitation events. Frequency increases over most areas (Very likely)	Damage to crops; soil erosion, inability to cultivate land due to water logging of soils	Adverse effects on quality of surface and groundwater; contamination of water supply; water scarcity may be relieved	Increased risk of deaths, injuries and infectious, respiratory and skin diseases	Disruption of settlements, commerce, transport and societies due to flooding; pressures on urban and rural infrastructures; loss of property
Area affected by drought increases (Likely)	Land degradation; lower yields/crop damage and failure; increased livestock deaths; increased risk of wildfire	More widespread water stress	Increased risk of food and water shortage; increased risk of malnutrition; increased risk of water- and food-borne diseases	Water shortages for settlements, industry and societies; reduced hydropower generation potentials; potential for population migration
Intense tropical cyclone activity increases (Likely)	Damage to crops; windthrow (uprooting) of trees; damage to coral reefs	Power outages causing disruption of public water supply	Increased risk of deaths, injuries, water- and food-borne diseases; post-traumatic stress disorders	Disruption by flood and high winds; withdrawal of risk coverage in vulnerable areas by private insurers, potential for population migrations, loss of property
Increased incidence of extreme high sea level (excludes tsunamis) (Likely)	Salinisation of irrigation water, estuaries and freshwater systems	Decreased freshwater availability due to saltwater intrusion	Increased risk of deaths and injuries by drowning in floods; migration-related health effects	Costs of coastal protection versus costs of land-use relocation; potential for movement of populations and infrastructure; also see tropical cyclones above

Note: Table based on IPCC, WGII, 2007, Table SPM-2. The descriptions of likelihood of future trend refer to a probabilistic assessment and the associated probability measures are listed as follows: virtually certain, greater than 99% chance; very likely, 90 to 99% chance; likely, 66 to 90% chance. More details in IPCC, WGII, 2007.

Table 1. Examples of possible impacts of climate change due to changes in extreme weather and climate events.

correlated with climate change. Another example is the expected rise in cattle ticks that carry blood pathogens to non–immune cattle. According to the final report by the Allen Consulting Group (2005), the estimated potential impact (without adaptation) of cattle ticks rise in Queensland and New South Wales (NSW) could range from between $18 million to $192 million, depending on the discount rate used. Also, plant disease pressure may also increase (USCCSP, 2008).

2.1.1.8 Fires

Disturbances from forest, grass and crop fires have important consequences for grassland production, timber production, species composition, infrastructure and public perception. Increased temperatures in spring and summer, earlier spring snowmelt, dieing vegetation and altered woodland growth have been found to be associated with increased fire risk (Westerling et al., 2006; Rapp, 2004). Since climate change will exacerbate forest fire on a regional basis, new fire and fuels management strategies may be needed to manage such fire risks (Brown et al., 2004).

2.1.1.9 Sea level induced inundation

Sea level rise and associated innundation of agricultural lands can be a serious threat. The rate of sea level rise has been accelerating with the 100 year average 1.8 mm per year and the 1993-2003 periods showing an average of 3.1 mm per year (Douglas, 1997; Church & White, 2006; Bindoff et al., 2007). Some predict yet larger rates for the future. For instance, Dasgupta et al. (2009) project 1 to 3 meters but also suggest as much as 5 meters is possible if the unexpected rapid breakup of the Greenland and West Antarctic ice sheet occurs while Hansen (2007) suggests up to a 5 meter rise is possible and Hansen and Sato (2011) argue for a nonlinear, rapid response later in the century.
The effect from sea level rise induces agriculture and the global food market vulnerable. Dasgupta et al. (2009) show substantial land loss in Southeast Asia, East Asia, South Asia, and the Southeast US. Chen et al. (2011) estimate the economic impacts of sea level rise in terms of rice production showing substantial regional effects on the rice market.

2.1.2 Productivity implications

The above forces have been shown or simulated to affect productivity of crops, livestock and forest. For the effects of climate drivers on crops, in general northern regions in US have positive yield changes, while southern regions increase less or even decline in some cases (Reilly et al., 2002; McCarl, 2006; Antle, 2009). Productivity of livestock is directly influenced through climate stress and indirectly impacted through pasture growth, forage production and grain availability (Seo & Mendelsohn, 2008a, 2008b). Besides, forest production is affected by the interaction of temperature, precipitation, nitrogen and CO_2.

