THREE ESSAYS ON CLIMATE CHANGE IMPACTS, ADAPTATION AND MITIGATION IN AGRICULTURE

A Dissertation

by

WEI WEI WANG

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2012

Major Subject: Agricultural Economics

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Approved by:

Chair of Committee, Bruce A. McCarl
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ABSTRACT

Three Essays on Climate Change Impacts, Adaptation and Mitigation in Agriculture.

(August 2012)

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Chair of Advisory Committee: Dr. Bruce A. McCarl

This dissertation investigates three economic aspects of the climate change issue: optimal allocation of investment between adaptation and mitigation, impacts on a ground water dependent regional agricultural economy and effects on global food insecurity. This is done in three essays by applying mathematical programming.

In the first essay, a modeling study is done on optimal temporal investment between climate change adaptation and mitigation considering their relative contributions to damage reduction and diversion of funds from consumption and other investments. To conduct this research, we extend the widely used Integrated Assessment Model—DICE (Dynamic Integrated Climate Economy) adding improved adaptation modeling. The model results suggest that the joint implementation of adaptation and mitigation is welfare improving with a greater immediate role for adaptation.

In the second essay, the research focuses on the ground water dependent agricultural economy in the Texas High Plains Region. A regionally detailed dynamic land allocation model is developed and applied for studying interrelationships between limited natural resources (e.g. land and groundwater), climate change, bioenergy demands and agricultural production. We find out that the effect varies regionally across hydrologically heterogeneous regions. Also, water availability has a substantial impact on feedstock mix. In terms of biofuel feedstock production, the model results show that limited water resource cannot sustain expanded corn-based ethanol production in the future.

In the third essay, a Computable General Equilibrium (CGE) model is applied in an attempt to study potential impacts of climate change on global food insecurity. Our results show that climate change alters the number of food insecure people in a regionally different fashion over time. In general, the largest increase of additional food insecure population relative to the reference case (no climate change) is found in Africa and South Asia, while most of developed countries will benefit from climate change with a reduced proportion of food insecure population.

In general, climate change affects world agricultural production and food security. Integrated adaptation and mitigation strategy is more effective in reducing climate change damages. However, there are synergies/trade-offs between these two options, particularly in regions with limited natural resources.

DEDICATION

To my family

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It is a rewarding experience of pursuing my doctoral degree in Texas A&M University. My sincere gratitude goes to my committee chair, Dr. Bruce McCarl, for his inspiration and encouragement in the past several years. Without his dedication, advice and research support through my doctoral studies, this dissertation would not have been possible.

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1. INTRODUCTION

The issue of global climate change and what to do about it has emerged as a major scientific and public policy issue. Scientific studies indicate that accumulated carbon dioxide (CO_2) emitted from the burning of fossil fuels, along with contributions from other human-induced heat-trapping greenhouse gas emissions, is leading to warmer surface temperatures. These increases in temperature and greenhouse gas (GHG) concentrations are driving a multitude of related and interacting changes in the earth systems, including increased frequency of extreme temperature events, altered precipitation patterns, sea-level rise, and reversal of ocean currents. These changes, in turn, pose significant risks to both human and natural systems. Although the details of how the future impacts of climate change will unfold are not as well understood as the basic causes and mechanism of climate change, we can reasonably expect that the consequences of climate change will be more severe if actions are not taken to limit its magnitude and adapt to its impacts.

There are two fundamental response options to the risks posed by anthropogenic climate change. The first (and more prominently discussed option) is mitigation. Mitigation addresses the *cause* of climate change by reducing the emissions of harmful greenhouse gases to avoid future climate change.

This thesis follows the style of *American Journal of Agricultural Economics*.

The second response is adaptation which aims at moderating the adverse effects of unadaptable climate change through a wide range of actions that are targeted at reducing the impact on vulnerable systems. Owing to the major differences in the typical temporal and spatial scales at which mitigation and adaptation take place and in their respective information needs, these two options are formulated largely independent of each other (Füssel and Klein 2006).

Mitigation has traditionally received much greater attention than adaptation in the climate change community, both from a scientific and from a policy perspective. Important reasons are:

- Mitigation helps to reduce climate change damages in all climate-sensitive systems, whereas the potential of adaptation measures is limited for many systems. For humans, adaptation is a risk-management strategy that may be planned and undertaken by private decision makers, by public agencies or governments and is never foolproof.
- GHG emission reductions are relatively easy to monitor quantitatively, whereas it is much more difficult to measure the effectiveness of adaptation in terms of avoided damages, or to ensure that assistance to facilitate adaptation would be fully additional to existing development aid budgets.

Mitigation actions are essential to reduce future climate change and related irreversible and potentially catastrophic consequences. However, even the most stringent mitigation efforts cannot avoid further impacts of climate change in the next few decades, because

- Climate system and energy system/GHG emissions have a great deal of inertia so that some degree of climate change is inevitable even under the most ambitious emission reductions (IPCC 2007b; Rose and McCarl 2008).
- The effect of mitigation takes several decades to fully manifest itself, whereas most adaptation measures have more immediate benefits.
- Optimal provision of mitigation requires creating incentives for international cooperation (Viguier 2003), whereas adaptation can be effectively implemented on a local or regional scale such that their efficacy is less dependent on the actions of others.

Therefore, in addition to the need for mitigation there are also convincing arguments for adaptation as a response measure to climate change. The first indications that adaptation is desirable appeared in the 1997 Kyoto Protocol, that were subsequently strengthened in Bali in 2007, and then were subject to an investment agreement in the 2009 Copenhagen Accord. Such a growing emphasis on adaptation attests to the political and scientific consensus of the necessity of a joint mitigation and adaptation effort. However the means to optimally finance mitigation and adaptation actions and the choice of actions to pursue are issues today. The accelerating pace of climate change, combined with increasing population and limited natural resources threatens food security. Therefore, cost-benefit studies on both adaptation and mitigation activities are priority research needs and here I will examine their synergies/tradeoffs in an agricultural context.

Agriculture is highly sensitive to climate as it is highly dependent upon temperature, precipitation and other climatic attributes. As such climate change poses a challenge and will play an important role in future food supply security. Significant efforts to assess the potential impacts of climate change on agriculture began in 1978. Since then, more scientific studies have resulted in a growing consensus on the interactions between climate change and agriculture. The scope of research spans across direct effects of climate change on crop yields/production and livestock (Adams et al. 1995; McCarl et al. 2008; Seo and Mendelsohn 2008), local farmers' responses to changing climate conditions (Butt et al. 2005), and global perspective on the agricultural impacts of climate change and adaptive responses (Parry et al. 2004; Reilly et al. 1996). In general, agronomic and economic impacts from climate change are primarily manifest in terms of the following two factors (Feng et al. 2010):

- The rate and magnitude of change in climate attributes and the agricultural effects of these changes.
- The ability of agricultural production to adapt to changing environmental conditions.

A report issued by U.S. Climate Change Science Program (USCCSP) provides detailed consideration of potential impacts of climate change on major crops, pastureland, rangeland, and livestock operations in the US (USCCSP 2008). The major findings are the following:

- Much of the United States has experienced higher precipitation and stream flow, with decreased drought severity and duration, over the 20th century. The western and southwestern region, however, are likely to become drier.
- Grain and oilseed crops will mature more rapidly, but increasing temperatures will increase the risk of crop failures, particularly if precipitation decreases or becomes more variable.
- High temperature will negatively affect livestock, which will result in reduced productivity of livestock and dairy animals.
- Significant impacts are likely to felt on irrigation water supply and demand which is sensitive to higher temperatures and increased precipitation variability.

To reduce such negative impacts, adaptation may occur in three fundamental types (Howden et al. 2007; Rose and McCarl 2008):

- Shifts in management practices (e.g. changing irrigation practice, changing drainage management regimes, altering timing or location of cropping activities, etc.).

- Changes in enterprises employed at a particular site (e.g. altering crop mix to use more heat tolerant crops, land use change including the abandonment of some agricultural land).

- Adoption of new technology involving direct capital investment and/or practice improvements developed by agriculture research (addressing plant/animal species or varieties, genetic improvements, water harvesting, conserving soil moisture, etc.).

One should notice that adaptation is nothing new for the agriculture sector and it is an ongoing activity. Farmers routinely make land-use and management decisions in face of climate and market variability. Successful adaptations in U.S. history include agricultural production in irrigated areas of the High Plains of Texas and the dryland areas in the Midwestern Corn Belt. These productive areas are usually supported by substantial local research and technology diffusion efforts as well as investment in appropriate technologies. However, even with adaptation, the profit loss associated with climate change will still be faced by farmers. The need for adaptation presents a number of challenges to agricultural system, including the following:

- The autonomous adaptation activities by individual farmers or private agents are limited and highly depending on the own capacity to adapt. Planned adaptation supported by regional or national government may lead to more effective actions.

- Investment and capital intensive agricultural practices may need to spread to new locations. For example, there are increased needs for enhanced irrigation water management in areas where soil moisture is expected to decline due to warmer and drier weather.

- Keeping the farming community well informed about climate risks; extension activities may need to be broadened to include educational outreach and dissemination of adaptation strategies.

Currently, agriculture has been active in activities that contribute to climate change mitigation also, as demonstrated in part by the dramatic expansion of biomass production in the past decade. The term ‘biomass’ is defined as any organic material that is available on a renewable or recurring basis—agricultural crops, dedicated energy crops, wood waste and residues, plants (including aquatic and grasses) and fibers. Liquid biofuels (e.g. ethanol, biodiesel) and biopower are two major biomass productions as a solution to the country’s energy and climate change problems. Recent federal and state policies have established ambitious goals for biofuels and electric power from renewable sources (Energy Independence and Security Act of 2007). However, concerns exist that bioenergy expansion may have sever negative impacts on biodiversity and the use of natural resources through increasing competition over land and water resources (McCarl et al. 2000). Increased biofuel production particularly the grain-based ethanol production has already had significant impacts on agricultural markets and food security.

Food security has always been the most import issue around the world. Recently, this focus is strengthened by growing concerns over the potential impacts of climate change and identified opportunities for agriculture in mitigation (e.g. soil carbon sequestration and biofuel production, etc.). Food security is a broad term, which is defined in at least 30 ways by a number of organizations around the world (Maxwell and Smith 1992). Currently, the widely accepted definition of food security is that provided by FAO as a "situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 2001). This definition comprises four key dimensions: availability, stability, access, and utilization. *Availability* relates to the supply of sufficient food, i.e., to the overall ability of the agricultural system to meet food demand; *access* refers to having the means to acquire food through production or purchase; *stability* relates to individuals who are at high risk of temporarily or permanently losing their access to the resources needed to consume adequate food; and *utilization* refers to the appropriate nutritional content, food safety and quality and the ability of the body to use it effectively. Climate change and bioenergy development will affect food security in all of these four dimensions.

- Food availability: Climate change affects food production in complex ways—directly through changes in agro-ecological conditions and indirectly by affecting growth and distribution. Climate change will have potentially large effects on both agricultural yields and potential cropped area. Developing countries could experience a decline of 9%-21% in overall potential agricultural productivity as result of global warming (FAO 2009). Increased demand for biofuels may actually increases production of food commodities, but much of the increased production would be diverted away from use as food.

- Food access: Impacts on access will be mixed, as a reduction in agricultural incomes associated with climate change will reduce access for people in poorer countries, while increased demand for agricultural commodities due to biofuels will increase agricultural incomes for some producers but also increase food prices for consumers. The strongest impact of climate change on the economic output of agriculture is expected for sub-Saharan Africa, which means that the poorest and already most-food insecure region is expected to suffer the largest contraction of agricultural incomes. On average, prices for food are expected to rise moderately in line with moderate increases of temperature (until 2050) (Schmidhuber and Tubiello 2007).

- Food stability: Increased frequency of extreme climate events will increase the variability of agricultural production. Droughts and floods are the primary causes of acute food shortages in semi-arid and sub-humid areas. With the expanding of biofuel production, agriculture will become more closely linked with energy markets, introducing additional variability in agricultural commodity prices.

- Food utilization: Climate change has the potential to affect health status directly, in ways that affect an individual’s ability to utilize food. Diarrheal disease in areas with limited access to clean water is a leading killer to children. Warming temperatures will likely expand the range of vector-borne diseases such as malaria and dengue (McMichael et al. 2006) and also raise the frequency of food poisoning. By contrast, employing of bioenergy could improve indoor air quality in poor households otherwise reliant on fuel wood or animal dung. Substitution of biomass for coal in power plants has the effects of reducing sulfur dioxide (SO_2) emissions.

Summarizing, the relationships between climate change (with impacts, adaptation and mitigation strategies) and agriculture (food security) are complex and manifold. They involve biophysical and environmental aspects as well as social and economic response. Several key areas have been identified that could help overcome the challenges of climate change on agriculture production and food security.

- Where are the key synergies between climate change adaptation and mitigation in terms of technological, institutional and financing options for agriculture?

- What are the tradeoffs between land and water use for food, bioenergy and carbon sequestration need to be considered in facing of changing climate?

- Given current and predicted impacts on food security due to climate variability and exposure to extreme weather events, what are the key constraints to adaptation and mitigation?

- How can the global and national agendas for achieving adaptation to climate change, food security and climate change mitigation be made more coherent and mutually supportive to address these interrelated challenges posed by climate change?

All of these questions are receiving increasing concern nowadays but few are completely answered due to the limitation in reliable methodology and data and the complication themselves.

This dissertation aims to shed light on some of above open questions through three essays:

- The first essay examines the optimal temporal investment in climate change adaptation and mitigation and their relative contributions to damage reduction.

- The second essay addresses the economic and groundwater use implications of climate change, agricultural adaptation and mitigation activities (e.g. bioenergy feedstock production) in Texas High Plains Region

- The third essay assesses the potential impacts of climate change on world food security by applying a computable general equilibrium (CGE) model

The primary objective of this dissertation is to investigate the synergies/tradeoffs between climate change damages, adaptation and mitigation strategies and their economic (e.g. social welfare, capital investment) and food security implications at the local, national and global scales. More specifically,

- In the first essay, we will examine the inter-temporal optimal mix between adaptation, mitigation and regular investment in production, and the final implication for damages reduction and social welfare.

- In the second essay, we will examine what climate change and biofuel feedstock production do to irrigated agriculture economics, land and water use over the 2010-2050 horizons in the Texas High Plains Region.

- In the third essay, we will examine technology development and climate change impacts on global agricultural production and the number of undernourished population in 2020 and 2050.

2. TEMPORAL INVESTMENT IN CLIMATE CHANGE ADAPTATION AND MITIGATION

2.1 Summary

Increasingly there appears to be recognition the need to simultaneously implement adaptation and mitigation since ambitious mitigation action aiming at reducing future climate change will not prevent much climate change before mid-century (IPCC 2007a, c). It is also understood that there are trade-offs and synergies between them with the competition of finite budget and resources (e.g. land, water and energy). Better modeling of costs and benefits in both adaptation and mitigation could have important implications for defining mitigation targets globally or regionally. However, the optimal combination between adaptation and mitigation that can best address climate change over time is still an open question. In this paper, we propose a new conceptual framework with both options and extend DICE (Dynamic Integrated Climate-Economy) model with comprehensively measured adaptation plus unadaptable damages and investment competition. Our empirical results suggest that while mitigation tackles the long run cause of climate change, adaptation is an economically effective complement to mitigation and is an important current policy option. We also find that optimal policy recommended by the model changes markedly with key uncertain parameters in climate sensitivity and damage function. More rapidly mitigation effort is called for with higher level of damages given temperature increase.

2.2 Introduction

Climate change has gained increased attention as scientific evidence has accumulated on changes and their impacts to society (IPCC 2007 a, b; Stern 2007). Estimates are that world economy will suffer substantial future climate change induced damages with estimated mean global GDP losses of 1.5 to 3.5% (IPCC 2007a). The study by Stern (2007) summarized that the business as usual damages could rise to 20% of GDP, with 35% losses or more at the 95% confidence threshold. Economic research on climate impacts has long revealed that several fraction of market economy is vulnerable to climate change: agriculture (including forestry), coastal resources, energy, tourism and water (Pearce et al. 1996). Crop and livestock production might fall in the low latitudes countries such as Africa, Latin America and China (IPCC 2007b), sea level rise can inundate substantial land in low-lying areas and threaten existing port facilities, extreme events will be intensified such that droughts and floods will become more sever in low- and mid-latitude regions again (McCarl and Reilly 1999), human health and ecosystem might be vulnerable to changing climate patterns.

The weight of the scientific evidence supports the conclusion that the continued buildup of greenhouse gases will cause the earth to warm. However, there is considerable debate about what is the sensible and effective policy response to this problem. In general, two major policy approaches are possible

- Adaptation by adjusting productive activities to the changing climate

- Mitigation of the degree of future climate change by limiting net anthropogenic greenhouse gas (GHG) emissions or exploiting carbon sinks.

Many have discussed mitigation (IPCC 2007b; NAS 2010b). Adaptation is today becoming an increasing topic of interest. Adaptation refers to actions that make adjustments in natural or human systems in order to moderate potential damages from climate change or exploit beneficial opportunities. Burton (2004) argues adaptation is extremely common and as old as mankind, but that it is largely to a stationary spatially or temporally varying climate without considering future climate change. Carter et al. (1994) classifies adaptation as autonomous and planned as do all of the subsequent IPCC reports and the most recent ones like UNFCCC (2010), Parry et al. (2009) and World Bank (2010). Autonomous adaptation involves the reactions that natural and human systems will undergo in response of changing conditions, irrespective of any policy plan or decision. Planned adaptation, on the other hand, is the deliberate policy options or response strategies, aimed at altering the adaptive capacity or facilitating specific adaptations. For example, R&D investment in new technical or management options. This paper is largely concerned with planned adaptation.

Scientists and environmentalists advocate near-term mitigation policies. However, an understanding of climate change physics and economic momentum yields the insight that mitigation will not prevent much climate change before mid-century and requires substantial effort to achieve lower atmospheric stabilization levels (IPCC 2007c; NAS 2010a). In fact, the mitigation plans of many alarmists would pose a serious risk to economic growth. The marginal cost function of mitigation is very steep, especially in the short run. Dramatic immediate policies to reduce GHG emissions would be very costly (Mendelsohn 2009). Also in countries like the US, policy action to reduce emissions seems unlikely in the near term while emissions growth continues worldwide. The inelasticity of the marginal cost function implies that mitigation programs that are not applied universally will be very wasteful. Thus it is virtually inevitable that climate change will continue into the coming decades and adaptation will be required (Rose and McCarl 2008; NAS 2010c). Consequently, adaptation is receiving growing attention in policy circles with an adaptation fund being the latest international agreement (Tol 2005; UNFCCC 2010) and adaptation for example taking a much more important role in the emerging IPCC AR5 report.

In the short run, a rushed public mitigation policy is likely to be inefficient. Increasingly there appears to be recognition of the need to simultaneously implement adaptation and mitigation. However, this presents significant policy challenges. Firstly, both the policy and research communities traditionally have treated such two responses independently. Secondly, they are, substantially, rival goods since investment in one diverts the resources available to the other. More fundamentally, there is a lack of both conceptual and empirical information that explicitly considers adaptation and mitigation together. Only recently have policymakers expressed an interest in exploring the interrelationships between them (IPCC 2007c). In this paper we follow the lead of de

Bruin et al. (2009) and do a further exploration of the optimal inter-temporal balance between mitigation and adaptation. Specifically, we will investigate

- What are the welfare maximizing investment allocations of mitigation and adaptation (including proactive and reactive) over time?
- Is it beneficial to invest in a mixed strategy of both adaptation and mitigation?
- What are the marginal contributions of adaptation and mitigation to damage reduction?

2.3 Literature Review

Climate change studies are often interdisciplinary by nature, incorporating many domains of science, economics, and political theory (Sarofim and Reilly 2011). Integrated assessment models (IAMs) have become a common tool for assessing climate change related strategies. Broadly, these models attempt to represent the earth system processes and include multiple regions and sectors, providing insights into areas such as optimal timing of emission reductions, weighting of different greenhouse gases, or impacts of biofuel policies (IPCC 2007c). However, the climate policy strategies addressed in IAMs have largely been limited to mitigation. In most cases, adaptation, when considered, is either a choice variable among technological options or assumed to be optimal and already included in the damage function (Nordhaus 1994; Schneider 1997; Patt et al. 2010). Furthermore, while some models include adaptation cost in the damage estimates, it is typically not explicitly distinguished nor is the level of adaptation optimized (Fankhauser 1994; Yohe et al. 1996). However several studies have dealt with adaptation and mitigation in modeling

- Hope et al. (1993) developed the PAGE (Policy Analysis of the Greenhouse Effect) model including a binary choice variable between no adaptation and aggressive adaptation. However, restricting adaptation measures to two extreme choices is contradictory to the array of choices and possibilities that could be employed as identified in the emerging adaptation literature (NAS 2010c; World Bank 2010; UNFCCC 2010; Parry et al. 2009).
- Tol (2007) considered adaptation to sea level rise in the FUND (The Climate Framework of Uncertainty, Negotiation and Distribution) model concluding that adaptation is very important and needs to be traded off with mitigation. However, Tol’s study follows Fankhauser (1994), limiting actions to coastal protection and assuming protection cost is exogenous.
- de Bruin et al. (2009) extended the DICE (Dynamic Integrated Climate and Economy) model to adding adaptation as a full control variable. They find that relative to mitigation that adaptation is the dominant earlier period option for reducing the costs of climate change, while mitigation is predominant in later periods. In their implementation they assume that adaptation investment costs and benefits are “instantaneous” and not persistent. Their assumptions on avoided damages due to adaptation are largely based on a survey by Tol and Fankhauser (1998) that again focused on coastal protection.

- Bosello (2008) added adaptation to the FEEM-RICE growth model then examined the optimal path of planned adaptation as well as the mix between adaptation, mitigation and R&D. His results showed that adaptation and mitigation are strategic complements. The adaptation costs were of an exponential form based on Tol and Fankhauser (1998).
- Bosello et al. (2010) did a study with the AD-WITCH model and assessed the optimal timing of mitigation and three different modes of adaptation (anticipatory adaptation, reactive adaptation and R&D in adaptation). Results indicated that the joint implementation of mitigation and adaptation is welfare improving. They found that mitigation started immediately while adaptation was delayed until somewhere later when gross damages were higher, quite the opposite of de Bruin et al.
- Patt et al. (2010) summarized how existing integrated assessment models describe adaptation and suggested many ways that could be applied to improve the treatment of adaptation within an integrated framework. They concluded that better modeling of adaptation costs and benefits could have important implications for defining mitigation targets. However, they did not do any quantitative study.

In this paper we extend these literature, particularly de Bruin et al. (2009), also modifying DICE model but with a number of key differences in assumptions. In particular,

- A less restrictive assumption on the persistence of effects from adaptation investment so that the proactive adaptation can be taken to avoid some damages.
- A more broadly based damage function that is based on economy wide possibilities drawing on the study of Parry et al. (2009).

2.4 The Conceptual Model

Before conducting a numerical study, we provide a conceptual framework for the joint optimization of adaptation and mitigation. A mitigation only optimal control model is,

(2-1) $$\min_{m} TCD = \{q(c) + IM(m)\}$$

s.t. $c=g(m)$

where q gives the losses as a function of realized climate change (c), m gives the mitigation effort, $g(m)$ gives the amount of climate change realized given mitigation effort m, and $IM(m)$ the cost of mitigation. In this setup q is an increasing function of the amount of realized climate change (c), IM is an increasing cost function of m, $g(m)$ exhibits decreases in realized climate change as mitigation effort increases. Total climate damage (*TCD*) is the summation of mitigation cost and total climate change impact (q(c)) which will label (*TIC*). The situation is portrayed in Fig 2-1 (a) where the optimal mitigation level m_1^* and mitigation cost IM_1^* corresponding to the lowest point on *TCD* curve illustrates the optimal solution. Now we add adaptation in:

(2-2) $$\min_{m,a} TCDA = \{q(c,a) + IM(m) + IA(a)\}$$

s.t. $c=g(m)$

where c, *m*, *g(m)* and *IM* have the same definitions as above and the new parameters are

- *a*, the level of adaptation effort,
- *IA(a)*, the cost of investment in adaptation

We also change the loss function *q* so it is the function of realized climate change and the degree of adaptation effort.

The resultant optimal investment simultaneous levels of adaptation a_2^* and mitigation m_2^* from model (2-2) differ from the above mitigation-only investment m_1^* level. We illustrate this in Figure 2-1(b) and (c). At a certain level of mitigation, total climate impact cost after adaptation (*TIC*) is the sum of residual damage cost (*RDC=q(c,a)*) and adaptation cost (see Figure 2-1(b)); while total climate damage after adaptation (*TCDA*) is the sum of total impact cost (*TIC*) and the associated mitigation cost (see Figure 2-1(c)). Since the optimal adaptation level minimizes the total impact cost, the lower curve TIC_1 in Figure 2-1 (c) is the lowered climate damages cost after adaptation efforts are optimized; while the upper curve TIC_2 is corresponding to no-adaptation. The range bounded by TIC_1 and TIC_2 corresponds to the range of total impact cost when adaptation level is varied.

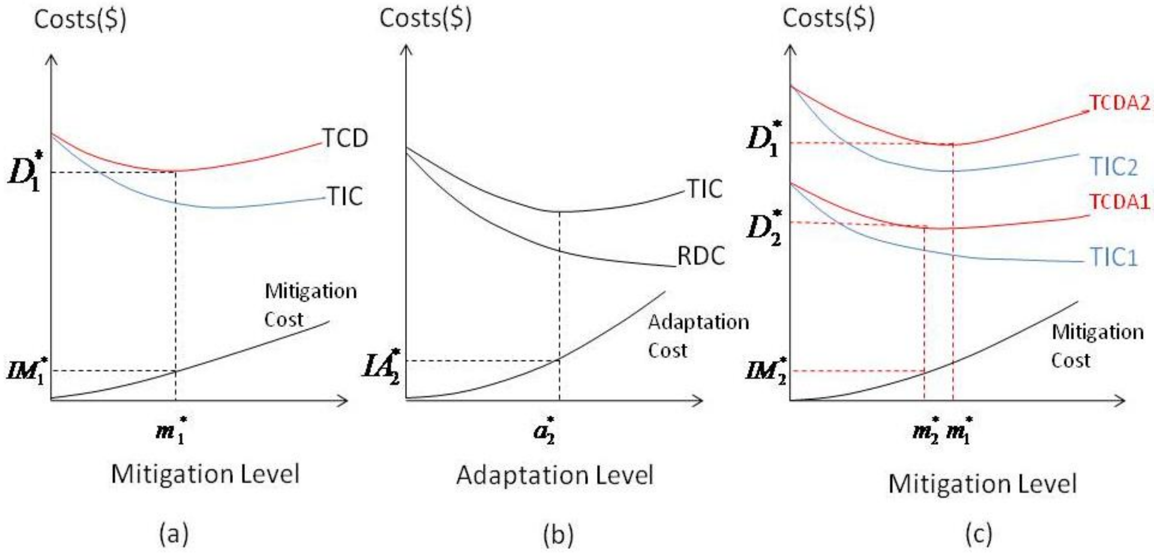

Figure 2-1. Optimal adaptation and mitigation investment. Panel (a) shows optimal investment in mitigation in the absence of adaptation; Panel (b) the corresponding optimal adaptation investment at the optimal level of mitigation; Panel (c) optimal mitigation investment when alternative adaptation efforts are introduced

The mitigation cost IM_2^* corresponding to the minimal $TCDA_1$ and is the optimal mitigation investment. The assumed residual damage curve (*RDC*) in Figure 2-1(b) employs the optimal mitigation level m_2^*. Thus, a_2^* and IA_2^* which minimizes the total impact costs (*TIC*) are the optimal level of adaptation effort and cost respectively. As indicated in Figure 2-1(c), total climate damage D_2^* with optimal mitigation and adaptation efforts is less than D_1^* which is the damage with mitigation only. However, the exact amount of IA_2^* depends on the shape of adaptation cost and residual damage curve.

2.4.1 Adding Explicit Adaptation to DICE

Now we discuss an empirical counterpart to the above theoretical model that examines optimal adaptation and mitigation. To do this, we follow de Bruin et al. (2009) and create a similar extension of the DICE model (Nordhaus and Boyer 2000).

The DICE model is a dynamic integrated assessment model of climate change which has been developed by William Nordhaus and colleagues over the course of more than thirty years. It is a modified Ramsey-style optimal economic growth model, in which economies make investments in capital, education, and technologies and an additional form of "natural capital"—climate system. In DICE, global regions are assumed to maximize social welfare function subject to a number of economic and geophysical constraints. The social welfare function is increasing in the per capita consumption of each generation, with diminishing marginal utility of consumption. The geophysical relationships that link together the economy with the different factors affecting climate change are included in the model. These relationships include the carbon cycle, a radiative forcing equation, climate-change equations and a climate-damage relationship (Nordhaus 2007). DICE represents mitigation activities allowing "climate investment" that competes with current consumption and non-climate investment while reducing future climate change and associated damages. The DICE model assumes optimal reactive adaptation wherever possible but largely ignores proactive adaptation activities and costs.

To overcome the above limitations, de Bruin et al. modified the DICE model adding reactive adaptation as an explicit decision variable. In AD-DICE, proactive adaptation is a control variable that only has an effect in the current period so that one period's adaptation does not affect damages in the next period. Such an assumption is restrictive since some types of adaptive strategies have a "stock" nature that would have long lived effects. For example, building a seawall or identifying genes for drought resistant crop varieties have effects for a longer period than just the current one. Moreover, adaptation restrictions applied in their model calibration are generally based on coastal adaptation and are not reflective of the more recent, broader set of possibilities.

2.4.2 Extensions Beyond AD-DICE

In our model, we extend AD-DICE model (de Bruin et al. 2009), in three major ways:

1) We introduce features that create a stock of adaptation effort based on proactive investment that depreciates over time.

2) We introduce an alternative form of the adaptation production function i.e. the relationship between climate change damages abated and adaptation investment. In particular we calibrate the function to data from Parry et al. (2009) work on the relationship between adaptation costs and residual damages.

3) We explicitly model adaptation investment as a use of capital diverted from total net output over time.

To add the "stock" nature of proactive adaptation to DICE/AD-DICE, we add a capital stock account, which accumulates as adaptation investments are made but depreciates over time. Therefore, the resulting optimal adaptation decisions adjust to current and future climate change damages rather than those in a single decade. Mathematically we denote the choice of adaptation investment level in period t as IA_t. The state variable SA_t is added to represent the stock of adaptation for decade t as:

(2-3) $$SA_{t+1} = (1-\beta)^{10} SA_t + 10 IA_t$$

with the initial condition SA_t=0, where β is the annual depreciation rate of capital invested in adaptation; t represents the decade beginning from 2005. We initially assume β is 0.1 per year so that carryover adaptation investment depreciates after a decade equals $(1-0.1)^{10}$=0.35. Sensitivity analysis in later sections investigates the implications of different depreciation rates.

In AD-DICE07 (de Bruin et al. 2009), authors modify the net damage function in DICE to be a combination of separable adaptation costs and residual damages. In our model, we try to separate reactive adaptation costs ("flow") and proactive adaptation investments ("stock") from damages. We assume that planned adaptation investment is done by public interests to avoid the negative effects of current and future climate change, thus restate the realized damages D_t as:

(2-4) $$\mathrm{D_t = RD_t(GD_t, P_t)}$$

where *RD*$_t$ is a function giving the "left-over" climate change induced damages (or residual damages) after the effects of adaptation efforts are considered, *GD*$_t$ is the gross damages which is adjusted for mitigation effort, P_t gives the sum of autonomous and planned adaptation effort.

Regarding the form of the residual damage function, AD-DICE and many other available IAMs (e.g. FEEM-RICE, AD-WITCH) do not use a functional form that refers to the direct relationship between adaptation costs and reduced damages with the possibility of unadaptable damages (for discussion of the concept see Parry et al. (2009)), rather using forms that assume residual damages can be totally reduced to 0 under full adaptation efforts. We use an alternative form following Parry et al. (2009) as portrayed in Figure 2-2, where damages decrease non-linearly with adaptation investment and a degree of unavoidable damages is indicated by the horizontal dotted line that the curve asymptotically approaches. Accordingly, the functional form of residual damages is:

(2-5) $$RD_t(GD_t, P_t) = GD_t \cdot (1 - P_t), \quad 0 \le P_t \le 1$$

(2-6) $$1 - P_t = \alpha + (1 - \alpha)e^{-rPC_t}$$

(2-7) $$PC_t = FA_t + SA_t$$

where α is the percentage of unavoidable damages; P_t is the normalized resulting level of adaptation in year t and ranges from 0 (no protection) to 1 (full protection). Equation (2-

6) thus gives the proportion of residual damages as a function of the amount of unavoidable damages (α) and the total adaptation costs (*PC*) which is the sum of adaptation investment stocks (*SA*), and flow adaptation costs (*FA*).

To empirically specify these functions, we calibrate the function reflective of a statement in Parry et al. (2009) which indicates "unavoidable impacts are about one fifth of all damages in 2030 and, over the longer term, may account for up to two-thirds". For simplicity, we take the unavoidable damages as 0.2 for our parameter α in equation (2-6). The sensitivity of effectiveness of adaptation to the level of unadaptable damages will be analyzed in the later section. Moreover, Parry et al. (2009) stated that avoiding the first 10% of damage will be disproportionately cheaper than the other 90%. If we define MARR as the marginal adaption reduction rate, then in Figure 2-2, point B, where 1/MARR=1, can be taken as a "breakpoint" with corresponding damage level *d* and adaptation cost level *sa*; the slope 1/MARR>1 for the points (on the curve) above (*pc,d*) and 1/MARR<1 for those below (*pc,d*). Thus *d=0.9GD,* and 10% of damages above *d* can be reduced with lower adaptation costs, while the difficulty increases with the further damages to be reduced. At point (*pc,d*), the incremental adaptation cost equals the reduced damages,

$$\frac{\partial RD_t}{\partial PC_t}\bigg|_{(FA_t+SA_t)=pc} = -GD_t(1-0.2)re^{-rpc} = -\frac{1}{MARR} = -1 \tag{2-8}$$

and

(2-9) $$GD_t \cdot [0.2 + (1 - 0.2)e^{-rPC}] = 0.9GD_t$$

Equation (2-8) and (2-9) hold simultaneously. The resultant value of r is $10/(7GD_t)$. Thus, the parameters in equation (2-6) are specified as $\alpha=0.2$, $r=10/(7GD_t)$. This specification is more realistic than the functional form assumed in de Bruin et al. (2009) mainly in two aspects: 1) the adaptation cost is not only related to the relative adaptation level (as the fraction by which gross damages are reduced), but current stage gross damages as well; 2) explicit inclusion of unadaptable damages excludes the extreme response of full adaptation at some finite cost.

In original DICE model, optimal adaptation is assumed to have taken place and the costs of that are part of climate change damages. Thus in our model we explicitly address two forms of adaptation: proactive and reactive. Accordingly, the gross damage equation in our model takes the similar form as in DICE in which damage-output ratio is assumed to be exponentially linked to global temperature increase, however, the parameters are different and left to be determined through calibration:

(2-10) $$\frac{GD_t}{Y_t} = \pi_1 TE_t + \pi_2 TE_t^{\pi_3}, \quad \pi_2 > 0 \; and \; \pi_3 > 1$$

where Y_t is net output of goods and services, adjusted downward for climate change damages after abatement in year t, TE_t represents the average temperature change since 1900. The sensitivity analysis of optimal investment path with respect to damage function parameters is conducted in later sections.

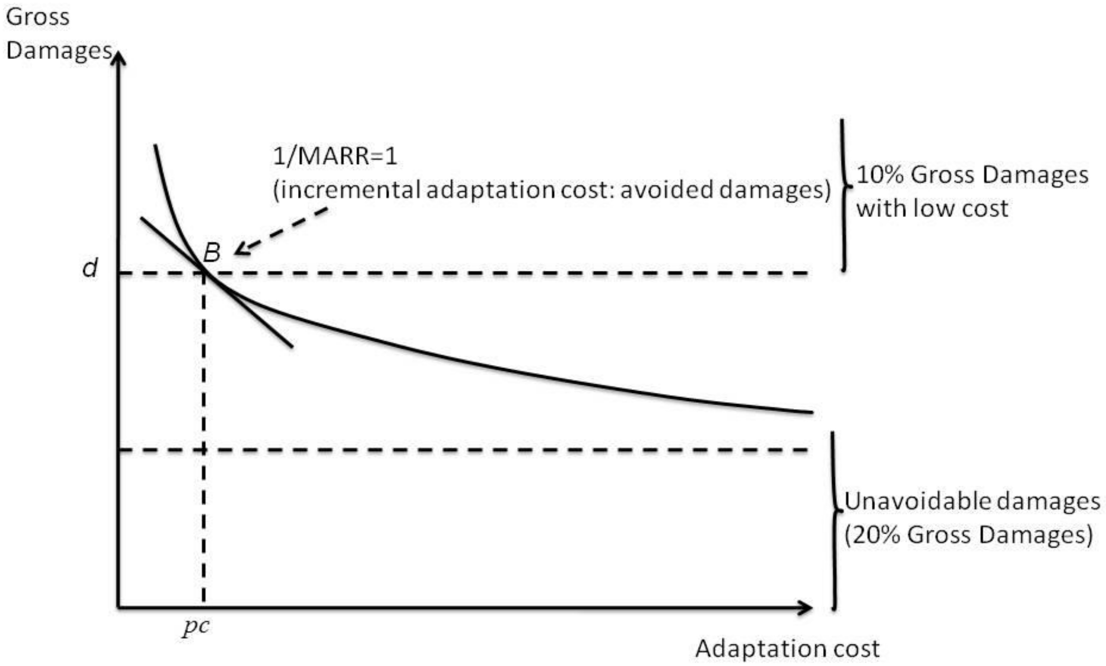

Figure 2-2. Portrayal of relationship between adaptation investment, residual damages, and unavoidable damages. Following Parry et al. 2009.

We calibrated the coefficients of the damage function: $\pi_{1,}$ π_2 and π_3 to best replicate the DICE model results. The same point as used to calibrate the damages in the DICE model is chosen: global surface temperature rise of 2.5 degrees Celsius above the preindustrial average at year 2105 in an uncontrolled environment. At this point, the net damage cost as the sum of residual damages and total adaptation costs are roughly 1.5% of global economic output, as implemented in original DICE model. Furthermore, we assume protection effort (P) from autonomous adaptation (FA) is no less than 0.15 in each period. The parameters of damage function (2-10) are therefore calibrated as π_1=0, π_2=0.001 and π_3=3.036.

To complete our model, we make the same assumption as in Bosello et al. (2010) that decisions on the levels of adaptation and mitigation are separable but compete for investment funds. Therefore, we add a term to the identity relating total output with consumption and investment that includes adaptation investment:

(2-11) $$Y_t = C_t + I_t + IM_t + IA_t + FA_t$$

where C_t is consumption; I_t is "traditional" investment contributing to the production capital stock only; IM_t represents the mitigation investment which is increasing with the emission control rate; IA_t represents the adaptation investment and FA_t is flow adaptation costs.

2.5 Model Use

Now suppose we use the modified DICE model hereafter AD-DICE++ to examine the optimized roles of adaptation versus mitigation. Model is running over a 600 year time period as in DICE model with the same terminal condition that at least 2% of the capital stock at the beginning of period should be invested annually during whole time periods. Note that if adaptation is undertaken, model reproduces the original results of DICE model. So let us use the model to investigate

- What are the social optimal allocations of mitigation and adaptation investment over time?
- Is it beneficial to invest in a mixed strategy of both adaptation and mitigation?
- What are the relative contributions of adaptation and mitigation to damage reduction?

In our analysis, we build AD-DICE++ on top of the GAMS version of the DICE-2007 model.

2.5.1 Optimal Investment in Adaptation and Mitigation

Figure 2-3 portrays the investment results with and without adaptation. There we see that when optimal adaptation investment is undertaken, the optimal mitigation investment level is less than that in the without adaptation case before year 2200. Total mitigation investment averages 58% lower than under the mitigation only case. The optimal flow of adaptation investment increases over time and adaptation uses more than 50% of the total climate related investment expenditures in the first 185 years but decreases afterwards with mitigation efforts dominating from thereon (see Figure 2-4). Reasons for such different investment time paths are discussed in the later section. These results are qualitatively similar to what de Bruin et al. estimated. Namely adaptation is the main climate change damages reducer in the earlier periods after which mitigation dominates. But in our model there is more adaptation investment with longer prevailing periods than in AD-DICE model due to the added stock nature. This is quite different from the findings in Bosello et al. (2008, 2010) where they show that aggressive mitigation is the starting point and it is not initially worthy to invest in adaptation.

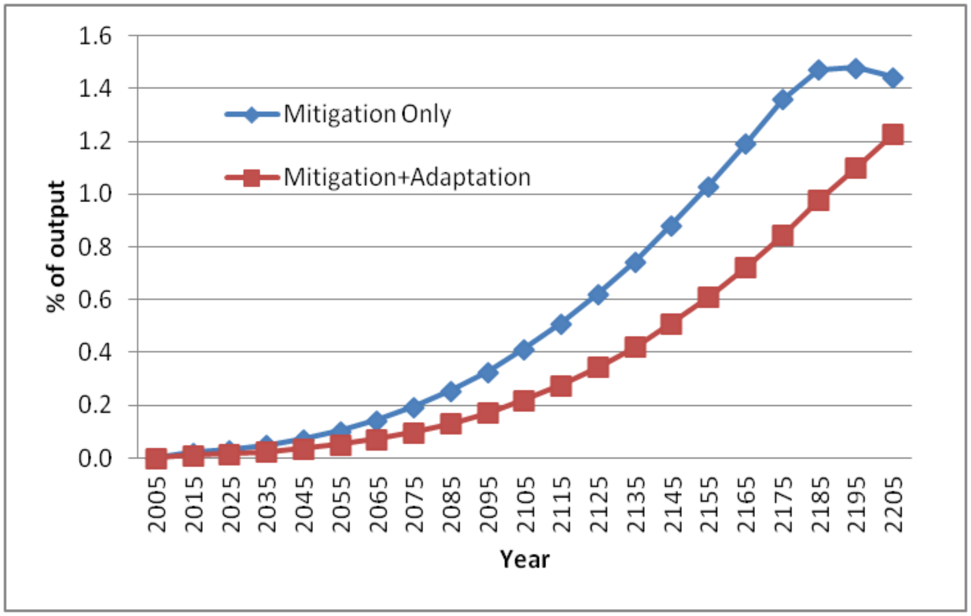

Figure 2-3. Optimal mitigation investment with and without adaptation investment allowed

2.5.2 The Effectiveness of Adaptation

Figure 2-5 shows total climate change residual damages with and without the adaptation investments allowed. It is clear that total damages are reduced over all periods through use of adaptation. Also with adaptation active, total gross world product net of abatement and damages (*Y*) increases on average by 19% (Figure 2-6), indicating that an integrated adaptation and mitigation strategy is more effective. In the optimal scenario with both adaptation and mitigation, the benefit of adaptation in terms of avoided damages increases up to 3% of total net output before year 2175, after which it decreases (Figure2-7).

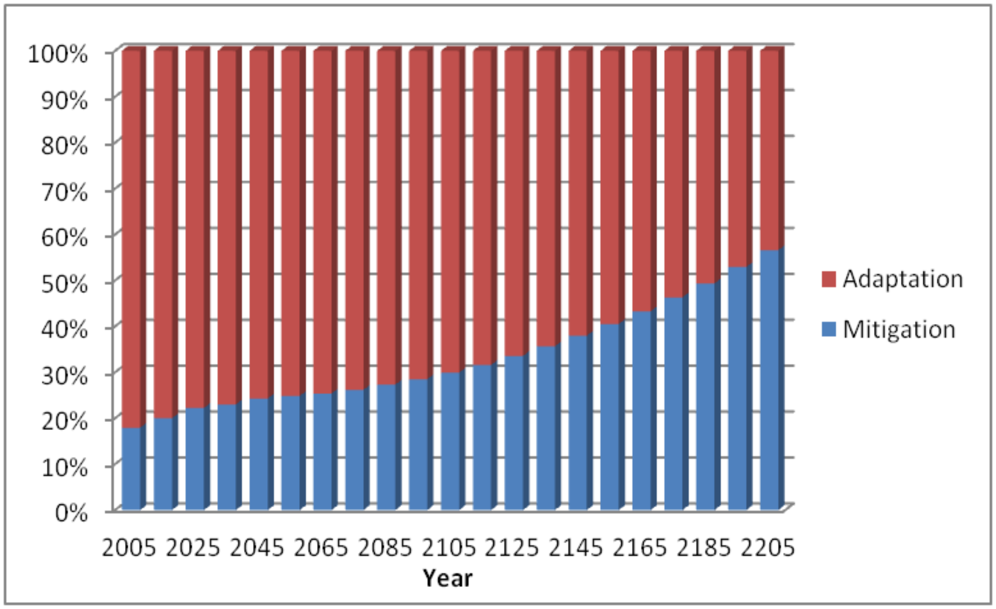

Figure 2-4. Temporal investment (percentage) of adaptation and mitigation in the model with both adaptation and mitigation investment allowed

2.5.3 Temporal Management of Adaptation and Mitigation

The above results indicate that adaptation is an effective damage reduction strategy and a complement to mitigation. However, because of the finite resources, they are also competitive in that investment capital use for one diverts it from the other and both divert funds from other output enhancing investment. Thus, studies about the relative shares are of interest.