2.1.2.1 Crop productivity

The effect of climate change on crop production is expected to vary by crops and regions owing to regional climate and resource conditions (Adams et al., 1998; Lewandrowski & Schimmelfennig, 1999; Reilly et al., 2001). At the national level, productivity of many major crops is likely to increase under the climate scenarios (National Assessment Synthesis Team [NAST], 2000). Although more frequent and/or severe extreme events, e.g., droughts and floods, cause agriculture to be more vulnerable with the increasing agricultural losses, concentrations of CO_2 tend to overcome much of the climate-altered yield dampening effects (Adams et al., 1995).

The crop productivity effects of changing climate, such as increasing temperature and possibly drier conditions has been extensively studied using crop simulation models and econometric methods. Both the mean and variance of crop yields in a crop specific fashion are expected to be modified by changes in climate (Chen et al., 2004; Kim & Pang, 2009). Moreover, the effects of CO_2 concentrations have been evaluated through FACE (Free-Air Concentration Enrichment) experiment and other experiments (Kimball et al., 2002) and then built into simulation models.

2.1.2.2 Livestock productivity

Hotter temperatures can alter animal mortality, feed conversion rates, rates of gain, milk production, conception rates and suppress appetite (Hahn, 1995, 2000; Mader et al., 2009; Adams, 1998) although again on a regional basis. Mader et al. (2009) review evidence that temperature increase will have negative effect on milk production in the central United States, while in northern areas swine producers may gain some benefit to climate effects and beef producers would need to feed cattle up to 16% longer with more common average increases of 4% to 5%. Extreme events are also important, for example, the heat waves of 1995 and 1999 caused severe documented cattle losses in individual states in US approaching 5,000 heads each year (Hahn et al., 1997, 2001).

Livestock will also be affected by climate influences on availability and quality of feed (Easterling et al., 1993; Ehleringer et al., 2002; Morgan et al., 2005). Swine and beef production are found to be affected most in the south-central and southeastern United States and dairy production is expected to be influenced the most in the mid-west and north-east regions (Frank et al., 2001). Forage production will be altered as climate alters grass growth (Reilly et al., 2002). Also higher concentrations of CO_2 could alter forage chemical content, nutritional value and digestability (The Allen Consulting Group, 2005; Adams et al., 1998).

2.1.2.3 Forest productivity

Climate change alters forest productivity. Increases in temperature, precipitation, nitrogen deposition and atmospheric CO_2 can raise forest growth and carbon storage (Irland et al., 2001). Sohngen et al. 2001 indicate climate change is predicted to increase global timber production. Producers in low-mid latitude forests react quickly with more productive short rotation plantations and drive down timber prices. Contrarily, because of long-rotation species, it is likely that producers in mid-high latitude forests are hurt by the lower prices, dieback, and slower productivity increases. On the other hand, carbon sequestration is an important characteristic of forests. Currently long-lived wood products offset about 20 percent of annual US fossil fuel carbon emissions (USCCSP, 2008). This carbon sequestration mitigates future climate change.

2.2 Economic vulnerability

Climate change potentially increases economic vulnerability of agriculture in a number of ways including altering the contribution of agriculture to the overall national economy, comparative advantage relative to other countries or regions, welfare distribution, and market prices (Fischer et al., 2002; McCarl et al., 2010).

In terms of extreme events, Chen et al. (2001) estimated the economic damages and the welfare change from Timmerman et al.'s projections of stronger and more frequent ENSO events. They found that the frequency shift caused the aggregate economic welfare loss while the frequency and strength shifts caused substantially larger damages.

2.2.1 Contribution of agriculture to the overall national economy

Since agricultural production is highly affected by climate, then countries with a higher proportion of agriculture in gross domestic product (GDP) have economies that are more likely to be vulnerable to climate change. This proportion in developing countries is about 13%, compared with 2% in developed countries (Fischer et al., 2002). Agriculture plays an important role in developing countries, such as Asian-Pacific region. For example, the share of agriculture in GDP in Thailand is 20%. Earning from exports of agricultural products occupies about 70% of the substantial foreign exchange earnings in Philippines (Luo & Lin, 1999). China produces the largest agriculture output in the world, but only about 15% of its total land area are arable, which causes the highly vulnerability of China's agriculture. In China meteorological disaster has become a major factor limiting the growth of grain production. During the period of 1996-2003, loss of grain production from meteorological disasters reached 50.9 million tons a year (Li & Lin, 2007). Another major agricultural producer, US, accounts for more than 25% of the total global trade in corn, soybeans, wheat, and cotton. The projection results show that the effect of climate change on agricultural production varies across the types of crops (NAST, 2000).