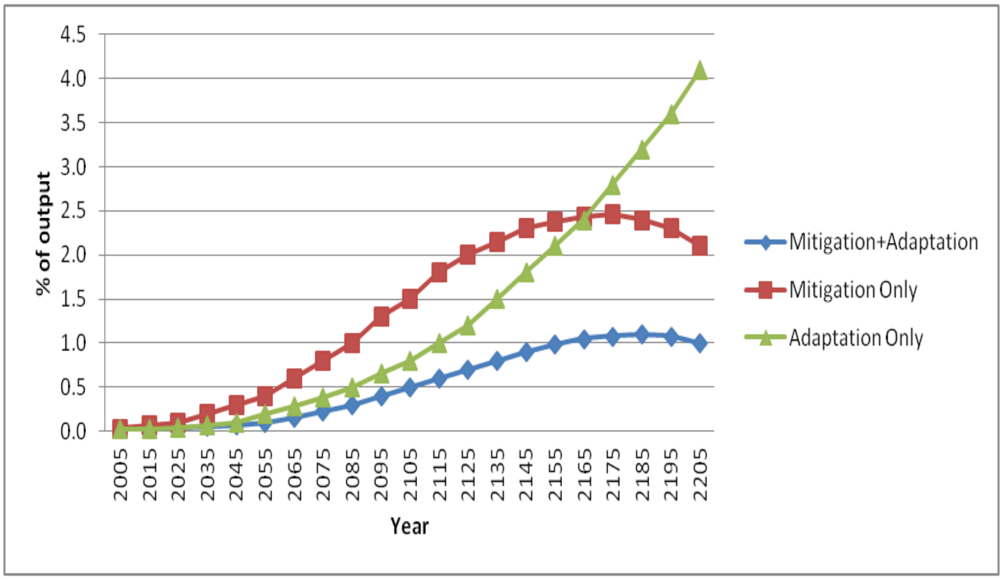

Figure 2-5. Total residual damages with and without adaptation

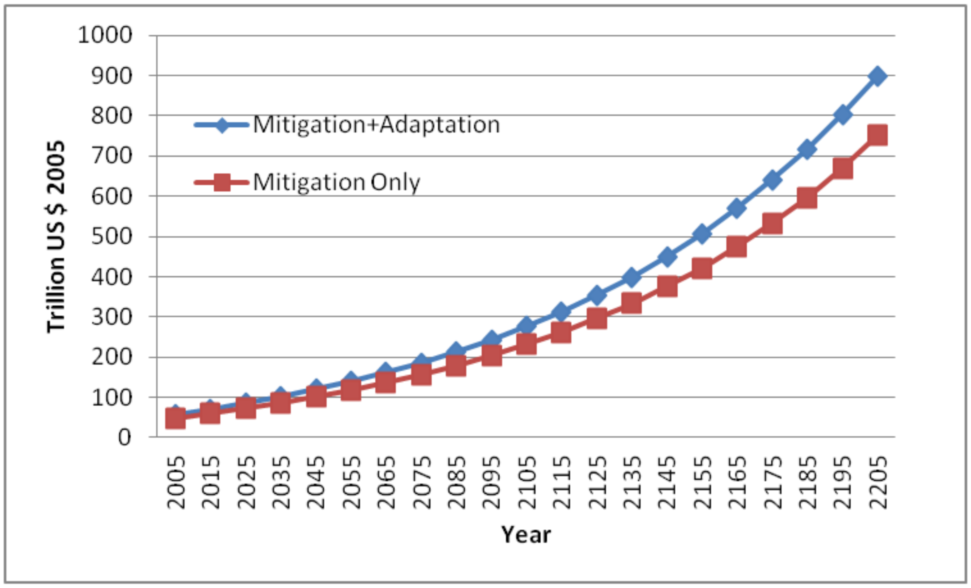

Figure 2-6. Gross world product (net of abatement and damages) with and without adaptation

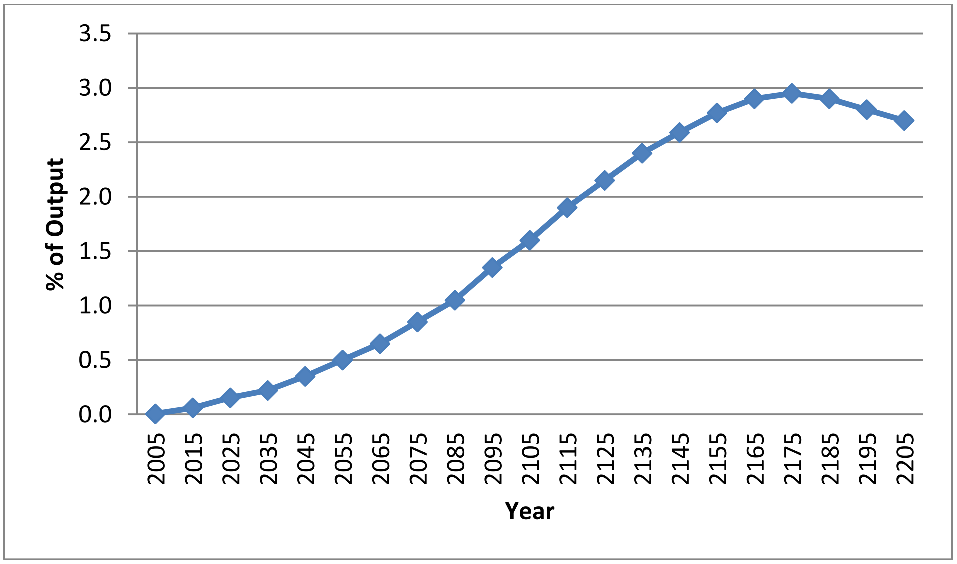

Figure 2-7. Damages avoided by adaptation in the model with both adaptation and mitigation investment allowed

Figure 2-8 highlights that both proactive and reactive adaptation are the dominant climate change damage reduction means until about 2125 and mitigation dominates after that. This optimal time path of relative shares between the two strategies is mainly due to the different timing of results from adaptation and mitigation investment. Initially, damage stocks are low, hence marginal benefit of reducing carbon emissions is also low. The results of mitigation investment are constrained by climatic inertia and the slow workings of the carbon/GHG cycle and hence take more time to be effective. While potentially more expensive, adaptation could have larger effects on impacts more quickly. Accordingly, it is not profitable to invest a lot in abatement in the short-run and rather adaptation is pursued which has a relatively lower cost and direct effect in adjusting to the first 10% damages. Well planned adaptation avoids the inefficient costs of mitigation at the beginning, while the effectiveness of mitigation in reducing GHG emissions prevails later when damage stock is big enough that adaptation is not cost-efficient.

In terms of adaptation strategy mix, investment in stock adaptation is slightly more than flow adaptation before year 2115, after which flow adaptation dominates. The different timing path between these two adaptations is due to the different mechanism of stock and flow adaptation. Even though both adaptations refer to the direct adjustment capacity for climate change to moderate vulnerability, stock adaptation has to be undertaken well ahead of time to realize the benefits. The well planned investment in stock adaptation can anticipate more benefits in the longer run, however, there are large part of damage-reducing actions are undertaken by private actors automatically due to changing prices, income and environmental conditions as consequences of climate change such as installing air conditioners. Therefore, investment in stock adaptation is changing prices, income and environmental conditions as consequences of climate change such as installing air conditioners. Therefore, investment in stock adaptation is expected to be taken in earlier periods and decreases steadily in later periods, whereas instant adaptation increases with damages and is close to being stabilized due to the prevailed mitigation efforts in the long run.

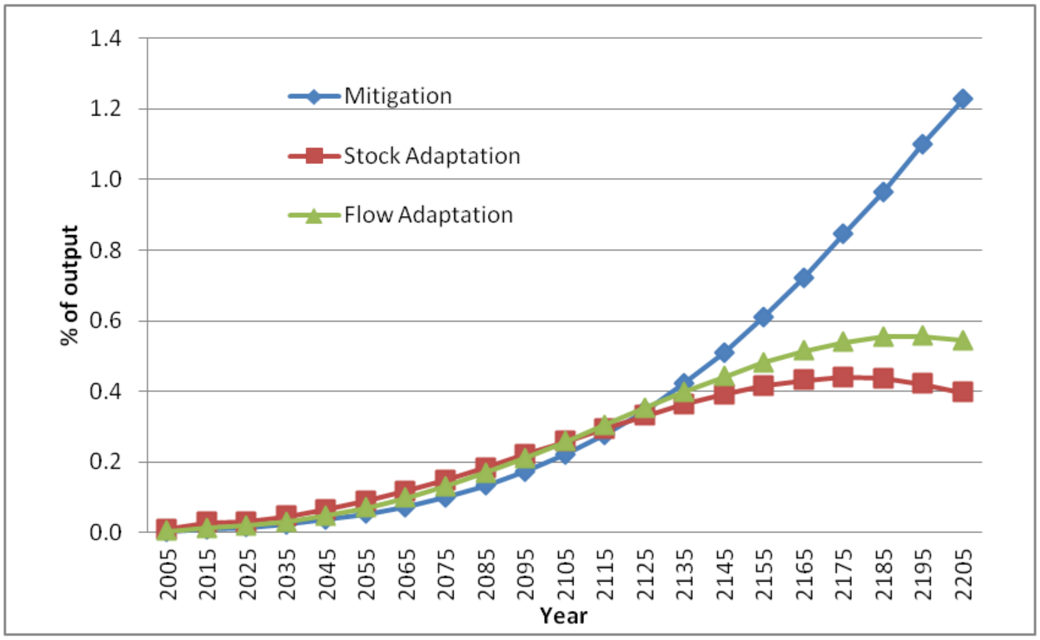

Figure 2-8. Time path of mitigation and adaptation costs in the model

2.6 Sensitivity Analysis

2.6.1 Unavoidable Damages

It is important to consider the costs of damage not adapted to, because the amount may be significant and is likely to increase over time. However, there is no reliable estimation of how much such damage might be expected over time. In the base case, we simply assume the unadaptable damage is 20% of all damages over all periods. To study the effects of unavoided damages on optimal strategy, two other alternative levels are examined—30% and 50% of all damages. The result in Figure 2-9 implies that investment applied for adaptation diminishes with the increase of (percentage) unavoidable damage whereas the mitigation costs goes up (Figure 2-10).

2.6.2 Persistence of Adaptation

The results in de Bruin et al. (2009) arise under an assumption that adaptation in one period does not have persistent, long lasting effects into future periods, i.e. the effect of current investments on future adaptation faced a very high depreciation rate (β). We feel some adaptation actions can have longer term effects and thus added stock consideration plus a depreciation factor into the model. To see the effect of such an assumption we ran the model with alternative per year depreciation rates in particular the base (0.1) plus 0.05, and 0.5. Intuitively a higher depreciation rate lowers returns to adaptation investment, and thus would lower capital invested. Numerically as expected, more adaptation occurs when the depreciation rate is smaller; and less when it is larger (Figure

2-11). Moreover, as the depreciation rate rises our results move closer to those in de Bruin et al.'s model where adaptation is proposed as a flow variable only.

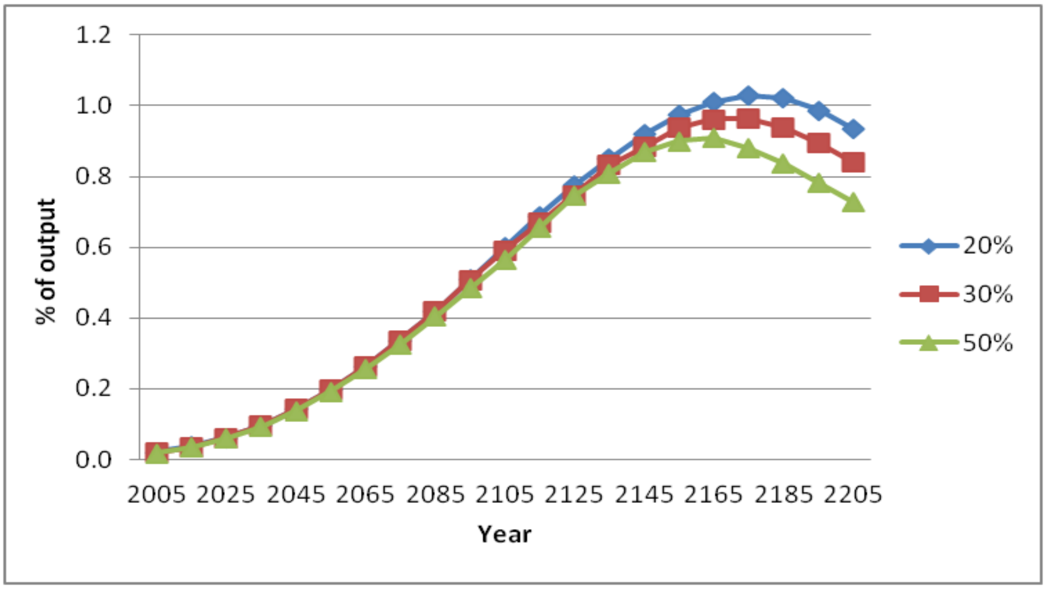

Figure 2-9. Adaptation investment with alternative level of unavoidable damages[1]

2.6.3 Damage Uncertainty

There are two central uncertainties that challenge the climate-related economic damages assessment. One is climate sensitivity — that is how much temperature change that will result from a doubling of atmospheric CO_2 concentration? The other is the magnitude of

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[1] 20%, 30% and 50% represent the different level of unavoidable damages. Adaptation investment as the percentage of total output is measured under each (percentage) level of unavoidable damages.

marginal climate-related damage — that is how much economic damage will be caused by a unit temperature increase? (Ackerman et al. 2010).

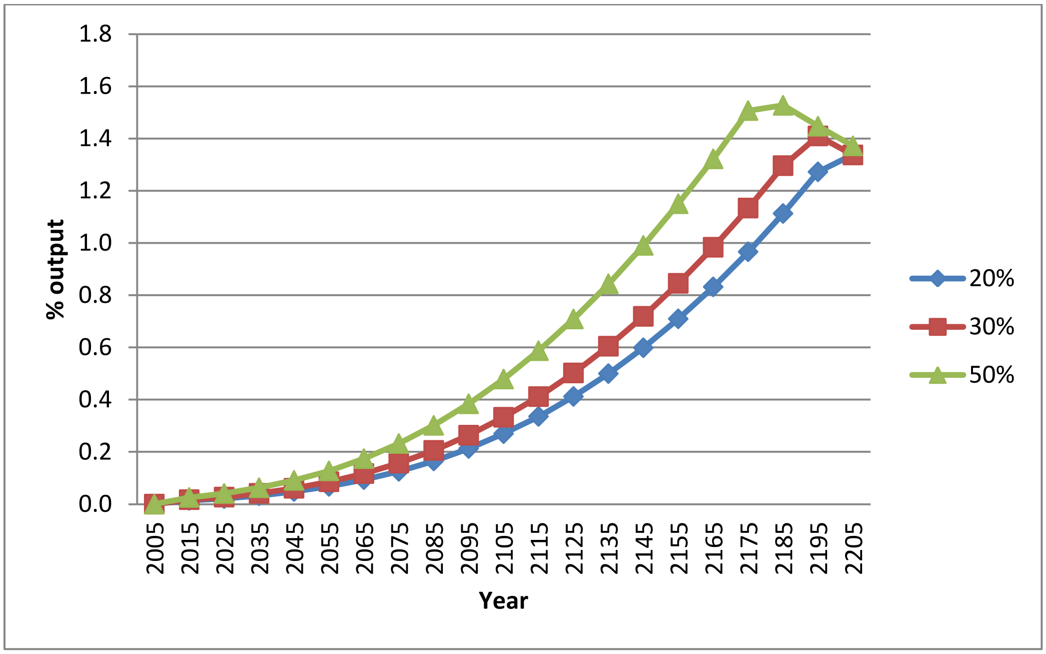

Figure 2-10. Mitigation investment with alternative level of unavoidable damages

According to IPCC (2007a) assessment, it is likely (two-thirds probability) that the true value of climate sensitivity falls between 2ºC and 4.5ºC; the central projection is 3 ºC. In the original DICE model, the default climate sensitivity is 3ºC that is every time atmospheric CO_2 doubles the global average annual temperature would increase by 3ºC. To examine the uncertainty about the temperature increase that will result from rising greenhouse gas emissions, we experiment with alternative values for climate sensitivity — 2ºC, 3ºC and 4.5ºC, denoted as 'CS2', 'CS3' and 'CS4.5' respectively. As indicated in Figure 2-12, under higher climate sensitivity, adaptation investment increases but with shorter prevailing period, while mitigation investment increases at a larger rate particularly after mid-century than adaptation. It is reasonable to expect an optimal policy of very rapid abatement process if CO_2 concentration causes more climate change. We also ran the climate sensitivity scenarios with alternative levels of utility discount rate and adaptation depreciate rate. As indicated in Figure 2-13~2-16, earlier and more stringent mitigation with higher level climate sensitivity is robust.

Now we turn attention to how adaptation and mitigation activity are affected by the changes in damage parameters. In the DICE model, the aggregated damage as a fraction of world output is assumed to be a quadratic function of temperature increase from 1900. However, as demonstrated by Nordhaus (2008), the DICE model has limited utility to display responses to uncertainties and catastrophic events. Therefore, we do sensitivity analysis by choosing a marginal damage value that is 1.2 times higher (denoted as '1.2xMD') than in the base DICE specification. This reflects concerns that DICE may understate damages (Stanton et al. 2011; Hanemann 2008; Ackerman et al. 2011) and allows us to examine what a higher rate of damages may do to mitigation/adaptation investment. Figure 2-17 shows that a 20% increase in the marginal damage function increases adaptation by an average of 33% until 2170 and decreases it after that. Simultaneously the mitigation investment increases on average by 55% more and the mitigation share exceeds that of adaptation 20 years earlier.

Table 2-1 shows the percentage changes of net present value of adaptation and mitigation investment in ‘1.2xMD’, ‘CS4.5’ and ‘1.2xMD+CS4.5’ (changes in both parameters) cases relative to the base case in which climate sensitivity is 3 and no change to the original damage function. We see that with more rapidly rising damages there is a larger increase in mitigation than there is in adaptation. Even though adaptation is still an effective short-term strategy, higher climate-related damage drives additional mitigation effort in the nearer term.

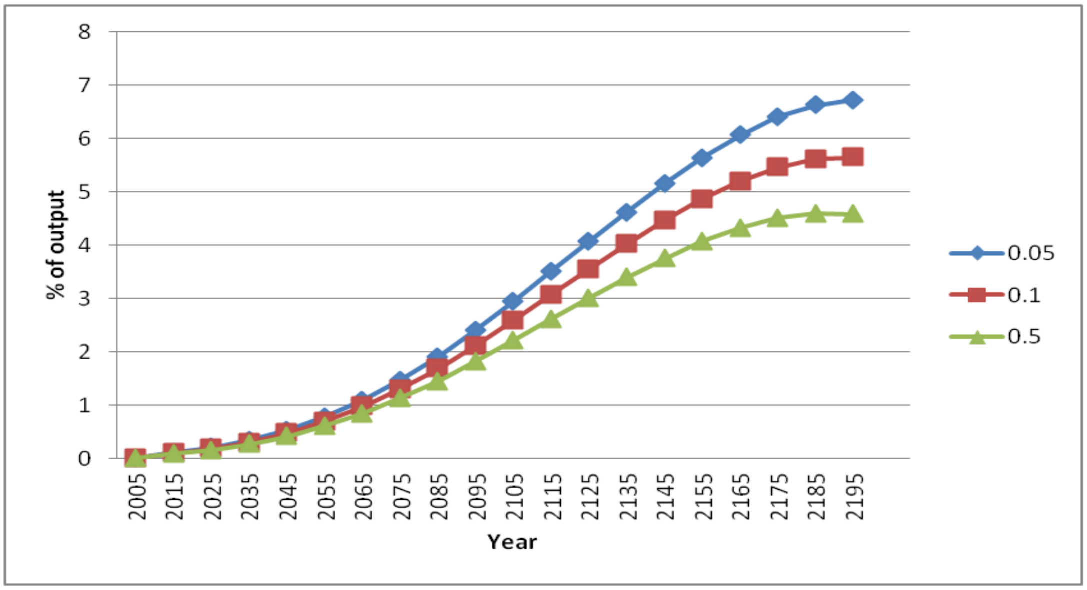

Figure 2-11. Stock of adaptation investment with different depreciation rates[2]

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[2] 0.05, 0.1 and 0.5 denote the different adaptation investment depreciation rates.

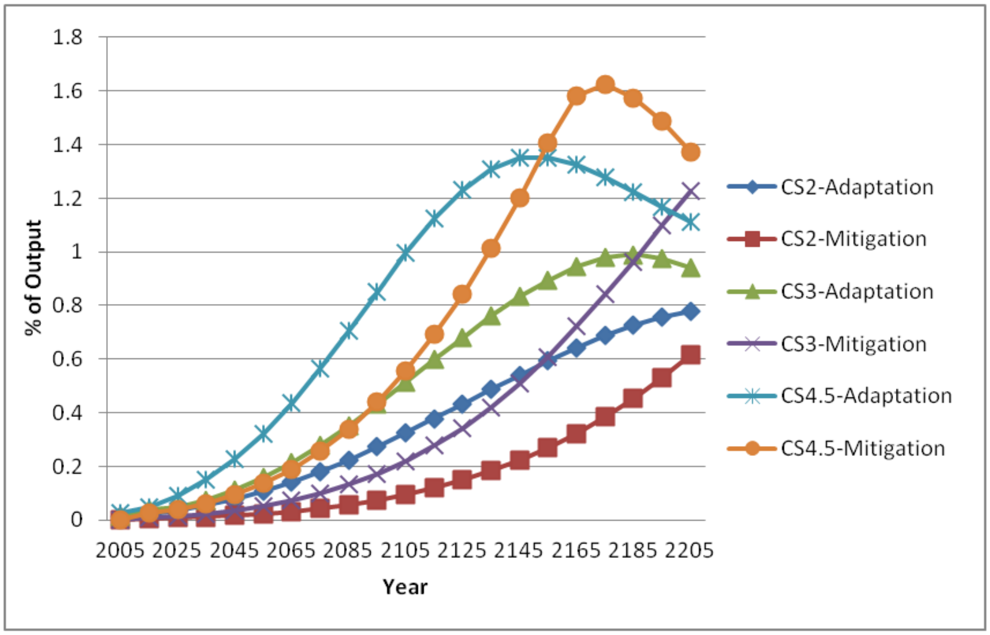

Figure 2-12. Adaptation and mitigation investment with different level of climate sensitivity with original level of utility discount rate (0.015) and adaptation depreciate rate (0.1)[3]

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[3] CS2, CS3 and CS4.5 denote the climate sensitivity of 2ºC, 3ºC and 4.5ºC, respectively. Figure 2-13~2-16 follow the same definitions.