2.2.2 Comparative advantage shift

Changing climate is likely to alter agricultural production but on regionally specific bases. Regions near the equator where production is limited by heat may reduce production while higher latitude regions where production is limited by cold may gain. This will affect interregional agricultural production and trade patterns plus interregional comparative advantage, both within countries and internationally (Reilly et al., 1994; Darwin et al., 1995). Such shifts has been found in a number of settings. For example Adams et al. (1990) and Reilly et al. (2000) perform modeling studies that find such shifts in the US while Mendelsohn et al. (1994) show shifts in land values and Seo et al. (2010) show shifts in land use.

2.2.3 Welfare distribution

When assessing agricultural vulnerability, two major groups who are potentially vulnerable to changing climate are producers (e.g., farmers, retailers and people working in ancillary agro-industries) and consumers (e.g., who consume agricultural goods and/or agricultural services). Due to lower adaptive capacity, smaller farms are more vulnerable to climate change than larger farms. For instance, in Europe, more and more large farms grow at the cost of small farms. Consumers benefit from the process of fewer smaller farms since prices of agricultural products are lower than before (Adams et al., 1990; Berry, 2006).

A number of studies have conducted welfare assessments on the effects of climate change. In earlier studies, the total welfare change from climate change was found to be negative, but this effect has tended to be less and even beneficial over time, which is partly due to milder temperature and precipitation estimates emerging from the global circulation models, treatment of CO_2 fertilization effects, and inclusion of adaptation alternatives (Adams et al., 1990, 1995, 1999; McCarl, 1999, 2006; Reilly et al., 2001). Different from the results in Berry (2006) and Mendelsohn et al. (1994), US agricultural studies considering market price adjustments have found reductions in crop productivity induced by climate cause rising prices and turn out to be harmful for consumers and beneficial to producers.

2.2.4 Market price of agricultural commodities and inputs

Climate change affects agricultural production through the variability of commodity prices and input costs that determine one country's comparative advantage in international markets. Adams et al. (1995) present the importance of market-level changes using estimated wheat yield changes from the research by Rosenzweig et al. (1995) for the US. Market prices are likely to shift and stimulate production mix and other adjustments (McCarl, 2006). What's more, the interaction between climate change, CO_2 level, adaptation, and economic conditions such as relative output prices determines the relative and absolute measures of vulnerability (Antle et al., 2004).

2.3 Reallocation of land use

Climate change will cause alterations in land. Humans change their land use from crops to pasture because of adaptation of drought (Mu & McCarl, 2011). Droughts, and excessive grazing cause grassland degradation and desertification. Irrigated crop land expands substantially if water is available as irrigation allows adaptation to the hotter and drier climate (Adams et al., 1999).

Land competition is also induced by adaptation or mitigation policies against climate change. For example, alternative energy is proposed as a response to climate change. However, the excess demand of crops promotes the rising of global crop prices which induce the incentive to Brazilian agricultural producers to increase deforestation and expand the scope of tillage (Searchinger et. al., 2008).

3. Adaptation to climate change

As shown above agriculture is vulnerable to climate. However by its very nature agriculture has historically adapted to climate. There is also an inevitability of a substantial degree of climate change due to the energy emission development linkage plus the projected growth of population and income (Antle, 2009; IPCC, WGII, 2007; Rose & McCarl, 2008). Adaptation is the inveitable response to such developments. It seeks to maintain the current productivity even under climate change by using adaptation strategies such as change of planting dates, crop mix, and livestock feeding management, or migration strategies (Adams et al., 1999; Reilly et al., 2002, 2003).

3.1 Means of adaptation

A variety of adaptation options are available. They may be privately or publically implemented. Private or autonomous adaptation to climate change (IPCC, WGII, 2001; Smit et al., 2000) occurs by the people who produce agricultural goods, and manage the land, trees, waterborne transport, water facilities, and other capital resources related to the production. Those are able to select to alter their management practices, crop mix, and other strategies. These adaptation behaviors are referred to as "autonomous adaptation" in that most of them can be made without governmental intervention.

Planned or public adaptation is made by governmental interference. This adaptation is often addressed in the case unlikely met by autonomous actions because of the existence of externalities and/or the needs for large scale and resource requirements. Both of them are not mutually exclusive and the planned adaptation can increase the possibility of autonomous adaptation in the way of education, subsidies, and other regulations.

Both private and public actions to facilitate adaptation to changing climatic conditions can be pursued by different parties at different levels of operation and forms, the features of which have different investment needs. Some of the adaptation strategies would go further without demanding direct investment but several of them would need some mix of capital and research investments with information and technology dissemination. The degree of needs for agricultural adaptation depends on the level of mitigation, anticipated potential local climate change, capacity to adaption, and relative effects with other sectors (Rose & McCarl, 2008).

3.1.1 Means of private adaptation

Private, autonomous, or market adaptation decisions are made by individuals, households, and businesses. In managed systems, they react to the climate alterations through changing such things as planting and harvesting date, varieties, crops grown, species, etc. For instance, the private decision makers can adjust insurance premiums, and air-conditioning as human system adaptation against the altering climate (Klein et al., 1999). Other common strategies of private adaptation include altering the management or practice of crop, forage and tree varieties, livestock breeds and species, soil moisture, pest and disease, natural area, fire, and land use.

3.1.2 Means of planned adaptation

Planned adaptation including facilitation of autonomous ones, as carried out by governments, international organizations, and NGOs. Such actions can have a significant impact on the increased public related investments. A number of possible strategies can be pursued including the following as summarized from McCarl (2007).

3.1.2.1 Research and extension investment

Public investments on research and extension can provide and disseminate adaptation strategies that could be implemented by individual agricultural producers. Public investments would need to go into adaptation increasing technology and adaptation information dissemination designed to help private level implementations.

3.1.2.2 New infrastructure

Investment for the planned adaptations to climate change may need to address providing or altering transport and municipal infrastructure, developing new lands, improving of existing lands, constructing irrigation/water control structures, protecting coastal resources, incubating of new industries, and other possible facilities.

3.1.2.3 Adaptation adjustment assistance

Migration of facilities and land uses may be required to adapt to climate change. Needed would be the investments on supporting the new industries, creating job opportunities, assisting incomes, developing new institutions, relocating industry, improving market functions, developing insurance, and others.

3.1.2.4 Trade policy

Governments may facilitate adaptation by modifying trade policies to allow imports and exports to alleviate lost production and cope with surpluses by lowering the international trade barriers.

3.2 Limits to adaptation

IPCC, WGII (2001) identified six determinants that will influence the degree of adaptation: economic resources; technology availability; information and skills; infrastructure;

institutions; and equity. There are also relevant affecting factors: degree of realized climate change; the amount of public and private investment undertaken; asset obsolescence; generated research findings; information availability and producer flexibility. Furthermore, the change of the regulations may change the ability of adaptation in agriculture. For example, implementing the GHG cap and trade policy may allow agricultural industry to provide alternative energy sources as opportunities for improving income.

The availability of the affecting factors is very diverse across nations. For instance, differences in the agricultural technology research and investments would differ the degree of adaptation. A country might choose the other economic investments rather than the agricultural technology and hence linger the improvement of food production in spite of the large demands for food security (Pardey et al., 2006a; Pardey et al., 2006b; Roseboom, 2004).

3.3 Findings about effectiveness and extent of adaptation

Literatures on adaptation are now emerging and diverse but deal with merely partial issues. Moreover, they do not fully address the potential and the constraints of adaptation along with the costs since adaptation measures are often narrowly studied in small regions thanks to geographical and climate factors as well as institutional, political and financial constraints (IPCC, WGII, 2007). Here are some research findings of analyses of adaptation to climate alterations.