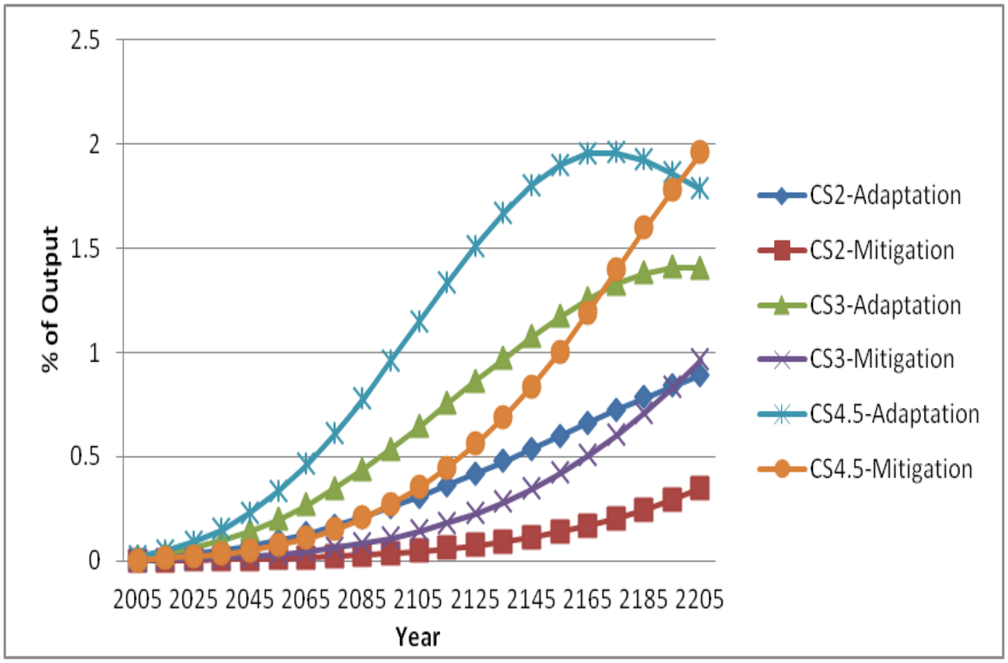


Figure 2-13. Adaptation and mitigation investment with different level of climate sensitivity at mid-level discount rate (0.03)

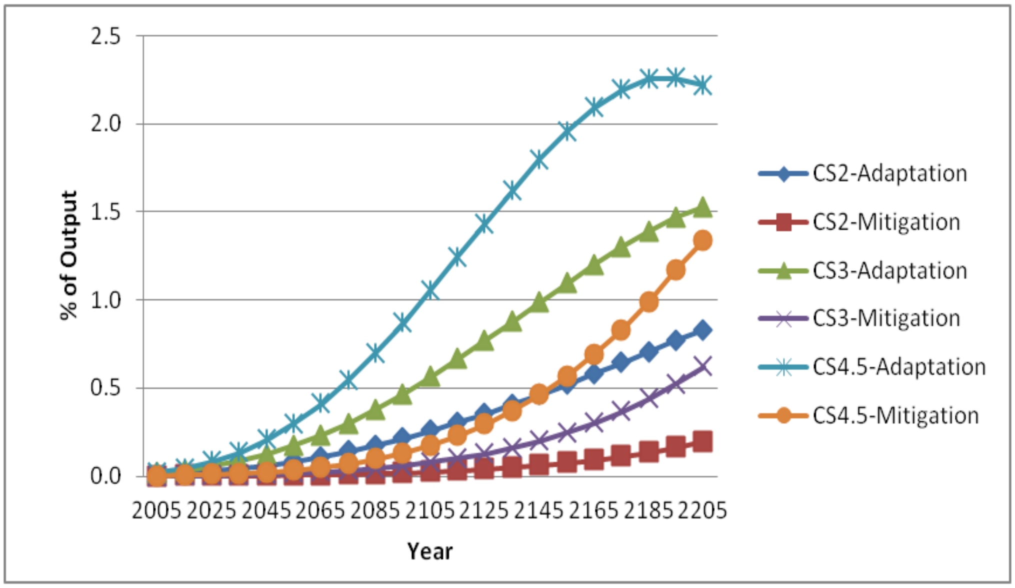


Figure 2-14. Adaptation and mitigation investment with different level of climate sensitivity at high level discount rate (0.045)

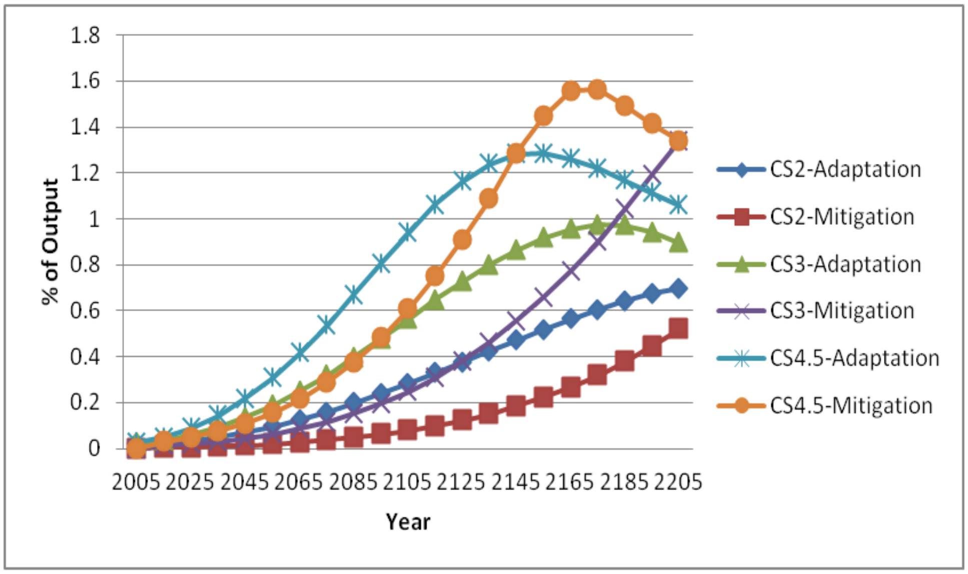


Figure 2-15. Adaptation and mitigation investment with different level of climate sensitivity at low level adaptation depreciate rate (0.05)

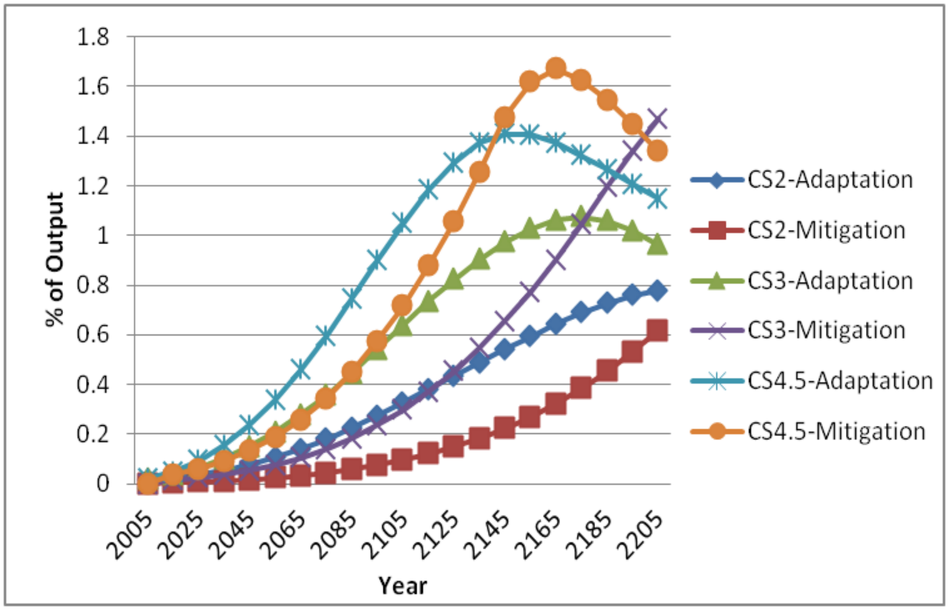


Figure 2-16. Adaptation and mitigation investment with different level of climate sensitivity at high level adaptation depreciate rate (0.5)

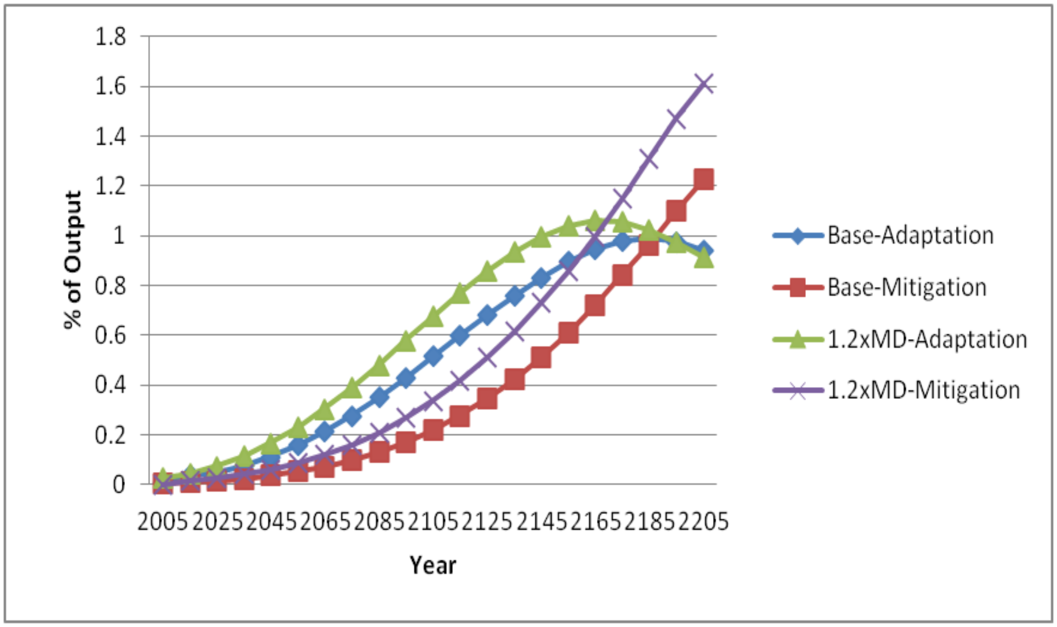


Figure 2-17. Flow of adaptation and mitigation investment with different marginal climate damage functions

Table 2-1. Percentage changes of net present value of adaptation and mitigation investment relative to the base case

	NPV-Adaptation	NPV-Mitigation
1.2xMD[4]	14. 55%	24.17 %
CS4.5	53.59%	128.2%
1.2xMD+CS4.5	74.06%	178.5%

---

[4] Marginal damage value is 1.2 times higher than that in the base DICE specification.

2.7 Discussion and Conclusions

Currently, different dimensions of mitigation strategies have been investigated in policy analysis, and the primary focus of international climate policy has been on the use of mitigation through cap-and-trade and energy substitutes with little heed paid to adaptation (IPCC 2007b).

Adaptation is usually modeled as optimally applied and not an investment option (as argued in de Bruin et al. 2009). However, a number of adaptation possibilities require levels of public and private investment (see estimates on public needs in the UNFCC and World Bank reports) as is behind the adaptation fund that is now emerging. In terms of an overall investment shared between mitigation and adaptation our simulation shows that while mitigation tackles the long run cause of climate change, adaptation tackles the short run reduction of damages and is more preferred when damage stocks are small as also found in de Bruin et al but contrary to Bosello et al. (2008, 2010). Instead of taking adaptation as a ‘residual’ strategy adjusting to the non-accommodated damages by mitigation (Bosello et al. 2010), we find public and private adaptation investment is an economically effective complement to mitigation since the beginning due to the interdependent nature between mitigation and adaptation. The near term nature of the benefits given an adaptation investment makes it an important current policy option.

In many parts of the world, current levels of projected investment in adaptation are considered far from adequate, and lead to high vulnerability to the current and future climate, including the effects of systematic changes, variability and extremes, which

Burton (2004) called the ‘adaptation deficit’. Most current Integrated Assessment Models do not explicitly model adaptation or are limited to autonomous adaptation. Some have modeled planned adaptation but under strong assumptions like no adaptation effect on future damages or no unavoidable climatic damages. Here we extended that work to have persistent adaptation plus unadaptable damages and investment competition.

Our temporal investment allocation results show that both adaptation and mitigation are simultaneously employed strategic complements much as found in de Bruin et al. We do show a greater immediate role for planned adaptation with a longer run transition to mitigation. The sensitivity analysis towards uncertainties in climate change damages indicates that as expectations of damages rise so does the desirability of mitigation.

In terms of study limitations, the lack of reliable data on costs and effectiveness of adaptation is an important obstacle to the economic analysis of integrated strategy. It is worth noting that, with the availability of data, we have a number of assumptions herein could be relaxed in future research including

- A lack of modeling of any direct interaction between adaptation and mitigation in terms of their specific effectiveness and trade-offs.
- A lack of consideration of regional differences.
- Omission of extreme events and other risks.

3. ECONOMIC AND GROUNDWATER USE IMPLICATIONS OF CLIMATE CHANGE AND BIOENERGY FEEDSTOCKS PRODUCTION IN THE TEXAS OGALLALA AQUIFER REGION

3.1 Introduction

The Ogallala Aquifer or High Plains aquifer underlies about 174,000 square miles of the states of South Dakota, Wyoming, Colorado, Nebraska, Kansas, Oklahoma, Texas and New Mexico (Figure 3-1). It provides drinking water to 82% of the people who live within its boundaries and accounts for 30% of all groundwater withdrawn for irrigation in the United States (Guru and Horne 2000; Hughes and Wyatt 1969) . The High Plains crops, livestock, and meat processing sectors as well as oil and gas production literally run on water from the Ogallala Aquifer (Peterson et al. 2003). However, depletion of the Ogallala Aquifer is one of major challenges to the rural economy of this region. Substantial pumping over at least the past 50 years has caused aquifer capacity to decrease by about 33% (Pimentel et al. 2004). In general, recharge has not compensated for withdraws which are about three times faster than the natural rate of recharge (Gleick et al. 2002). Increased agricultural irrigation, growing population and increased livestock production are all demanding more aquifer water.

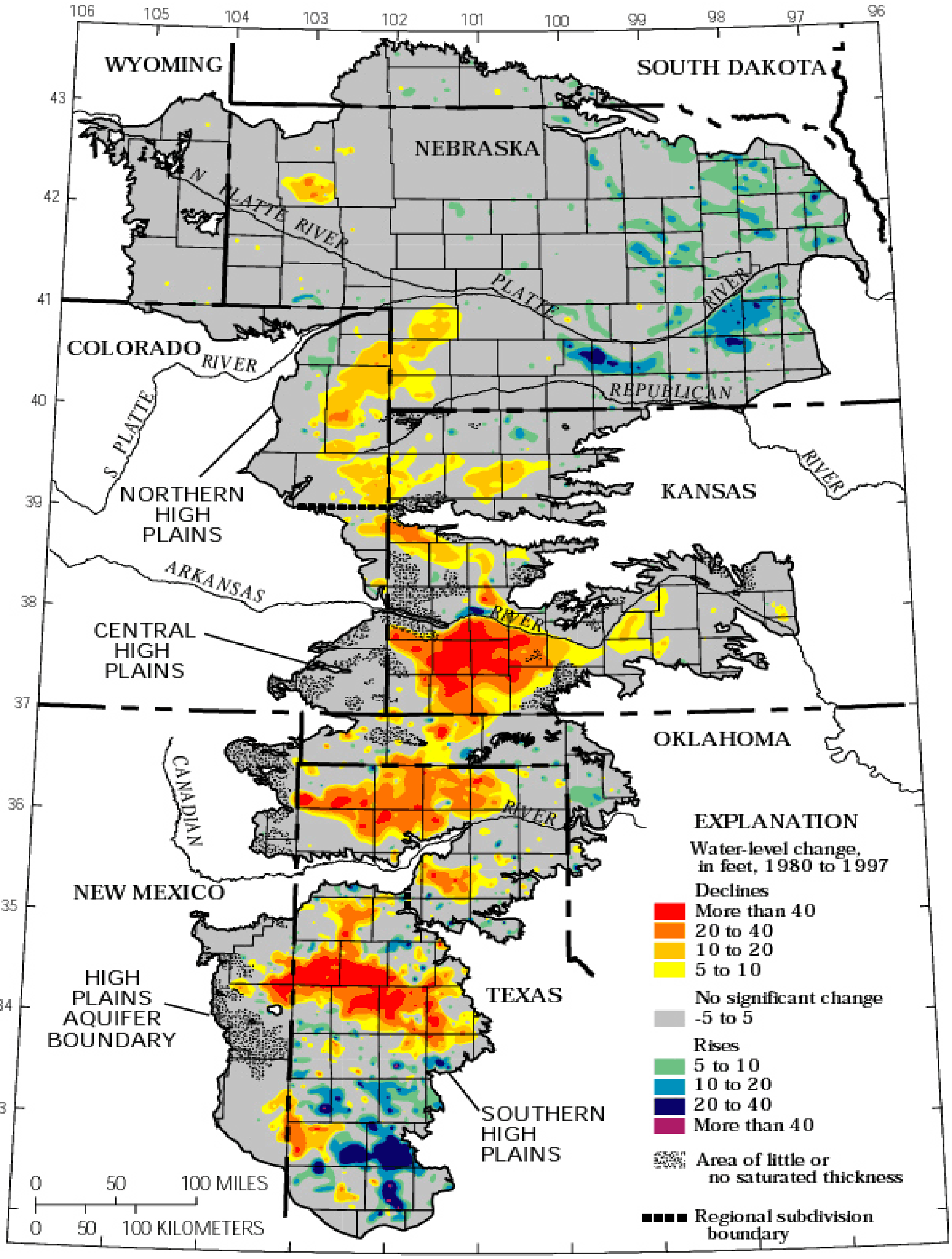


Figure 3-1. Location of the Ogallala Aquifer (Source: U.S. Geographic Survey)

Climate change is also a factor. Projections of a warmer future for this region increases water demand and in turn could hasten depletion. The resulting increase in irrigation water use under these predicted conditions are not sustainable economically or environmentally.

Currently, there is growing interest in bioenergy production as a renewable alternative to fossil fuels. Also there is increasing interest in using cellulosic feedstock due to concerns about the implications of expanding demand for corn ethanol on food prices, as well as the greater potential of cellulosic biofuels to mitigate climate change. Moreover, perennial grasses such as switchgrass can be grown on marginal land with fewer inputs, including water and chemicals. However, a key issue to the expansion of feedstock production for bioenergy is the allocation of limited agricultural land and water between crop and biomass production to meet the needs for food, feed, and fuel and its potential implication to raising prices of food/feed crops. Because the High Plains region is a major producer of corn, wheat, sorghum, and cotton, a significant change in the crop mix in this region will affect the market prices of these commodities as well as groundwater use. Therefore, understanding the interactions of limited resources (land and groundwater), markets and policies for energy, and climate change will become critical when the agricultural sector is increasingly viewed as the center piece in climate mitigation efforts. However, there is little comprehensive research on the impacts of climate change and production of bioenergy feedstock on the regional natural resources, environment, and economy.

In this essay, we will address current and future resource capabilities for the Ogallala Aquifer, and the interrelationships with future climate change forecasts, cropping patterns and biomass production. More specially, our objectives include

- Examining climate change impacts on land use change, groundwater allocation and agriculture economics over the 2010-2050 horizon in the Texas High Plains Region
- Examining the optimal adaptation strategies taken by farmers in face of climate change and water depletion in the hydrologically heterogeneous sub-regions
- Evaluating the land use and economic implications of bioenergy feedstock production in the Texas High Plains Region

This paper presents an integrated agro/hydrological based assessment that examines water depletion, agricultural production, climate change and regional economics. The analysis quantifies the extent to which climate change and bioenergy production may alter the short- and long-term outlook for regional food, agriculture and resource availability and how farmers may effectively adapt their production.

3.2 Literature Review

The Ogallala Aquifer represents a classic “common pool resource” problem, in which individual water users do not pay the social cost of water extraction. As pump and irrigation equipment became more powerful, farmers’ withdrawal rate quickly surpassed the aquifer’s natural recharge rate. Water table declines are just beginning to make groundwater unavailable for irrigation in some shallow areas, which will have further impacts on local economic outcomes (Hornbeck and Keskin 2011). A large number of studies have addressed the hydrological character and economic impact of the Ogallala. Grubb (1966) examined its historical importance to the economy of the High Plains. With the continuing decline of the water level, the latest focus was on depletion and sustainable management. Guru et al. (2000) examined the impacts of crop choice finding it beneficial to promote diversity of crops. The reports on the water availability in eight states concluded that the volume of water in storage in year 2000 has been depleted by about 200 million acre-feet (McGuire et al. 2003). Their evaluation also indicated the heterogeneity in depletion estimating a rise of 4 million acre-feet in Nebraska but a decline of 124 million acre-feet in Texas.

Almas (2008) projected income and hydrological changes in the Texas Panhandle region for 60 years. The results indicated a significant decline in water use and a transition from irrigated agriculture to dryland farming. However, they indicate their optimization model often yielded results that were substantially different from observed behavior(Almas et al. 2006). Das et al. (2010) examined two water conservation policies—extraction tax and extraction quotas and found that neither policy significantly inhibited groundwater use. They also pointed out that integrated hydrological and economic optimization model was able to capture spatial variability of water table elevation. Willis et al. (2011) concluded that cost-benefit estimation of agricultural and groundwater conservation policies required the establishment of an accurate baseline condition for homogeneous areas.

The recent report by the International Panel on Climate Change (IPCC 2008) highlights the importance of examining climate change issues in groundwater regions stating that "water and its availability will be the main pressure on, and issues for, societies and the environment under climate change." Also Stone et al. (2009) concluded that the development of bioenergy feedstocks in the US should carefully consider water resource limitations and their critical connections to sustainability of human food. There have been some simulation studies of the potential effects of climate change and/or biofuel feedstock productions on agricultural productivity in the High Plains Region (Rosenberg et al. 1999; Rosenzweig 1989), but to our knowledge, neither of the existing models considers depletion, nor possible adaptation options.

This paper aims to explore the economic and groundwater use implications of climate change and bioenergy feedstock production. To do this we develop a GIS-based dynamic hydrologic and economic optimization model of agricultural production and water use then subject it to climate change and biofuel scenarios. More specifically, we quantitatively study how climate change and bioenergy production may alter regional crop mix and the economy while considering the limited water resource.

3.3 Model Specification

We modeled economic returns to land and groundwater management over a forty year planning horizon following the basic framework of an optimization model of groundwater allocation originally developed by Feng (1992) and later expanded by Terrell (1998), Johnson (2003) and Das (2004), but we further modified and complemented the model with the following features in order to take accurate simulation of spatial-temporal agricultural land use change,

- Addressing spatial heterogeneity by incorporating hydrologically homogenous subareas based on GIS-analysis.
- Taking “a historical crop-mix approach” (McCarl 1982) in programming agricultural supply responses in each homogenous area, which helps characterize the feasible decision space of the aggregate producer.
- Incorporating the climate change factors to project its impacts on agricultural production and dynamic adaptation options by farmers.
- Incorporating biofuel feedstock production sector to explore potential effects of biofuel production on crop mix.