- Cropping system management adjustments can deal with projected climatic and atmospheric changes (R. M. Adams et al., 2003; Butt et al., 2005; Challinor et al., 2007; Easterling et al., 2003; Travasso et al., 2006).
- Tubiello et al. (2000) examine crop adaptation in Modena, Italy and find that currently there are adaptations of varieties and planting times that avoid drought and heat stress during the hotter and drier summer months. Furthermore they show that these adaptations have avoided significant negative impacts on sorghum (-48 to -58%) moderating them to be neutral to marginally positive ones (0 to +12%).
- IPCC, WGII (2007) provides evidence on the benefits of adaptations which alter crop productions on temperature changes across regions. It estimates approximately a 10% yield benefits from adaptation comparing to yield with no adaptation.
- Crimp et al. (2008) find that benefits of adaptation would be diminished by increasing temperature.
- Parry et al. (2009) provide an estimate that there will be a needed $8 billion in costs for adapting crop irrigation systems to climate change by 2030.
- McCarl (2007) assumes adaptation will require a 10% increase in research and extension funding and a 2% increase in capital infrastructure costs and develops global marginal estimates for additional funding for adaptation of the agricultural sector due to climate which are $12.6 billion and $11.3 billion – without and with mitigation, respectively, in the year 2030.
- Changes in tree harvesting rates, composition of species, pest control, and location of managed woodland could result from the adaptation of unmanaged forest (Parry et al., 2009).
- Adaptation in forest is a complementary strategy with mitigation of greenhouse gas emissions (Parry et al., 2009).
- Sohngen et al. (2001) find that producers in low-mid latitude forests can adapt with more productive short rotation plantations, driving down timber prices.

- Many studies have discussed the necessity of adaptation in water management system but they do not take account of the feasibility of adaptation options (Hayhoe et al., 2004; Hurd et al., 2004; Mote et al., 2003; Roy et al., 2001).
- Adaptive strategies to deal with climate change are beginning to be considered in conservation of ecosystems (Chopra et al., 2005; Lemieux & Scott, 2005), and have emphasized the importance of planning guided by future climate scenarios (IPCC, WGII, 2007).
- Competition among land use is a big issue in agricultural adaptation (Hertel et al., 2009). As one of the results from land use competition, Fischer et al. (2002) expect that globally there will be major benefits from agricultural land by 2080, specifically in Russian Federation (40-70%) and North America (20-50%), but losses of up to 9% in sub-Saharan Africa.
- Adaptation is regionally specific and capacity to adapt varies. Consequently equity and burden sharing are an issue. It is likely that highly vulnerable developing countries have lower adaptive capacity due to lower per capita incomes, weaker institutions, and less access to technology, credit and international markets (Burton et al., 2006; Green et al., 2010).
- Climate variability can play a significant role in changing the cropping system productivity (Porter & Gawith, 1999; Wheeler et al., 2000).

4. Concluding comments

As reviewed above agriculture is vulnerable to climate change. This will stimulate a wide array of climate change adaptations plus public efforts facilitating adaptations. The following list contains a few of the unresolved issues in need of further studies in agricultural adaptation.

- The distribution of positive and negative impacts from climate change is uneven depending on the regions. Parry et al. (2009) argue that the positive effects would happen in agriculture at the higher latitudes unlike the more immediate negative impacts at the lower latitudes. They emphasize the needs of studies on balancing different parts of the world and over a range of time projections in a complex environment.
- Adaptation and development costs will be dominated by other changes like population growth (McCarl, 2007). However, there are many intrinsic links between increases in productivity and resilience to climate (Parry et al., 2009).
- Producers and processers in agriculture will be required to adapt to altered variability in patterns of rainfall and temperature including alterations in extremes. Parry et al. (2009) argue that adapting to this altered variability is a significant challenge.
- Competition will occur between food, energy, adaptation and mitigation in terms of resources and funds.
- The optimal degrees of adaptation and practical levels of the extent to which climate change vulnerability can be addressed needs examination.
- Understanding of the process in which adaptation is taking place and the future limits plus needed institutional innovation is needed (IPCC, WGII, 2007);
- Further studies need to address means for adapting existing crops and livestock, moving varieties of heat tolerant crops and livestock breeds into regions, and altering management (Antle, 2009; McCarl, 2006).
- Examinations of the levels of investment required for adaptation are needed.

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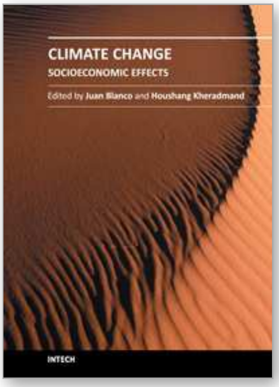

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This book shows some of the socio-economic impacts of climate change according to different estimates of the current or estimated global warming. A series of scientific and experimental research projects explore the impacts of climate change and browse the techniques to evaluate the related impacts. These 23 chapters provide a good overview of the different changes impacts that already have been detected in several regions of the world. They are part of an introduction to the researches being done around the globe in connection with this topic. However, climate change is not just an academic issue important only to scientists and environmentalists; it also has direct implications on various ecosystems and technologies.

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