This is a dynamic nonlinear programming model with agricultural and hydrological components. The model assumes that farmers maximize the net present value of income while facing constraints on land, water, and production inputs. The withdrawals of the aquifer for crop farming are path of the choice set. The whole region is divided into sub regions (defined as zones) in each county. The division is based on initial saturated thickness and water depth levels while yields and other production costs are assumed homogeneous within a county. The objective function and net returns identity are:

(3-1)
$$max\, NPV = \sum_{t=1}^{T} (1+r)^{-(t-1)} NR_t$$

(3-2)
$$NR_t = \sum_{z} \sum_{i} \sum_{l} [P_{it} Y_{ilt} ACR_{zilt} - C_{zilt}] + \sum_{z} NB_t(PASTLAND_{zt})$$

where NPV is the net present value of net returns, r is the discount rate, and NR_t is the net return at time t, NR_t is defined as the difference between total revenue and the cost of agricultural production. z represents the alternative zones in a given county, i represents the crops grown, l is the land use which is categorized as irrigated land and dryland. P_{it} is the exogenous price of crop i at time t, Y_{ilt} is the yield which is related to crop, water use and land type, ACR_{zilt} is acreage of crop i in land type l zone z at time t, C_{zilt} is variable and fixed cost of production which includes energy cost of water pumping, depreciation cost for the irrigation system, harvest cost, maintenance cost and labor cost as further defined below, NB_t is net benefit of livestock grazing on pastureland which is the function of pastureland use in zone z time t ($PASTLAND_{zt}$). T is a finite time horizon (forty years). We do not include terminal conditions to reflect the value of in-process inventory beyond the final period rather we extended the time period to sixty-years instead of forty-year a period chosen which if extended beyond does not alter the solution in the first forty years, our time period of focus, following arguments in Nuthall (1980). Further details of the agricultural, hydrologic, climate, and biofuel feedstock aspects of the model follows

3.3.1 Agriculture

Crop yields are specified as dependent on water use allowing the possibility of deficit irrigation, defined as the application of water below full crop-water requirements (evapotranspiration). It is an important strategy to achieve the goal of reducing irrigation water use. Conceptually this is

$$Y_{ilt} = f(WUS_{zit}), \quad l = irrigated\ land \tag{3-3}$$

where WUS_{zit} is the water use per acre of crop i at zone z time t. The crop production function f(·) describing crop yield response to applied water for given soil types and climate condition is estimated by statistical method using simulation data from the EPIC (Environmental Policy Integrated Climate) model (The EPIC model is a single-farm biophysical process model that includes several simulation components for weather, hydrology, nutrient cycling, pesticide fate, tillage, soil erosion, crop and soil management and economics). Deficit irrigation is allowed for major irrigated crops such as corn, cotton, wheat and sorghum.

In our model, we assume cattle production is the major source of livestock grazing benefit, since it requires large grazing area. The usage of grazing land and cattle activity in each zone is restricted as:

(3-4) $$QCL_{zt} \leq PASTLAND_{zt}/gr$$

where QCL_{zt} is the number of cattle stock in zone z at time t. gr denotes the grazing rate which is the amount of grazing land required per unit of cattle.

The acreage of dryland and irrigated crops is required to be a convex combination of historical dryland and irrigated crop mix following McCarl and Önal (1989, 1991) and McCarl (1982).

(3-5) $$ACR_{zilt} = \sum_{j} CROPMIX_{zljt} \cdot hiscrop_{zilj}$$

(3-6) $$\sum_{i} \sum_{l} ACR_{zilt} \leq CROPLAND_{zt}$$

where j is the index for mixes drawn from historical year from 1990-2010, $CROPMIX_{zljt}$ is the a variable giving the amount of land plated to each of the historical crop mixes. $hiscrop_{zilj}$ is the proportion of each crop in the jth historical crop mix for dryland and irrigated crops, $CROPLAND_{zt}$ is total available crop land at zone z time t. Omitted considerations in crop choice such as rotations, resource endowments, risk attitudes etc. are implicitly included by requiring the crops in a region to fall within the mix of crops observed in historical (past 20 years) observations of farmers' aggregate response. Finally we have a total land constraint that restricts cropping plus pasture:

(3-7) $$PASTLAND_{zt} + CROPLAND_{zt} \leq OVERLAND_{z}$$

This restricts the total land allocation to pasture and crops at zone *z* time *t* should not exceed than total available land ($OVERLAND_z$) in that zone. We assume that benefit of livestock production is expressed in terms of the rental rate for pastureland.

3.3.2 Hydrology

Local irrigation potential from the aquifer is generally determined by three main characteristics: (1) pumping lift; (2) saturated thickness (distance from surface of the aquifer to the Triassic clay bottom of the aquifer); (3) specific yield (the volume of water that can be extracted from a unit volume of saturated ground). As water levels continue to decline, aquifer characteristics will have increasingly important economic implications for water-use. The hydrological component therefore involves four equations which reflect the dynamic relationship between depletion of groundwater table and water pumping.

(3-8) $$ST_{zt} = ST_{zt-1} - (TW_{zt} - rech_z)/(overall_z \cdot s_z)$$

(3-9) $$LIFT_{zt} = LIFT_{zt-1} + (TW_{zt} - rech_z)/(overall_z \cdot s_z)$$

(3-10) $$WUS_{zit} \le WUS_{zi0} \cdot \left(\frac{ST_{zt}}{IST_z}\right)^2$$

(3-11) $$TW_{zt} = \sum_i ACR_{zilt} \cdot WUS_{zit} \le ST_{zt} \cdot overall_z \cdot s_z$$

The first equation models saturated thickness where ST_{zt} is the current saturated thickness at zone *z* time *t*, TW_{zt} is total water pumping at zone *z* time *t*, $rech_z$ represents the annual recharge rate, $overall_z$ is the area of Ogallala Aquifer underlying zone *z*, s_z is specific yield (%). The initial levels of saturated thickness in Zone 1-5 are assumed to be 25 feet, 75 feet, 125 feet, 175 feet and 225 feet, respectively. The second equation relates lift to saturated thickness, where $LIFT_{zt}$ is the current pumping lift at zone z in time t. The initial levels of pumping lift in Zone 1-5 are assumed to be 400 feet, 350 feet, 300 feet, 250 feet and 200 feet, respectively.

Equation (3-8) and (3-9) indicate the dynamic relationship between saturated thickness (lift) and total water pumping. Equation (3-10) is based on the assessment of well yield decreasing rate that is the square ratio between current saturated thickness and initial saturated thickness(Hughes and Wyatt, 1969), where WUS_{zi0} is assumed to be water use per acre of crop i at baseline year 2010, IST_z is the initial saturated thickness at zone z. Equation (3-11) restricts that total water pumping at time t is no more than actual volume of groundwater which equals to saturated thickness times area and specific yield.

(3-12) $$PC_{zit} = WUS_{zit} \cdot EF \cdot (LIFT_{zt} + 2.31 \cdot PSI) \cdot ENP/PE$$

(3-13) $$C_{zit} = FC_z + PC_{zit} + LMR_{zt} + LC_{zit}$$

Equation (3-12) expresses the energy cost of pumping (PC_{zit}) for crop i produced by a specific irrigation system at zone z time t, where EF is the energy use factor for electricity or natural gas, *PSI* represents the irrigation system operating pressure (pounds per square inch of pumping head), *ENP* is energy price, *PE* is pumping engine efficiency, and the factor 2.31 (feet) is the height of a column of water that will exert a pressure of 1 pound per square inch. Equation (3-13) expresses total pumping costs for crop *i* at zone *z* time *t*, where FC_z is fixed costs including depreciation cost for the specific type of irrigation system, taxes, insurances and interest charges, LMR_{zt} is the lubrication, maintenance and repair costs and LC_{zit} is the labor cost per acre for irrigation. Equation 3-8~3-13 are derived from the study by Almas et al. (2006) and Das et al. (2010).

3.3.3 Climate Change

We used existing data of the effects of selected IPCC (Intergovernmental Panel on Climate Change) scenarios on crop yields drawn from Beach et al. (2009). We selected the A1B scenario with characteristics of a moderate/high rate of CO_2 emissions and the closest reproduction of the actual emission trajectories during the period since year 2000-2008 (van Vuuren and Riahi 2008). Crop yield were generated by four GCMs:

- Coupled Global Climate Model (CGCM3.1) developed by the Canadian Centre for Climate Modeling and Analysis, Canada;
- GFDL-CM2.0 and GFDL-CM2.1 models developed by the Geophysical Fluid Dynamics Laboratory (GFDL), USA;
- Meteorological Research Institute (MRI) Coupled atmosphere-ocean General Circulation Model (CGCM2.2) developed by the Meteorological Research Institute, Japan Meteorological Agency, Japan.

3.3.4 Biofuel Feedstock

A number of crops like switchgrass and miscanthus have been widely discussed as future biofuel feedstocks (Beach and McCarl 2010; Khanna et al. 2011). However, biomass yields from these bioenergy crops are identified as being highly susceptible to shortages of water (Stone et al. 2009). More recently, energy sorghum has been recognized as a potential feedstock particularly in Texas High Plains Region due to its greater water use efficiency, more drought tolerance and higher production volume. Therefore, in this study, four candidate cellulosic ethanol feedstocks, switchgrass, energy sorghum, corn stover and wheat straw were incorporated into the model. We noticed that "historical crop mix" described above could not be directly applied to energy crop responses which are rarely observed in historical supply. Thus, these crops were excused from the mixes but a set of restraints was imposed to limit the amount of land switching to new energy crops (including switchgrass and energy sorghum) in a given year.

$$\sum_{e}\sum_{l} ENACR_{zelt} \leq CROPTOEN_{zt} + PASTOEN_{zt} \tag{3-14}$$

$$CROPLAND_{zt} \leq CROPLAND_{zt-1} - CROPTOEN_{zt} \tag{3-15}$$

$$PASTLAND_{zt} \leq PASTLAND_{zt-1} - PASTOEN_{zt} \tag{3-16}$$

$$0 \leq CROPTOEN_{zt} \leq 0.1 * CROPLAND_{zt-1} \tag{3-17}$$

$$0 \leq PASTOEN_{zt} \leq 0.05 * PASTLAND_{zt-1} \tag{3-18}$$

Equation (3-14) models that cropland and grassland/pasture can be allocated to switchgrass and energy sorghum yearly, where $ENACR_{zelt}$ is the acreage of land for energy crop e in land type l zone z at time t, $CROPTOEN_{zt}$ and $PASTOEN_{zt}$ represent land diverted to energy crops from cropland and pastureland respectively. Equation (3-15) and (3-16) express the dynamic change of cropland and pastureland respectively after adding energy crops in. Equation (3-17) and (3-18) restrict that the percentage of cropland and pastureland converted to energy crops is no more than 10% and 5% respectively each year in any given county.

Crop budgets of switchgrass and energy sorghum including crop yield and water use were based on the Texas AgriLife Extension experimental data (Buttery et al. 2011). Table 3-1 presents water use and biomass yields of energy sorghum and switchgrass in Texas High Plains Region. As we see, energy sorghum has a higher yield than switchgrass and is more drought-tolerant. Large quantities of crop residues are produced, yet little is utilized, they are likely the lowest cost biomass source (Gallagher et al. 2003). Given that corn stover and wheat straw are byproducts of grain production, the quantity (measured in dry tons) of crop residue produced after harvest is calculated following the method in Beach and McCarl (2010) as

Crop Residue = (Crop Yield)*(Straw-to-Grain Ratio)

(Weight Conversion Factor)(Moisture Content)

Table 3-1. Yields and water use of energy sorghum and switchgrass in Texas High Plains Region (source: Buttery et al. 2011)

	Dryland (ton/acre)	Irrigated(ton/acre)	Water Use (feet)
Energy Sorghum	**6.19**	**15.4**	**1.20**
Switchgrass	**3.20**	**5.80**	**1.60**

Table 3-2. Straw-to-grain ratio, weight conversion factor and moisture content for corn and wheat (source: Beach and McCarl 2010)

Crop	Straw-to-Grain Ratio Content	Weight Conversion Factor	Moisture
Corn	**1.0:1**	**0.028 (tons/bu)**	**12%**
Wheat	**1.5:1**	**0.03 (tons/bu)**	**8.9%**

Table 3-2 presents the assumed straw-to-grain ratio, weight conversion factor and moisture content of corn and wheat. These values remain constant in the model.

3.4 Study Area and Data Analysis

The Texas Ogallala Aquifer Region includes 46 counties (Figure 3-2). The region has a semi-arid climate with low average rainfall, which results in little surface water being available for agriculture. Three counties of Texas Ogallala Aquifer Region—Dallam, Hartley and Sherman (as highlighted in Figure 3-2) are in the focus of this research, as they have been identified as critical groundwater depletion areas (Marek et al. 2009). Figure 3-3 shows a map of regional total change in saturated thickness level from 1990 to 2008. The water level changes are heterogeneous within and among counties and most areas are facing water depletion.

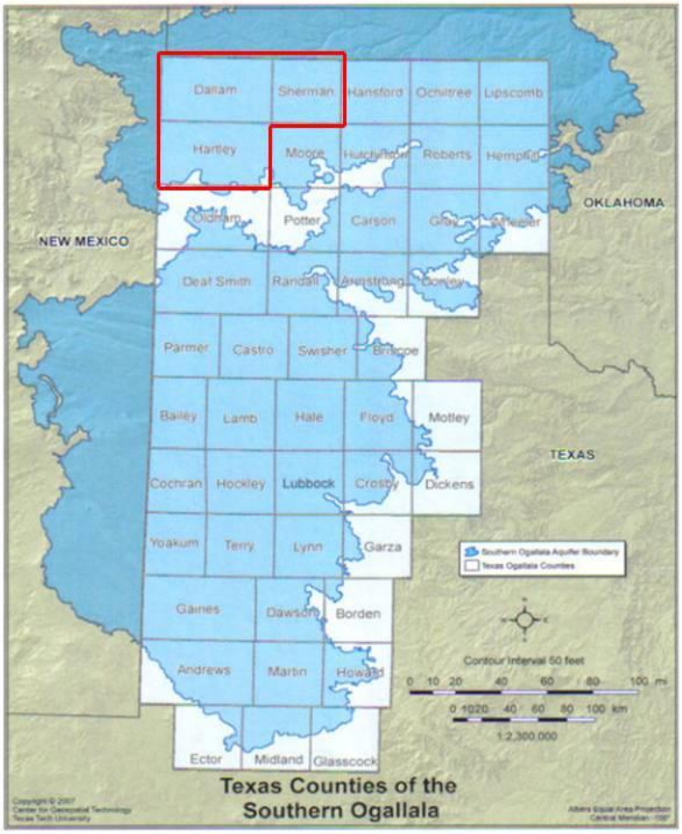


Figure 3-2. All counties in the Texas Panhandle Region that overly part of the Ogallala Aquifer (Highlighted: Dallam, Hartley and Sherman) (Source: Center for Geospatial Technology, Texas Technology University)

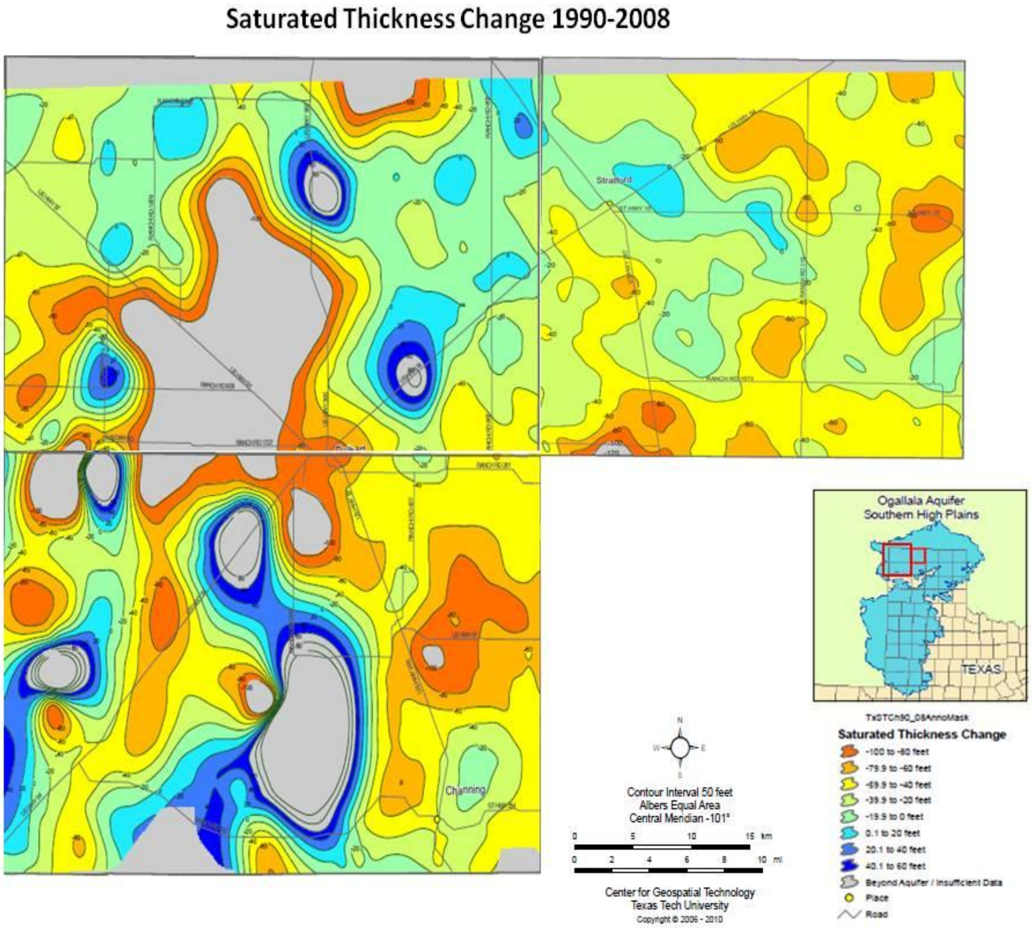


Figure 3-3. Saturated thickness change from 1990 to 2008 in Dallam, Hartley and Sherman County (Source: Ogallala Aquifer Program 2010, Center for Geospatial Technology, Texas Technology University)

Table 3-3. Amount of major cropland types in three counties (unit: Acres). The proportion of total land is given in parentheses

County	Corn	Cotton	Winter Wheat	Sorghum	Grassland/Pasture
Dallam	129361(13.43%)	5570(0.58%)	127035(13.19%)	9806(1.02%)	580935(60.31%)
Hartley	114727 (12.58%)	4838(0.53%)	80171(8.79%)	9066(0.99%)	617684(67.75%)
Sherman	83967 (14.07%)	32017(5.37%)	126707 (21.24%)	6816(1.14%)	323336(52.26%)

Land use data were drawn from a USDA/NASS source-Cropland Data Layer 2010. Table 3-3 lists statistics on crops incidence in 2010. Among the crops corn and wheat have the largest acreage, followed by sorghum and cotton. Grassland/pasture occupies more than 50% of the total area. Aquifer GIS-based hydrological data were obtained from the Center for Geospatial Technology, Texas Tech University. Saturated thickness is the volume of the aquifer in which the pore spaces are completely filled (saturated) with water. It is a critical determinant of groundwater availability. Five zones (zone 1-5) were identified in each county corresponding to five levels of initial saturated thickness: 0-50 feet, 50-100 feet, 100-150 feet, 150-200 feet and more than 200 feet, respectively. Figure 3-4 shows the proportion of each zone's area to total area of the county. The saturated thickness (ST) levels are not uniformly distributed. In Dallam and Hartley County, zone 3 with mediate ST level (100-150ft) occupies the largest area; while zone 1 and zone 5 , the lowest and highest ST levels, account for the smallest area. In Sherman County, most of areas are in zone 4 (150-200ft); while very little is found in zone 1. By overlaying the Cropland Data Layer 2010 with GIS-based hydrological data, we found the spatial distribution of crop patterns in each zone. Table 3-4 lists the estimated acreages of the major land uses within each zone in three counties.

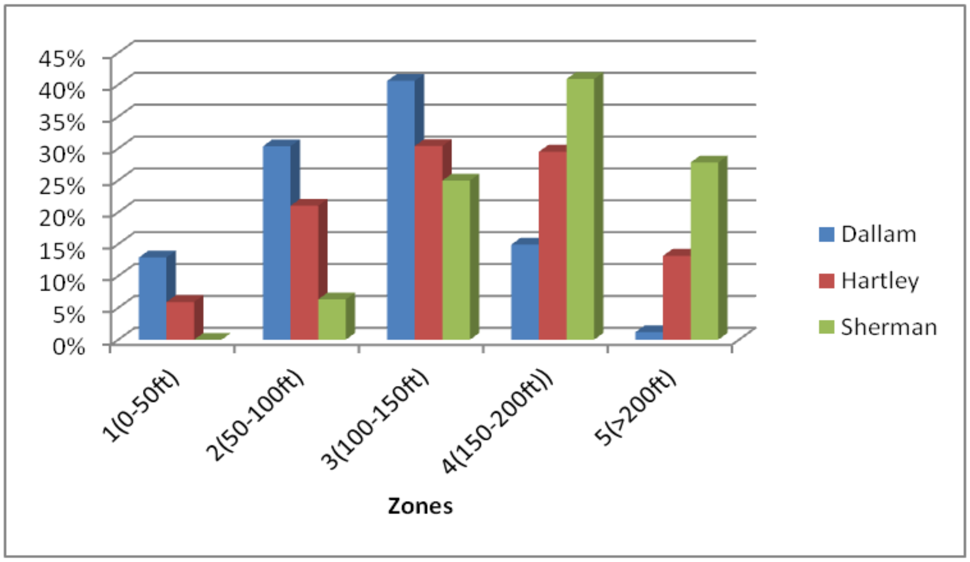


Figure 3-4. The proportion of identified hydrologically homogeneous zones in each county

Table 3-4. Cropland distribution within each zone in year 2010 (unit: acres)

County	Cropland	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
Dallam	Corn	2695	37248	63605	13353	12460
	Cotton	397	1016	1953	778	1092
	Winter Wheat	9093	40860	55088	12074	9973
	Sorghum	1255	2161	3339	913	1483
	Grassland/Pasture	59053	197556	233033	115142	38697
	Total Land	64489	292158	373839	148357	66511
Hartley	Corn	525	20936	51330	32587	9349
	Cotton	33	1920	1407	1143	335
	Winter Wheat	3486	18138	33716	15201	9629
	Sorghum	13	3502	3512	1580	460
	Grassland/Pasture	39221	126467	159724	199846	92427
	Total Land	54005	191623	277043	268948	120091
Sherman	Corn	0	2121	18882	35492	27472
	Cotton	0	614	8621	11539	11244
	Winter Wheat	0	7536	35922	52334	30915
	Sorghum	0	493	2080	2522	1721
	Grassland/Pasture	0	24342	72014	127563	87869
	Total Land	0	37746	148911	244007	165903

The above data are taken as baseline input on crop acreage into the dynamic optimization model. Pumping costs including variable costs and fixed costs are obtained from Amosson et al. (2001). Crop yields are assumed to be a quadratic function of applied irrigation water use and regressions are estimated based on outcomes from EPIC model. Detailed results of statistic regression for each crop yield on water use are in the Appendix.

3.5 Results

3.5.1 Baseline Assessment

First, we run the model without climate change and biofuel feedstock production as a baseline scenario. The results show that the average saturated thickness decreases by 39.65%, 35.63% and 42.48%, in Dallam, Hartley and Sherman Counties respectively by 2050. With water depletion, by year 2050, total irrigated acres in these three counties decline by 43.76%, 13.27% and 12.66%, respectively while total dryland increases by 109.44%, 115.61% and 116.47%, respectively.

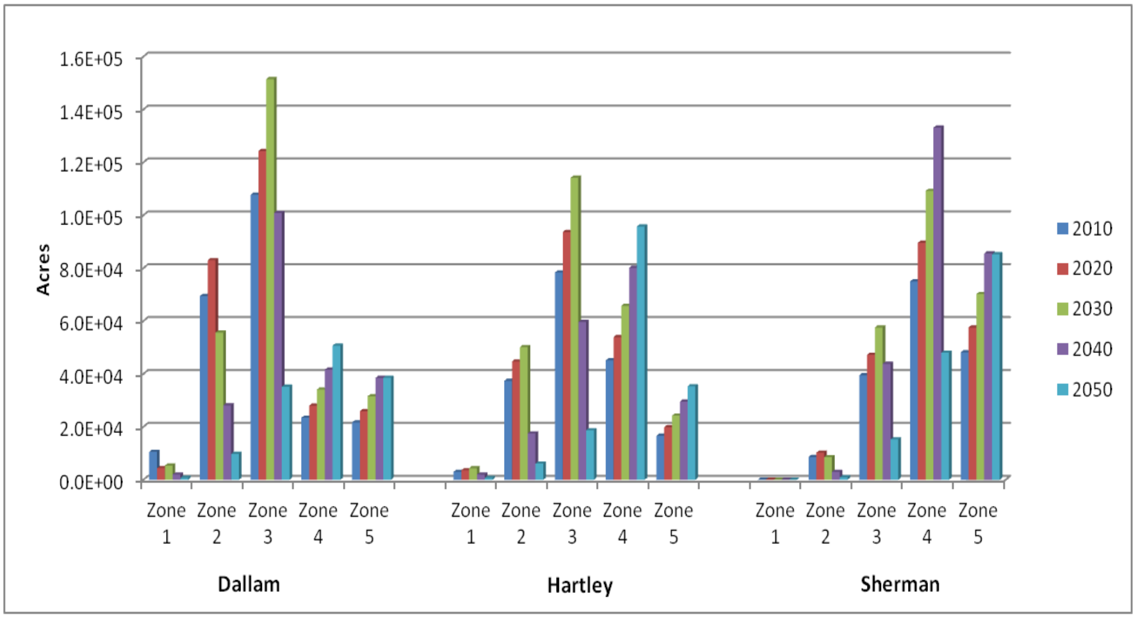


Figure 3-5. Acres of irrigated land over years within different zones in Dallam, Hartley and Sherman County

The changes in crop land irrigation status vary by zones (Figure 3-5). In zone 1, the lowest initial level of ST, irrigated land declines over years in all three counties till year 2050. In Zone 2 and Zone 3, irrigated land exhibits a short increase within the next 10 to 20 years then declines. In Zone 4 (except Sherman County) and Zone 5 with relative high level of ST, irrigated land steadily increases over the next 40 years. In Sherman County, irrigated land in Zone 4 goes up by 77.58% till year 2040 but then decreases by 63.90% after that (by year 2050).

The different crop patterns are in part due to the application of deficit irrigation. Traditional irrigation aims at applying sufficient water to crops to avoid water deficits at all stages (Lorite et al. 2007). Our results indicate that adoption of deficit irrigation is beneficial to the regional economy and maintains water use as opposed to full irrigation. Reduced crop yields are compensated by larger area and longer water availability. Dryland farming dominates after 2030 in the zones with low initial ST. Figure 3-6, 3-7 and 3-8 indicate the dynamic changes in cropland over Zone 2, 3 and 4. In Zone 2, the acreage of irrigated corn initially increases then decreases. Irrigated wheat and sorghum prevail during 2020~2030, after which dryland wheat, sorghum and cotton dominate cropland use. In Zone 3 irrigated corn prevails in the first 20 years. After 2030, irrigated wheat, sorghum and cotton take over but dryland wheat, sorghum and cotton also increase eventually exceeding irrigated land by 2050 (see Figure 3-7). In Zone 4, the production of irrigated corn dominates in Dallam and Hartley County with some irrigated wheat, cotton and sorghum while dryland production is much less. In Sherman County, the acres of irrigated corn increases by 52.54% till year 2030 but declines by 64.8% during year 2040-2050. Irrigated wheat shows largest increasing rate during 2020~2040 while irrigated sorghum, dryland wheat and cotton expand after year 2040.

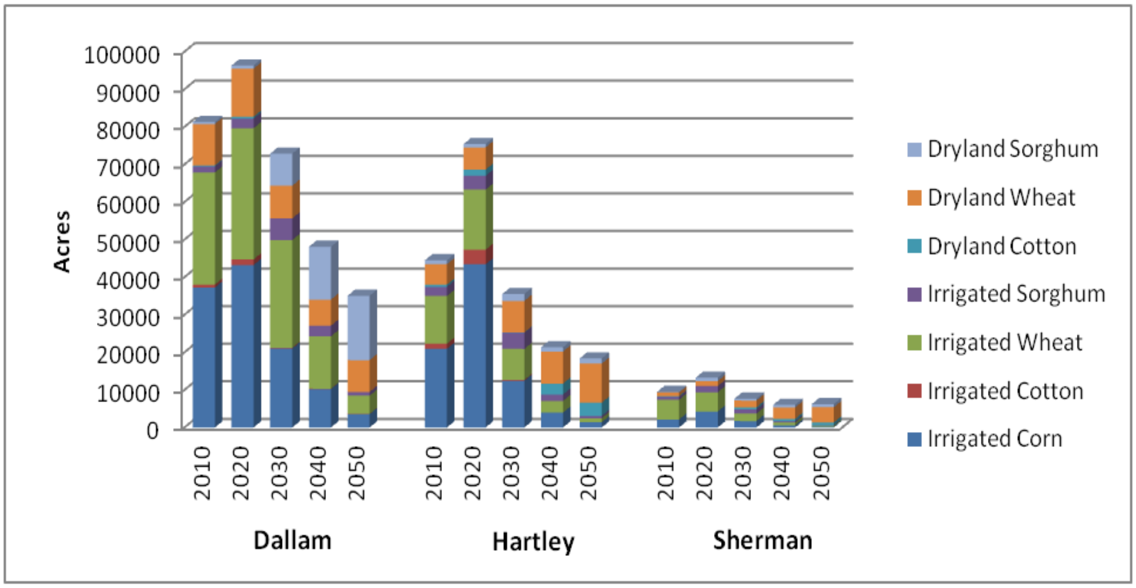


Figure 3-6. Acres of cropland use in Zone 2 in Dallam, Hartley and Sherman County during 2010~2050

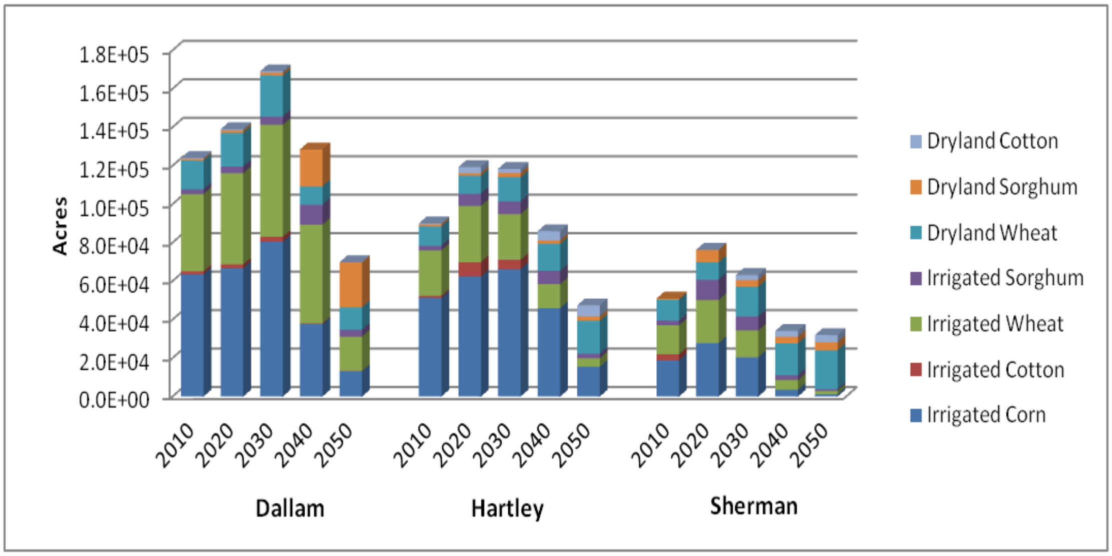


Figure 3-7. Acres of cropland use in Zone 3 in Dallam, Hartley and Sherman County during 2010~2050

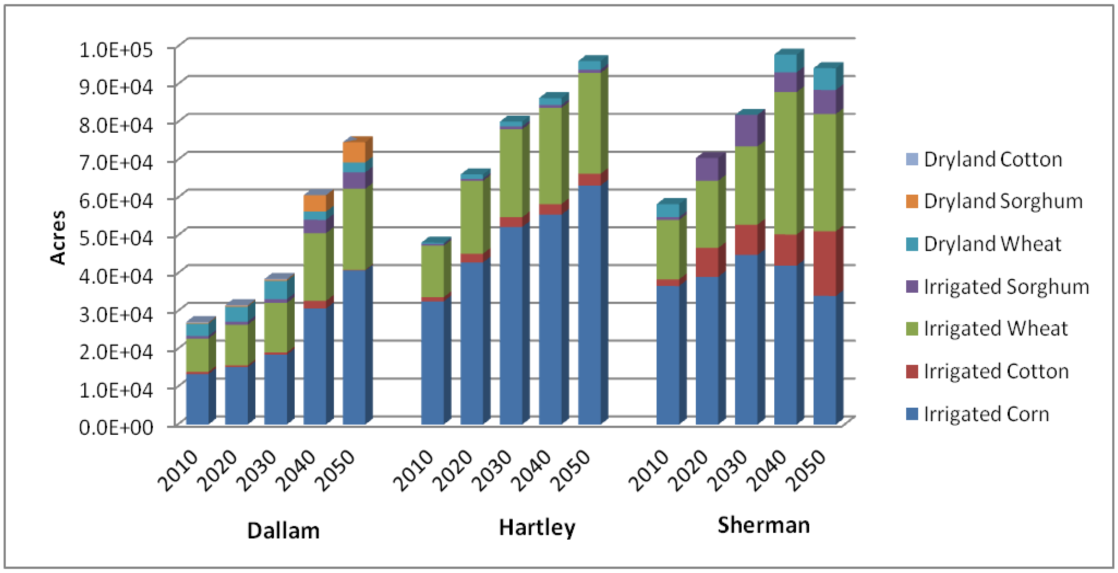


Figure 3-8. Acres of cropland use in Zone 4 in Dallam, Hartley and Sherman County during 2010~2050

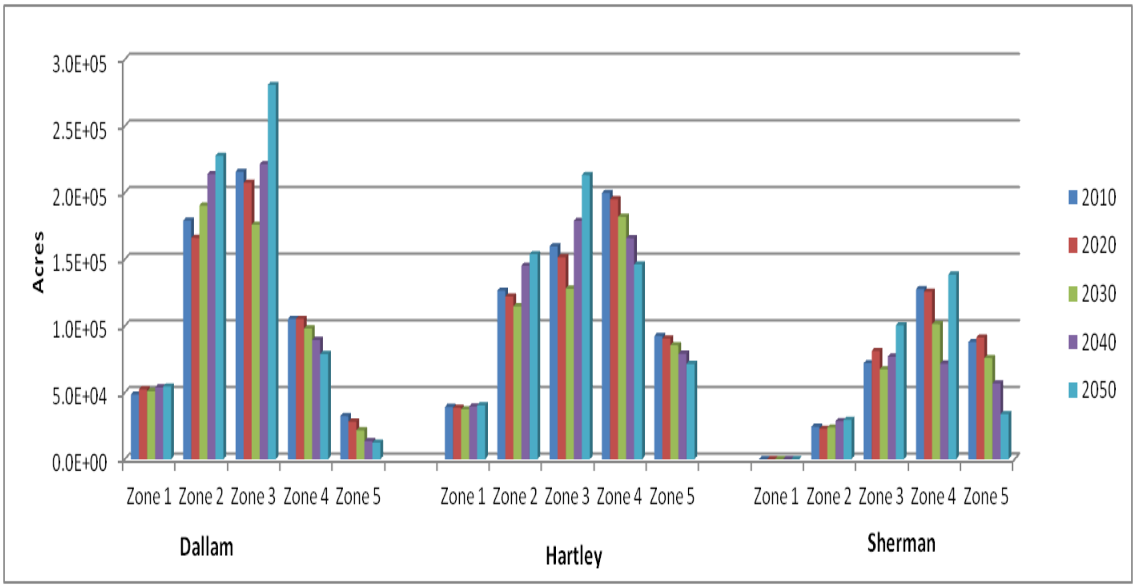


Figure 3-9. Acres of pasture land in Dallam, Hartley and Sherman County during 2010~2050

Dryland farming becomes more prevalent particularly after year 2030. Initially dryland averagely accounts for 17.96%, 15.11% and 17.89% by county of total cropland in year 2010 but represents 30.20%, 32.70% and 38.73% of total crop acres in 2050, respectively. Figure 3-9 indicates that pasture land increases over zones. In general, in the low ST zones irrigated corn is initially replaced by irrigated wheat and sorghum then land transitions to dryland wheat, sorghum and cotton. There is also an increasing trend in total pasture land reflecting a shift out of cropping (Water consumed by livestock and other processes within whole livestock industry is not counted in the model).

Table 3-5. Production of major crops in aggregated three counties over 2010-2050 time periods

Crop	Irrigation Status	2010	2020	2030	2040	2050
Corn (Million Bu)	Irrigated	63.3	65.2	52.2	46.8	43.3
	Dryland	-	-	-	-	-
Cotton (Million Lbs)	Irrigated	24.1	28.6	32.1	29.14	18.10
	Dryland	2.27	2.00	2.35	3.47	7.07
Wheat (Million Bu)	Irrigated	10.4	10.9	9.40	6.52	5.38
	Dryland	1.16	1.08	1.30	1.37	1.49
Grain Sorghum (Million Bu)	Irrigated	1.10	1.13	1.26	0.93	0.58
	Dryland	0.34	0.53	0.64	0.79	0.88

Table 3-5 presents the production of major crops in all three counties over 2010-2050 periods. It is noticeable that after a slight increase in 2020, the production of irrigated corn falls by 31.6% by 2050. Saved water from deficit irrigation will be diverted to sustain the relative low water-use crops production (e.g. sorghum, cotton) in the next 15-20 years. With continuing water depletion, irrigated cropping will be replaced by dryland farming which increase the production of dryland wheat, sorghum and cotton.

3.5.2 Climate Change Effects

Table 3-6 summarizes regional crop yield sensitivity to climate change under the four GCM projections in year 2045-2054 relative to the 1990-2000 baseline. This shows large effects on crop yields under the climate change scenarios modeled, both positive and negative, for some part both irrigated and dryland corn and cotton yields decrease while irrigated and dryland wheat yields increase. Table 3-7 indicates that climate change usually reduces irrigation water needs. The water use reduction is lowest for cotton in comparison to other major crops.

Table 3-6. Crop yields sensitivity to climate change in Texas High Plains Region under four GCMs modeled, 2045-2054 relative to 1990-2000 climate baseline (Source: Beach et al. 2009)

Crop	Irrigation Status	CGCM31	MRICGCM	GFDL2.0	GFDL2.1
Corn (%)	Irrigated	-2.27	1.57	-5.97	-10.98
	Dryland	19.47	15.25	22.39	-7.35
Cotton (%)	Irrigated	-1.16	7.33	-0.89	-9.66
	Dryland	-1.13	7.64	11.06	-18.81
Wheat (%)	Irrigated	7.74	3.82	1.67	4.83
	Dryland	45.11	15.99	18.32	20.12
Sorghum(%)	Irrigated	-3.85	5.81	0.36	-12.65
	Dryland	17.24	21.68	4.53	-1.88

Table 3-7. Irrigation water use sensitivity to climate change under four GCMs modeled, 2045-2054 relative to 1900-2000 climate baseline. (Unit: mm) (Source: Beach et al. 2009)

	CGCM31	**MRICGCM**	**GFDL20**	**GFDL21**
Corn	-40.019	-45.336	-44.065	-10.221
Cotton	-9.812	-0.562	-12.779	9.063
Wheat	-41.57	-4.142	-65.434	-36.653
Sorghum	-35.291	-25.916	-45.605	-19.025

To fully investigate climate change impacts on agricultural production, these crop yields and water demand sensitivity data were incorporated into our dynamic model. Figure 3-10 through 3-12 present the simulated temporal changes on acreage for selected major crops relative to the baseline (no-climate change) assessment. Shifts of crop mix in sub-regions with less water availability are more substantial. As indicated in

Figure 3-10, in Zone 1 with lowest water level, irrigated corn, wheat and sorghum acreage tends to increase. The acreage of dryland wheat also increases. Dryland sorghum shows mixed results varying with the climate scenario. There is less expansion in pasture land. In Zone 3, irrigated corn and wheat are larger (See Figure 3-11). In Zone 5, climate change has little effects on crop mix (See Figure 3-12). In later periods (after year 2030), there is more irrigated corn but less irrigated wheat under the CGCM3.1, MRI-CGCM and GFDL-2.0 climate projections. On the other hand, under GFDL-2.1, there is more irrigated wheat but less irrigated corn as influenced by the yield differences.

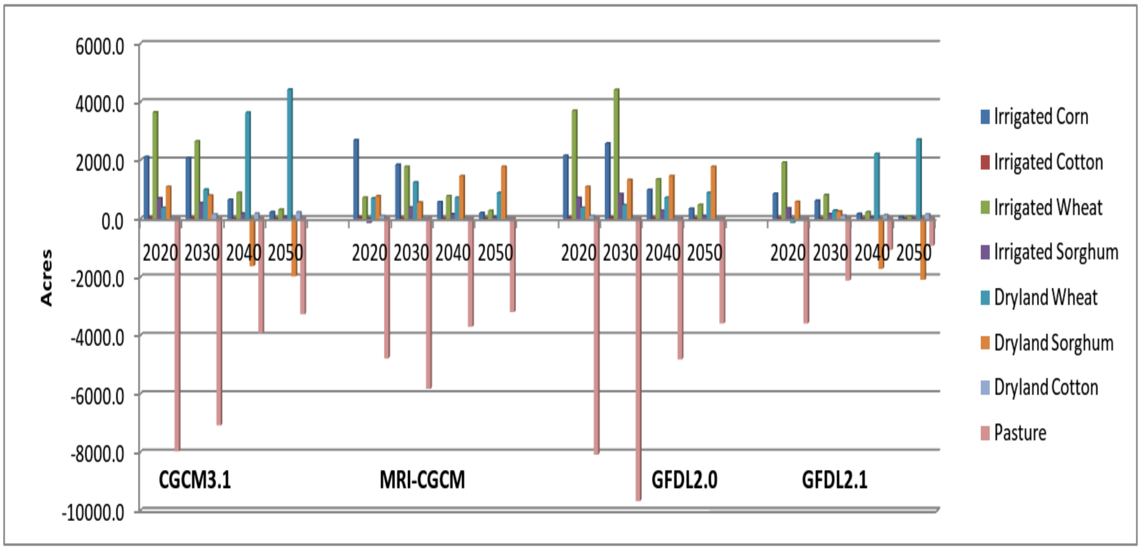


Figure 3-10. Crop pattern changes under four GCMs modeled in selective years relative to 2010 climate baseline in Zone 1, Dallam County

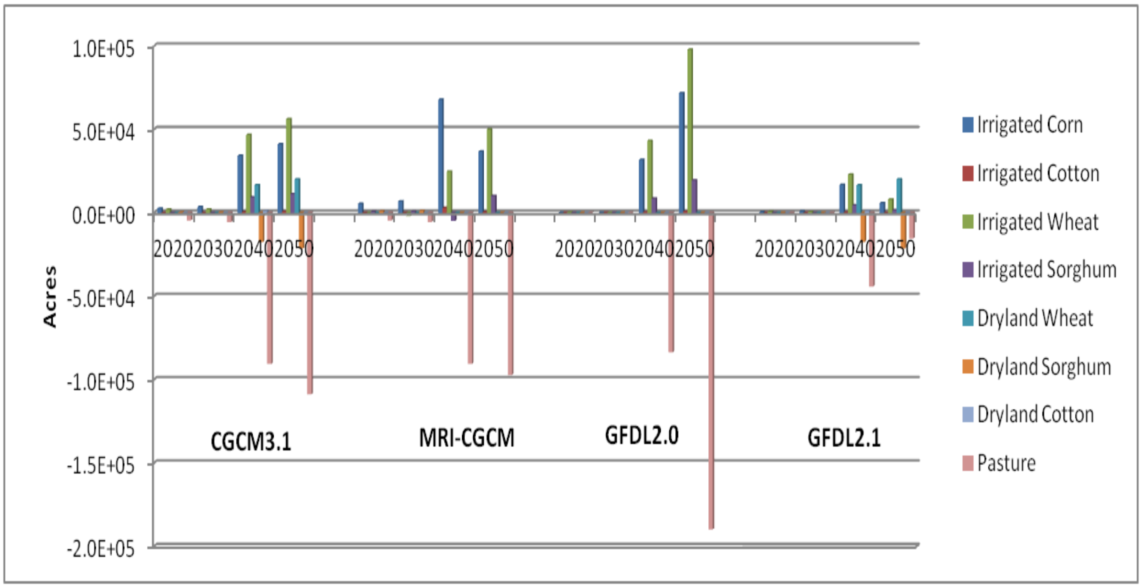


Figure 3-11. Crop pattern changes under four GCMs modeled in selective years relative to 2010 climate baseline in Zone 3, Dallam County

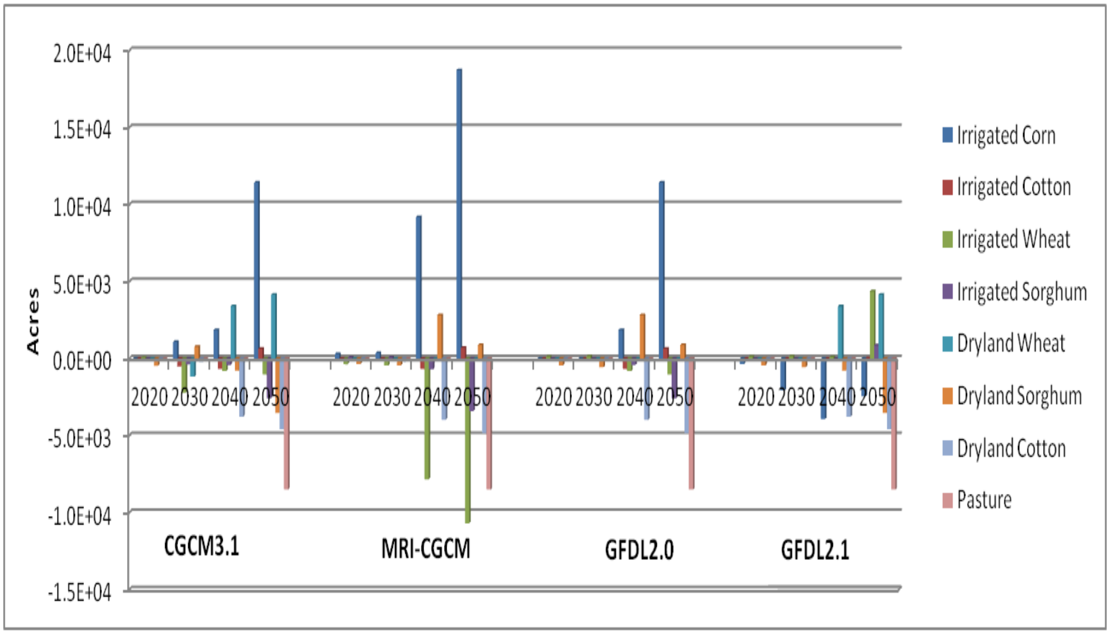


Figure 3-12. Crop pattern changes under four GCMs modeled in selective years relative to 2010 climate baseline in Zone 5, Dallam County

In general, we find that climate change has inconsistent effects on crop land use change over different zones and years. Regions with lower water availability are more sensitive to climate change— there are more acres of irrigated corn and wheat before year 2030 due to their reduced water demand as predicted while dryland wheat and sorghum expand more during 2030-2050 because of their higher yields estimated under climate change projections. As shown in Table 3-8, simulated optimal land allocation increases the net present value for all counties under the three GCM projections (except GFDL-2.1). Larger reduced crop yields and less enhanced water efficiencies as predicted over the majority of crops under GFDL-2.1 relative to the other three GCMs may be the possible reason.

Table 3-8. Percentage change for net present value over 40-year periods under four GCMs modeled relative to baseline case (Unit: %)

County\GCMs	CGCM3.1	MRI-CGCM	GFDL-2.0	GFDL-2.1
Dallam	36.7	33.5	10.95	-37.3
Hartley	12.8	14.2	12.4	-1.93
Sherman	21.7	18.7	21.6	3.42

We further test two more scenarios. The first one is to allow us to identify the consequences of neglecting water depletion as has been done in many more aggregate appraisals (Beach et al. 2009). The second one allows us to look at the value of adaptation in crop mix.

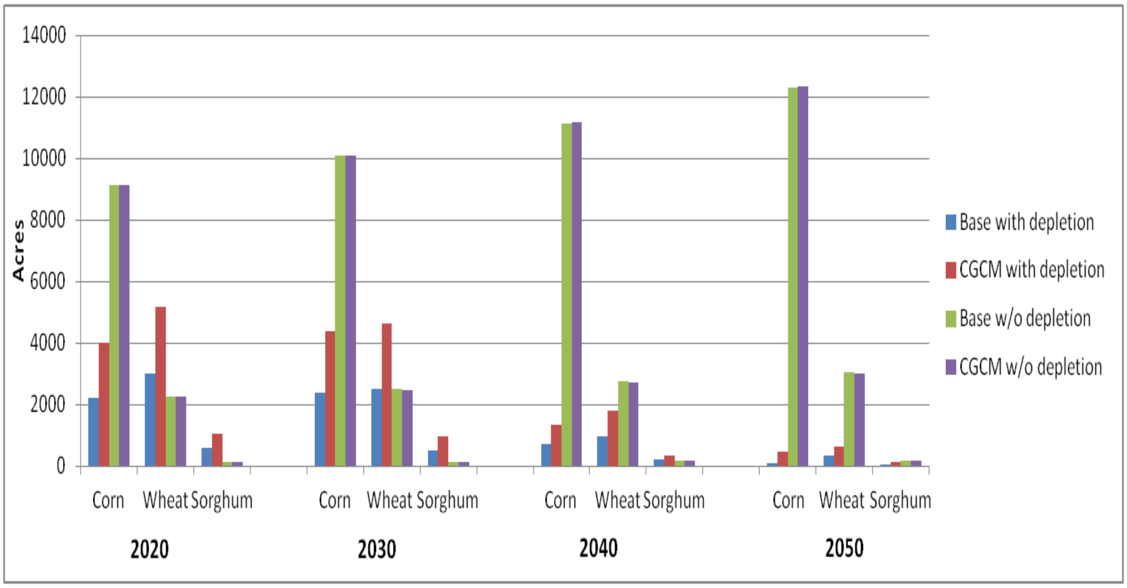


Figure 3-13. Acreage changes of irrigated crops under scenarios with and without water depletion in Zone 1, Dallam County

In terms of the effects of modeling depletion, our simulation indicates that irrigated crops tend to be little affected by climate change when depletion is ignored. Take zone 1 in Dallam County under CGCM 3.1 for example, as shown in Figure 3-13, there is very little difference of major irrigated crops acreages between baseline scenario (Base w/o depletion) and climate change scenario (CGCM w/o depletion) when there is no water depletion over years. To evaluate the value of a crop mix adaptation strategy, we create the scenario without changes in crop mix allowed. Table 3-9 lists the percentage changes of net present value for the 40-year period in relative to optimal scenario under four GCMs. This shows this adaptation is averagely worth 4.27%, 5.79% and 2.12% by county.

Table 3-9. Percentage change for net present value over 40-year periods when crop mix keeps the same proportion as in base year 2010 relative to the optimal land allocation cases (Unit: %)

County\GCMs	CGCM3.1	MRI-CGCM	GFDL-2.0	GFDL-2.1
Dallam	-2.34	-1.88	-10.95	-1.93
Hartley	-2.28	-7.40	-6.37	-7.12
Sherman	-1.32	-0.46	-0.64	-6.05

Table 3-10. Definition of energy crop scenarios applied in the model

	Switchgrass	Energy Sorghum	Crop Residues
Baseline	-	-	-
RFS2-Switchgrass	√	-	√
RFS2-Energy Sorghum	√	√	√

In sum, water availability and crop mix play essential roles in adapting agricultural production to climate change. Regions with sufficient water will be more resilient to changing climate, while water-scarce regions call for more effective adaptation strategies such as choosing more drought-tolerant crops.

3.5.3 Biofuel Feedstocks Effects

In this study, we employed the scenarios shown in Table 3-10 to examine the land use change and economic implications of introducing switchgrass and energy sorghum production. Note that in the "Baseline" scenario there is no feedstock involved; "RFS2-

Switchgrass" scenario includes switchgrass and crop residues (corn stover and wheat straw), but no energy sorghum; "RFS2-Energy Sorghum" scenario allows all four feedstock productions. In all scenarios, 35% corn is assumed to be applied in starch-based ethanol production annually according to the estimates by U.S. Department of Energy (2011). Because cellulosic ethanol production on large commercial scales has yet to commence, we exogenously set market price as $60 per dry ton (DT) for all cellulosic biomass in the model and assume it will stay constant over the 2010-2030 periods. Sensitivity analysis with respect to the price will be conducted in the later section.

Figure 3-14 presents the acreage changes of energy crops versus other crops that essentially consist of conventional crops in selected zones aggregated by all three counties under "RFS2-Switchgrass" Scenario. In Zone 2 and Zone3 with relative low ST level, there are increasing acreages of dryland switchgrass but little irrigated switchgrass. In Zone 4 with relative high saturated thickness, very little of switchgrass is found in crop mix. This heterogeneous land allocation shows that dryland switchgrass production is profitable in water-scarce zones, but is less competitive than irrigated high value crops in zones with more water available.

Under "RFS2-Energy Sorghum" scenario, we find that feedstock mix is largely changed after introducing energy sorghum. As shown in Figure 3-15, the amount of energy sorghum expanded in all three zones at the expense of switchgrass production. The mix of energy sorghum with different irrigation status varies with zones. In Zone 2, dryland energy sorghum increases as the major feedstock. In Zone 3, both irrigated and dryland energy sorghum are in crop mix, but the dryland energy sorghum is more preferred with water depletion over years. In Zone 4, irrigated sorghum plays the major role. These results imply that introduction of energy sorghum decreases the production of switchgrass significantly. More drought-tolerance and higher yield make energy sorghum more favorable than switchgrass over all zones.

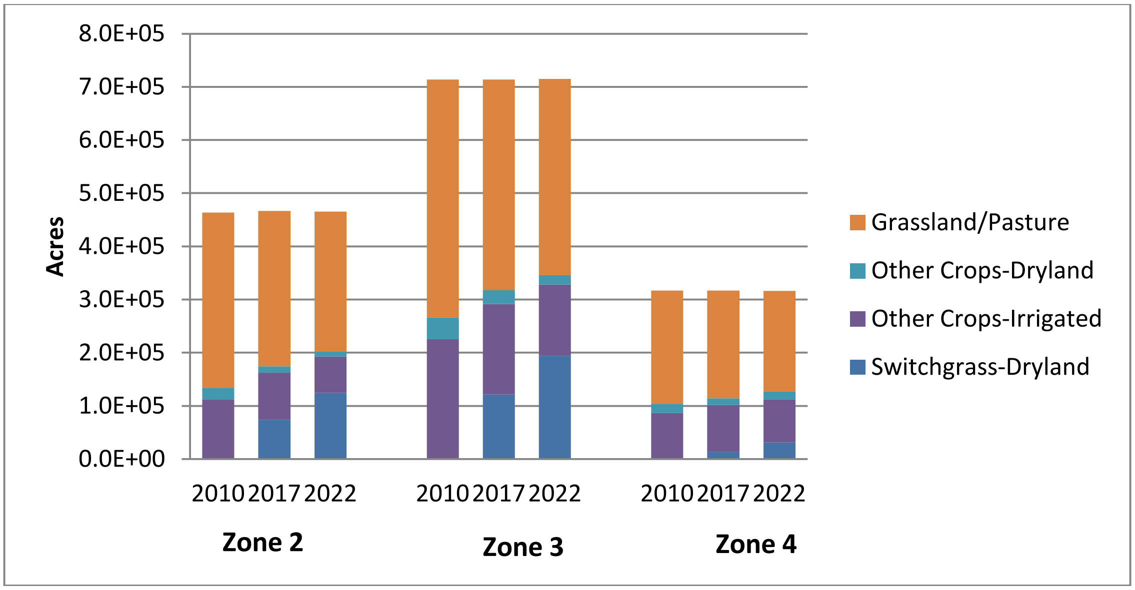


Figure 3-14. Land allocation among conventional crops and energy crops in selected zones and years in aggregated three counties under RFS2-Switchgrass scenario

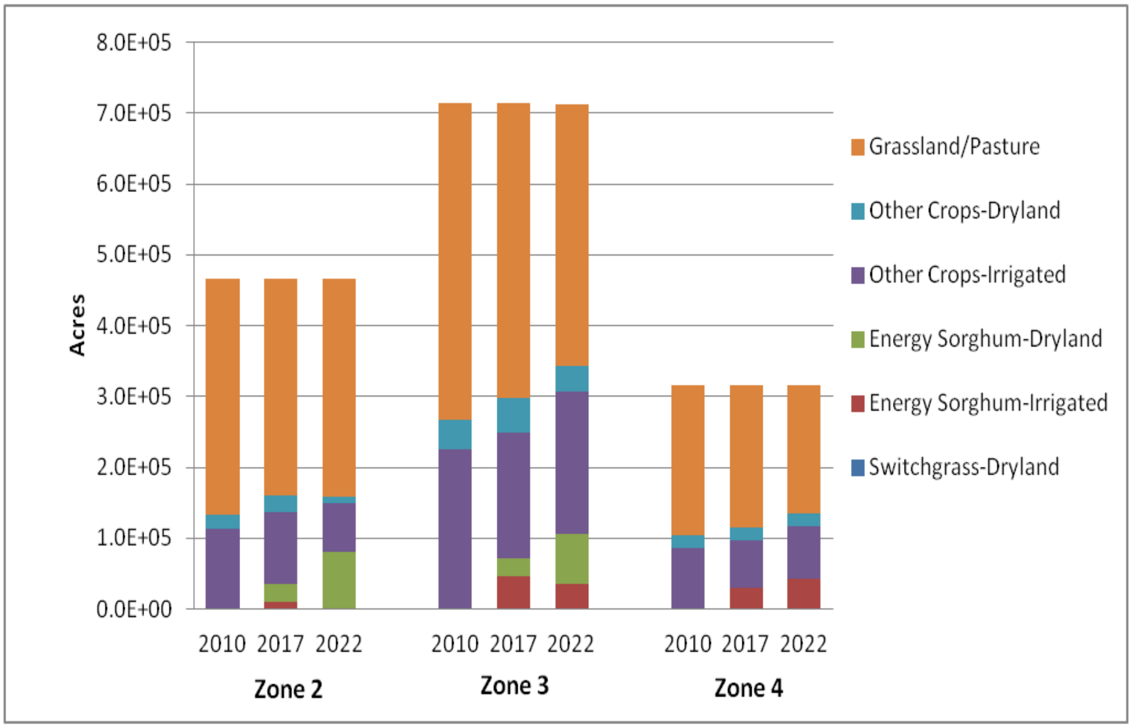


Figure 3-15. Land allocation among conventional crops and energy crops in selected zones and years in aggregated three counties under RFS2-Energy Sorghum scenario

Table 3-11 shows total land use change in different zones over all three counties under baseline and two energy crop scenarios by year 2022. In “RFS2-Switchgrass” case, the production of switchgrass increases the use of dryland by 289% and 329% in Zone 2 and Zone 3 respectively, while contributing to a decrease in irrigated land and grassland/pasture. In Zone 4, 3.9% grassland/pasture moves into crop land and results in increases of irrigated land and dryland by 23.5% and 18.6% respectively. The introduction of energy sorghum, as in “RFS2-Energy Sorghum” case, increases the dryland acreages at the expense of irrigated cropland and grassland/pasture in Zone 2, which is similar as in “RFS2-Switchgrass” scenario. However, in Zone 3 and 4, total irrigated land raises by 12.1% and 58.1% respectively with the increasing production of high-yielding irrigated energy sorghum, while grassland/pasture decreases. Compared with land use change under “Baseline” scenario, we can find biofuel feedstock production generally increases land allocation to cropland and reduce grassland/pasture acreages.

Table 3-11. Land use change of cropland and grassland/pasture under alternative scenarios in selected zones in 2022 relative to base year (2010) case

	Zone 2	**Zone 3**	**Zone 4**
	Baseline		
Cropland-Irrigated	-53.4%	4.5%	23.2%
Cropland-Dryland	-43.6%	24.3%	18.7%
Grassland/Pasture	11.3%	-4.5%	-4.0%
	RFS2-Switchgrass		
Cropland-Irrigated	-49.1%	-32.5%	23.2%
Cropland-Dryland	289.4%	328.6%	18.6%
Grassland/Pasture	-14.5%	-13.4%	-3.9%
	RFS2-Energy Sorghum		
Cropland-Irrigated	-43.6%	12.1%	58.1%
Cropland-Dryland	211.6%	142.0%	-44.7%
Grassland/Pasture	-5.4%	-10.9%	-19.9%

Table 3-12. Major crops production levels under alternative scenarios, 2022

Crop	Irrigation Status	Baseline	RFS2-Switchgrass	RFS2-Energy Sorghum
Corn (Million Bu)	Irrigated	64.8	65.5	62.1
	Dryland	-	-	-
Cotton (Million Lbs)	Irrigated	33.3	29.8	30.3
	Dryland	2.31	2.08	1.61
Wheat (Million Bu)	Irrigated	10.9	11.2	11.5
	Dryland	1.20	0.94	1.37
Grain Sorghum (Million Bu)	Irrigated	1.53	1.64	1.16
	Dryland	0.38	0.30	0.34

Table 3-12 shows the crops production levels over all three counties under alternative scenarios by year 2022. Corn and irrigated wheat production increase slightly under “RFS2-Switchgrass” scenario in relative to baseline case, while cotton (both irrigated and dryland) sees a reduction. The dryland wheat and grain sorghum production decreases with more land converting to dryland switchgrass under “RFS2-Switchgrass” scenario, but increases when energy sorghum enters the model. The introduction of energy sorghum results in a greater increase in irrigated wheat production relative to baseline than in the absence of energy sorghum. In general, the production results for major crops suggest that the presence of energy crops coupled with land and groundwater restraints does not necessarily lead to production changes in the same directions for all the crops but rather mixed outcomes.

With the commercial use of crop residues and increasing value of energy crops as the feedstocks, the value of cropland is expected to increase, as shown in Figure 3-16. The “RFS2-Switchgrass” scenario results in an increase in cropland value of 28.4% and 41.2% in year 2017 and 2022 respectively, relative to the baseline scenario. The “RFS2-Energy Sorghum” scenario increases the cropland value by 39.3% and 55.2% in 2017 and 2022, respectively.

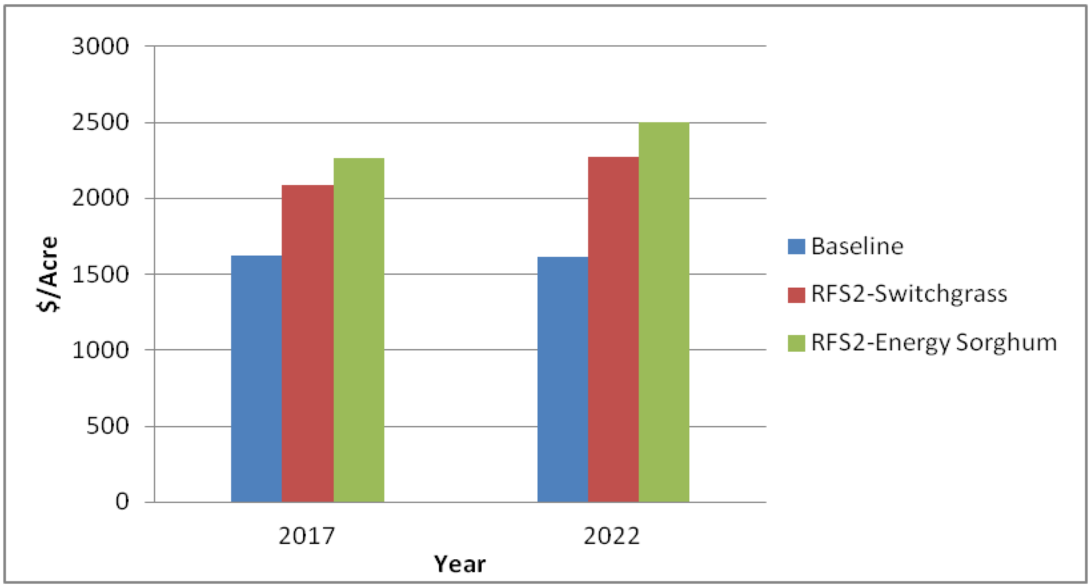


Figure 3-16. Land values for cropland under alternative scenarios in aggregated three counties.

Table 3-13. Production of major conventional crops and energy crops under alternative scenarios, 2022

Crop	Irrigation Status	RFS2-Switchgrass			RFS2-Energy Sorghum		
		With Depletion	No Depletion	Change	With Depletion	No Depletion	Change
Corn (Million Bu)	Irrigated	65.5	137	109.2%	56.1	101	79.4%
	Dryland	-	-	-	-	-	-
Cotton (Million Lbs)	Irrigated	19.8	17.5	-11.4%	35.3	26.3	-25.4%
	Dryland	2.08	1.45	-30.4%	1.61	2.40	49.2%
Wheat (Million Bu)	Irrigated	11.2	21.4	90.9%	11.5	13.0	13.1%
	Dryland	0.94	1.28	36.4%	1.37	1.19	-13%
Grain Sorghum (Million Bu)	Irrigated	1.64	2.44	48.9%	1.16	2.09	79.7%
	Dryland	0.94	1.28	33.3%	0.46	0.36	-22.7%
Switchgrass (Million Dry ton)	Irrigated	-	-	-	-	-	-
	Dryland	2.34	0.1	-95.7%	-	-	-
Energy Sorghum (Million Dry ton)	Irrigated	-	-	-	5.21	0	-100%
	Dryland	-	-	-	0.62	2.51	305%

To examine the potential impact that water availability would have on conventional and energy crops production, we also tested the scenario “No (Water) Depletion” associated with energy crop scenarios. Table 3-13 presents the production of major crops and energy crops by year 2022 under alternative scenarios. It is noticeable that water availability has a significant impact on crops and biomass production. With no depletion imposed, major irrigated major crops production increased by more than 70% under both energy crop scenarios. The total production of switchgrass and energy sorghum decreased by 95.7% and 56.9% under scenario “RFS2-Switchgrass” and

"RFS2-Energy Sorghum", respectively. This result implies that energy crops at $60 market price are not competitive with other high value and water-intensive crops (e.g. corn) if there is insufficient water resource. Table 3-14 and 3-15 show the ethanol production by feedstock with and without water depletion by year 2022 under RFS2-Switchgrass and RFS2-Energy Sorghum scenario, respectively. We find that corn-ethanol production will play the leading role if sufficient water resource is available. However, if there is water depletion, corn-ethanol production decreases by 39.4% and 44.1% in RFS2-Switchgrass and RFS2-Energy Sorghum scenario, respectively. Energy crop-based cellulosic ethanol will be the major part of total ethanol production followed by corn-ethanol and crop residue-ethanol.

To conduct the sensitivity analysis with respect to the market price of biomass, we examine two other biomass prices $40/Dry ton and $80/Dry ton. As indicated in Figure 3-17~3-20, the consequent land use change in the selected zones (zone 2-4) and years (2017 and 2022) under both RFS2-Switchgrass and RFS2-Energy Sorghum scenarios are qualitatively the same as that with $60/Dry ton market price. Increase in dryland switchgrass is found in Zone 2 and Zone 3 with continual water depletion, but much less is found in Zone 4 where there is relative high ST level. With the presence of energy sorghum, dryland switchgrass is largely replaced by the dryland sorghum in Zone 2 and Zone 3. In Zone 4, production of irrigated energy sorghum is competitive and increases with the market price of biomass. Table 3-16 shows land use and bioenergy feedstock production at each price level under RFS2-Switchgrass and RFS2-Energy

Sorghum scenarios in year 2022. Land under conventional crops declines by 25.2% and 8.3% as the biomass price increases from $40 per dry ton to $80 per dry ton in RFS2-Switchgrass and RFS2-Energ Sorghum, respectively. Increase of biomass price leads to more land in energy crops production. In RFS2-Switchgrass, the production of switchgrass increases as biomass price rises, while the production of other feedstocks (e.g. corn, crop residues) declines. A similar trend is found in RFS2-Energy Sorghum, where the production of energy sorghum increases by 40.4% as the price increases from $40 per dry ton to $80 per dry ton, while the production of corn (for ethanol), corn stover and wheat straw decreases by 27.3%, 26.3% and 33.3% respectively.

Table 3-14. Ethanol production by feedstock under RFS2-Switchgrass scenarios, 2022 (Unit: million gallons)

Feedstock	With Water Depletion	Without Water Depletion
Grain Ethanol		
Corn	70.74	116.8
Cellulosic Ethanol		
Switchgrass	221.84	10.25
Corn Stover	20.31	33.32
Wheat Straw	4.47	7.38
Total Ethanol	**317.36**	**167.02**

Table 3-15. Ethanol production by feedstock under RFS2-Energy Sorghum scenarios, 2022 (Unit: million gallons)

Feedstock	With Water Depletion	Without Water Depletion
Grain Ethanol		
Corn	61.02	109.08
Cellulosic Ethanol		
Switchgrass	-	-
Energy Sorghum	491.04	214.14
Corn Stover	17.52	31.32
Wheat Straw	4.25	4.99
Total Ethanol	573.83	359.53

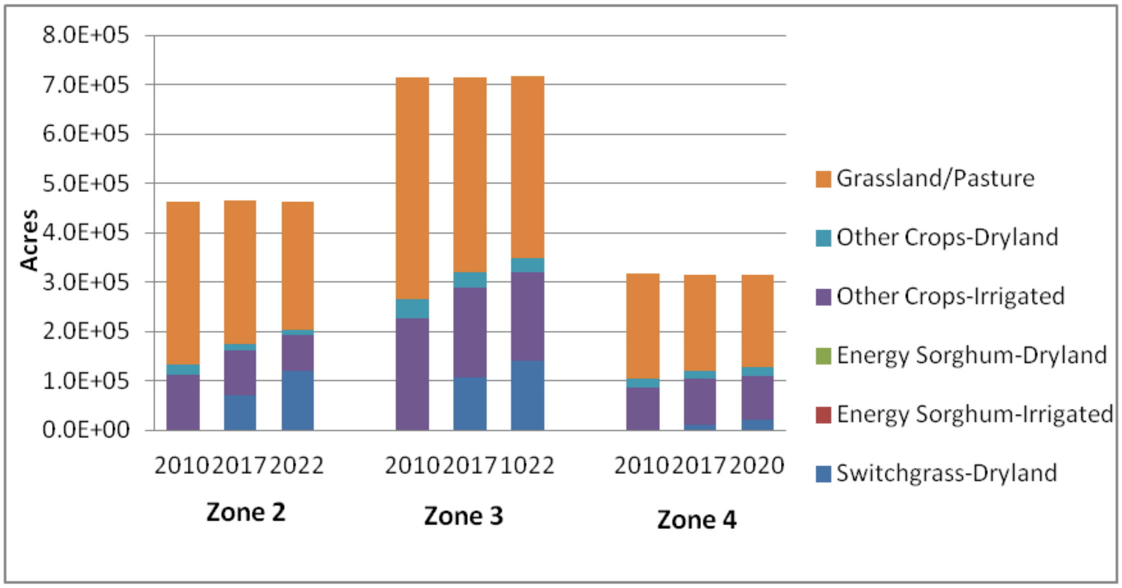


Figure 3-17. Land allocation among conventional crops and energy crops in selected zones and years in aggregated three counties at $40/dry ton biomass price under RFS2-Switchgrass scenario

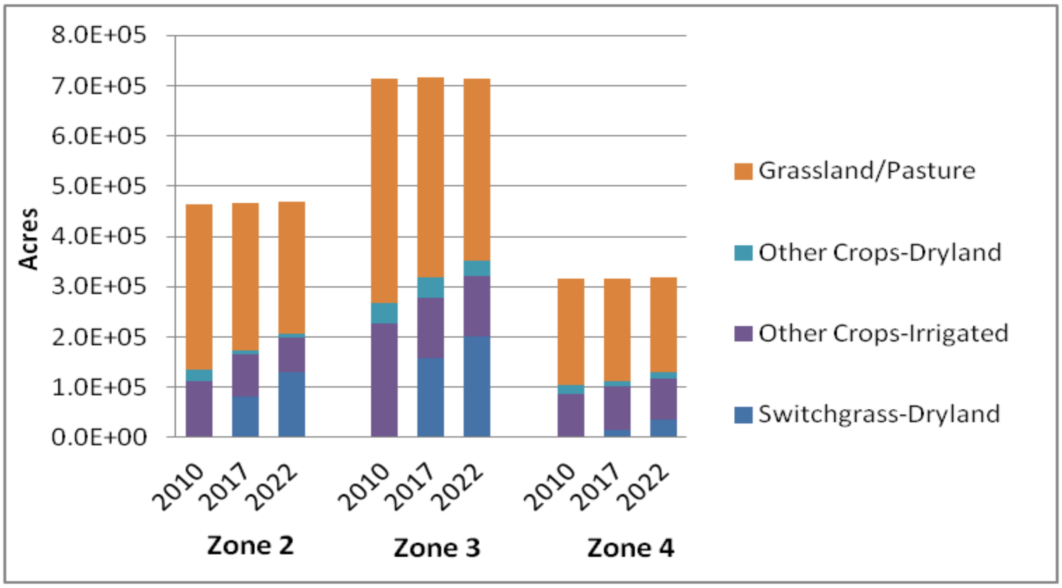


Figure 3-18. Land allocation among conventional crops and energy crops in selected zones and years in aggregated three counties at $80/dry ton biomass price under RFS2-Switchgrass scenario

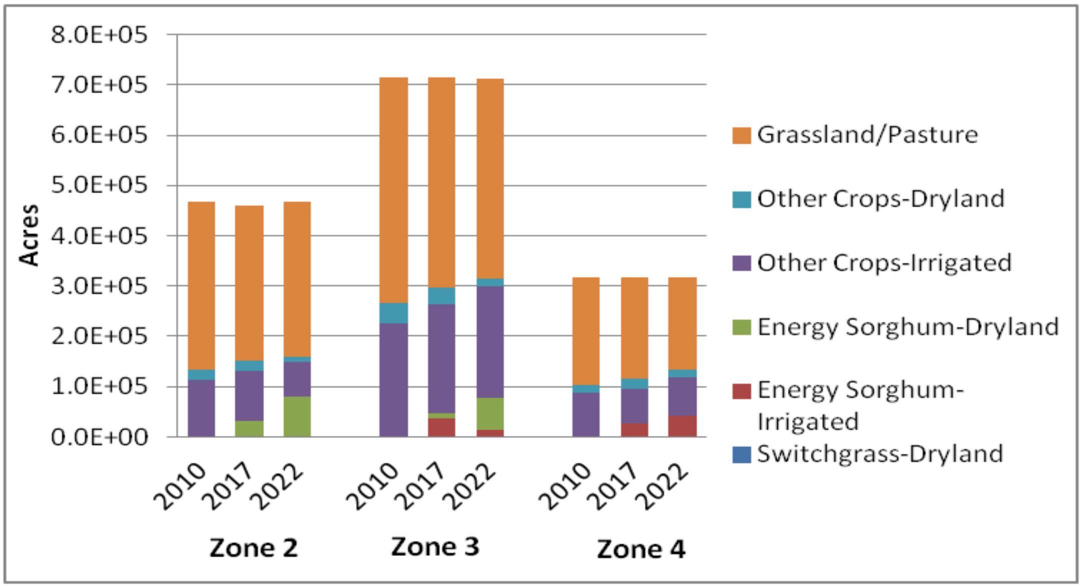


Figure 3-19. Land allocation among conventional crops and energy crops in selected zones and years in aggregated three counties at $40/dry ton biomass price under RFS2-Energy Sorghum scenario

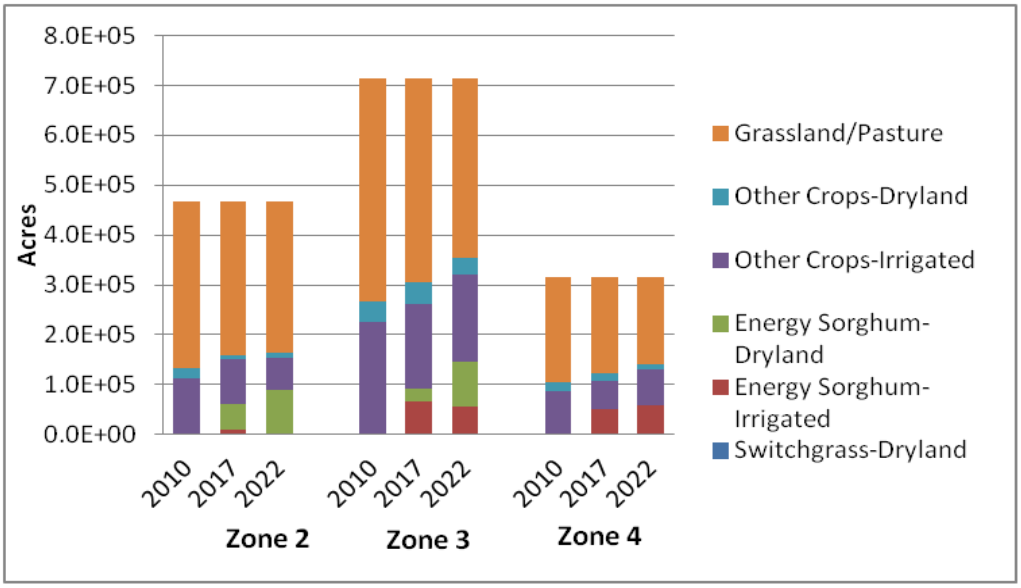


Figure 3-20. Land allocation among conventional crops and energy crops in selected zones and years in aggregated three counties at $80/dry ton biomass price under RFS2-Energy Sorghum scenario

Table 3-16. Land use and feedstock production at different price level under alternative scenarios, 2022

	RFS2-Switchgrass			RFS2-Energy Sorghum		
	$40	**$60**	**$80**	**$40**	**$60**	**$80**
Land Use (M Acres)						
Conventional Crops	0.67	0.56	0.50	0.62	0.60	0.57
Energy Crops	0.68	0.79	0.85	0.33	0.35	0.38
Feedstock Production						
Corn (M Bu)	23.10	22.90	18.30	19.88	19.64	14.45
Switchgrass (MDT)	2.20	2.34	2.81	-	-	-
Energy Sorghum (MDT)	-	-	-	4.48	5.90	6.29
Corn Stover (MDT)	0.22	0.20	0.17	0.19	0.18	0.14
Wheat Straw (MDT)	0.06	0.05	0.04	0.06	0.05	0.04

3.6 Concluding Comments

Groundwater depletion is of substantial concern in the Southern Ogallala Aquifer. Climate change imposes a potential contributing factor that can accelerate depletion. The expanded production of agricultural crops for bioenergy production has introduced new challenges for water and land management. In this paper we studied the potential impacts of climate change and bioenergy feedstock production on land use change and the rural economy in Texas High Plains Region. To do this, we develop and apply a spatially explicit dynamic integrated model of optimal water use, crop choice and land allocation. The spatial-temporal land/water use change and economic implications under different climate change projections and biofuel feedstock mixes are illustrated through case studies in three counties in Texas High Plains Region.

We find several things regarding water depletion. First, in zones with low saturated thickness, depletion is an optimal strategy with currently irrigated land switching to dryland and grassland/pasture. Second, in zones with mid-level saturated thickness, we find that heavy adoption of deficit irrigation is the short-term optimal choice. Saved water diversifies crop mix and enhances the cropland and water sustainability. In general, due to the non-uniform distribution of groundwater level, the optimal strategies for land and water management to sustain future agricultural production are highly spatially explicit even within the individual county.

In terms of climate change we find the effect varies among different crops and regions. As a result of changing yields and water use, optimal crop acreage allocation change as farmers switch crop patterns in response to changes in climate. While most climate change projections have positive effects on the net present value of agricultural production over the whole study region (Dallam, Hartley and Sherman), the sub-regions within a county with more water availability are more resilient to future climate change. Adopting a crop mix is an effective strategy for farmers in adapting to climate change and continuing water depletion.

In terms of bioenergy, both switchgrass and energy sorghum production beneficially enhance cropland value. However, their impacts on crop pattern and land use change are spatially different. In the absence of energy sorghum, dryland switchgrass production is more favorable in water-scarce regions, which results in more dryland acreage converted from both irrigated cropland and grassland/pasture. The presence of energy sorghum alters the feedstock mix of biofuel productions, in which switchgrass is significantly reduced. Greater expansion of crop land is found particularly in water sufficient regions relative to the switchgrass only case. Sensitivity analysis of biomass price indicates that the production of switchgrass and energy sorghum increases as the price rises, whereas the corn (for ethanol) and crop residues production declines.

Water availability has substantial impacts on biofuel feedstock production. With continual water depletion, corn and crop-residue-based ethanol will decrease, while drought-tolerant and high-yielding energy sorghum will take a leading role in ethanol production.

In summary, water resources are significant concern in regard to conventional crop and biofuel feedstock production in the High Plains Region. Land use change prediction without incorporating spatially explicit water condition could generate unrealistic results. Our model explores interactions between limited resources (groundwater and land), markets and policies for bioenergy production and climate change. We notice that combined effects of climate change and bioenergy production expansion may introduce new challenges to land and groundwater allocation and the rural economy. This issue deserves to be investigated applying the same model framework in the future work. The activity set of the model can be increased to consider conservation program options, environmental management options and agricultural policies. Further investigation of the social welfare gains from sustainable management in a spatially explicit integrated model is also left to future work.

4. CLIMATE CHANGE IMPACTS ON WORLD FOOD SECURITY: A COMPUTABLE GENERAL EQUILIBRIUM ANALYSIS

4.1 Introduction

Food security is a growing concern worldwide, particularly for poor women and children in developing countries. According to the United Nations Food and Agriculture Organization (FAO) estimates, a total of 925 million people are undernourished in 2010 and developing countries account for 98 present of these undernourished people (FAO 2010). By 2050, the world's population is likely to reach 9 billion (Nelson et al. 2010). Most of these people are expected to live in developing countries and have higher incomes than currently is the case, which will result in increased demand for food. In the best circumstances, the challenge of meeting this demand in a sustainable manner will be enormous. To those already daunting challenges, climate change adds further pressure.

Climate change is expected to have serious impacts on food production system over the next 50 to 100 years. Warmer temperatures have been observed along with more-frequent extreme weather events, altered precipitation patterns and changes in water availability among other effects. Notwithstanding some expected improvements in high latitudes, climate change is widely expected to reduce farm land and crop yields in the tropic regions (Cline 2007; Mendelsohn et al. 2009; McCarl et al. 2008). For a few farmers, the changes might ultimately be beneficial, but for many farmers particularly those with relatively low adaptation capacities, there will be more difficulty in managing risks. The agricultural system as a whole will have difficulty supplying adequate quantities of food to maintain constant real prices. And the challenges extend further to the global trading regime, to ensure that changes in comparative advantage translate into unimpeded trade flows to balance world supply and demand (Nelson et al. 2010).

But there have been questions raised like how big are these challenges? Who will be most affected? What could policy makers do to reduce negative effects and achieve food security? To provide answers to these questions is not easy. In fact, the relationships between climate change and food security are complex and manifold. They involve climatic and environmental factors, social and economic responses. The potential impacts of climate change on food security must therefore be viewed within a larger framework associated with a wider range of plausible futures— economic, demographic and climate. Understanding the potential economy-wide impacts of climate change on global food security is critical for designing appropriate adaptation strategies, as well as formulating effective global climate-policy agreements. The primary objective of this study is therefore to measure the potential impacts of climate change on food security across spatial and temporal scales in a computable general equilibrium system. More specifically, we will investigate

- What the impacts of technical change on global food production and food security in 2020 and 2050?

- To what extent future climate change (taking into account of adaptation and carbon dioxide effects) will affect food insecure population in the world?

The remainder of this essay is organized as follows. First, a review of climate change and food security studies is given. Then the CGE model to be employed and related key datasets utilized are introduced. After that, the estimation results are displayed and discussed. Finally, conclusions, limitations and future research are presented.

4.2 Literature Review

Here we review how literature approaches to the climate change and food security issue concentrating mainly on two aspects: 1) historical background and development 2) analytical methodologies used.

Food security was widely studied in the early 1990s with a general focus on the regional or domestic agricultural impact (Martin et al., 1988; Adams et al., 1990). Later, recognition of global climate change led to attempts to investigate impacts on agricultural production taking into account international trade (Rosenzweig and Binswanger 1993; Reilly 1994; Fischer et al. 1994). However, this research did not consider adaptation, which may lead to an overestimate of the likely impact. Explicit adaptation responses by farmers were thus taken into account (Mendelsohn 1999; Adams et al. 1999, 2000; Butt et al. 2005). Meanwhile, the competing uses of limited natural resources (e.g. land and water) were also introduced into the picture (Darwin 1995, 1999).

Next, the research started to investigate sustainability and uncertainty. Latter studies examined vulnerability defined in terms of crop yields, farm profitability, regional economy and hunger explicitly considering uncertainty about future climate change impacts (Acevedo 2011; Lal 2011; Chen et al. 2012). In particular with the increasing accumulation of meteorological evidence, the role of extreme events in particular of El Niño and La Niña Southern Oscillation driven phenomena were considered (Chen et al. 2001).

In terms of methodology two major approaches have been widely used: (1) structural modeling of crop and farmer response, which combines crop agronomic response with economic management practices; and (2) spatial analogue models that measure observed spatial differences in agricultural production.

The structural approach generally uses crop growth simulation models to determine the response of specific crop varieties to different climatic and other conditions. Economic impacts (e.g. acreage changes, crop supply and prices changes) are then estimated by incorporating yield estimation results from crop simulation models into economic models (Adams et al. 1990, 1999; Easterling et al. 1993; Dellal and McCarl 2010). Two types of economic models that have been used with agronomic models include: computable general equilibrium (CGE) model (Hertel 1997; Deke et al. 2001) and partial equilibrium models (Adams et al. 1990; Chang 2002; Kumar and Parikh 1998). Studies like Fischer et al. (1994) and Parry et al. (1999) use a slightly different class of partial equilibrium model—BLS (Basic Linked System) developed by IIASA (International

Institute for Applied Systems Analysis) to assess the climate change impacts on world food supply. Nevertheless the analysis focuses only on agricultural sector and the implications for the rest of the economic system are put aside.

The spatial-analogue approach on the other hand has been used to estimate climate change effects on agriculture base on observed differences in land values, agricultural production or other climate related costs (Mendelsohn et al. 1994; Chen and McCarl 2001; McCarl et al. 2008). The spatial analogue approach sidesteps the problems plaguing the structural approach of needing to accurately model yield and other physical implications of climate change. However, the approach cannot fully account for items which are expected to vary significantly from historic observation such as CO_2 concentrations, international production shifts and large price alternations (Feng, et al. 2010).

Recent research focuses more on the regional/national scale analysis of food security and takes use of regional crop yields estimates under climate change (e.g. Ringler et al. 2010; Aggarwal and Sivakumar 2011; Conway and Schipper 2011). In this essay, a global assessment of economic and food security implications of climate change are investigated. Different from the previous studies, we apply a CGE model which has a more disaggregated agricultural and land transformation sectors relative to other large-scale CGE models and more comprehensive sectors coverage relative to the partial equilibrium models (e.g. IIASA BLS framework). Moreover, the most recent estimates of country-level yield changes of major crops (wheat, rice and maize) based on multiple climate scenarios (Iglesias and Rosenzweig 2009) are applied for food security analysis.

4.3 Methodology

This study couples a static computable general equilibrium (CGE) model — World Energy and Agricultural Markets Model (WEAM) (Bryant et al. 2011) with a caloric intake probability distribution framework (Naiken 2002) to calculate the food security. In the first stage, climate change scenarios are incorporated into WEAM model. The changes in equilibrium levels of market variables and land use are determined for alternative scenarios after running the model. Food insecurity implications stem from a second stage analysis. In this stage, a method developed by the United Nations-Food and Agriculture Organization is applied (Naiken 2002; Butt et al. 2005). Changes in aggregate consumption of food commodities in different world regions from the CGE output in the first stage calculation are used to estimate changes in average daily caloric intake in each region. In the following sections, we will describe the models and datasets involved in the two stages.

4.3.1 Computable General Equilibrium (CGE) Model

WEAM (Bryant et al. 2011) is a static comparative, multi-region, computable general equilibrium (CGE) model, based on the full 7th version of the Global Analysis Project (GTAP) database. The model structure is similar to that of McDonald et al. (2005, 2006), but with three major improvements:

- High level of disaggregation in the agricultural and land transformation sectors relative to other large-scale CGE models

- Detailed representation of land use across 18 Agro-Ecological Zones
- More detailed representations of biofuel-related activities including feedstock and biofuels production

The default regional aggregation employs nine world regions in the model, as illustrated in Figure 4-1. The original database entities (including households, production sectors, governments, factor markets, commodity and capital markets) based on 113 individual world regions are therefore aggregated into nine regions accordingly. The behavior of production activities and households is described using constant returns to scale, nested constant elasticity of substitution (CES) production technology. The key elasticities of substitution are calibrated against demand elasticities reported in the existing econometric studies, while elasticities of transformation are calibrated against measured supply responses. The heart of the model follows standard CGE practice in that there is a set of inequalities describing a Walrasian market equilibrium within and among regions (Shoven and Whalley 1992). In this model, the primary factors of production are fully mobile across production activities, which facilitate analysis of the long-run general equilibrium effects of climate change and policies in various sectors (e.g. agriculture and energy). More detailed description of the WAEM model can be found in Bryant et al. (2011).

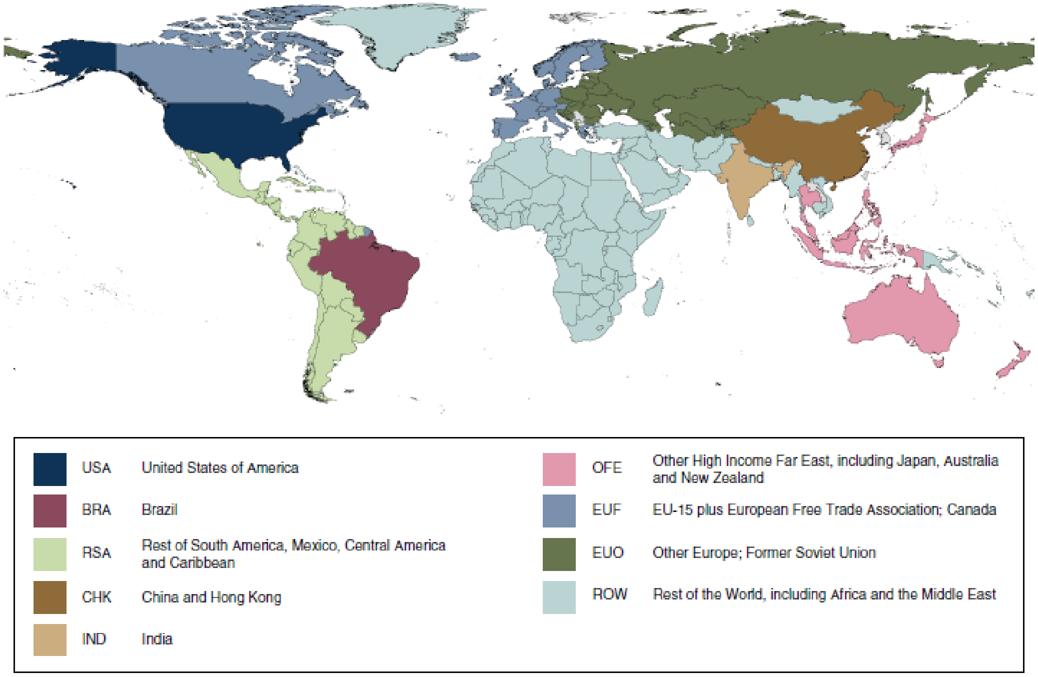


Figure 4-1. Model regions

4.3.2 Estimation of Food Insecurity

The FAO measure of food insecurity is based on a comparison of usual food consumption expressed in terms of dietary energy (kcal) with certain energy requirement norms (FAO 2008a). The part of the population with food consumption below the energy requirement norm is considered undernourished. Note that the FAO measure endeavors to capture those whose food consumption level is insufficient for body weight maintenance and work performance rather than malnutrition, which has a broader nutritional connotation. The probability distribution framework applied in the study is depicted in Figure 4-2.

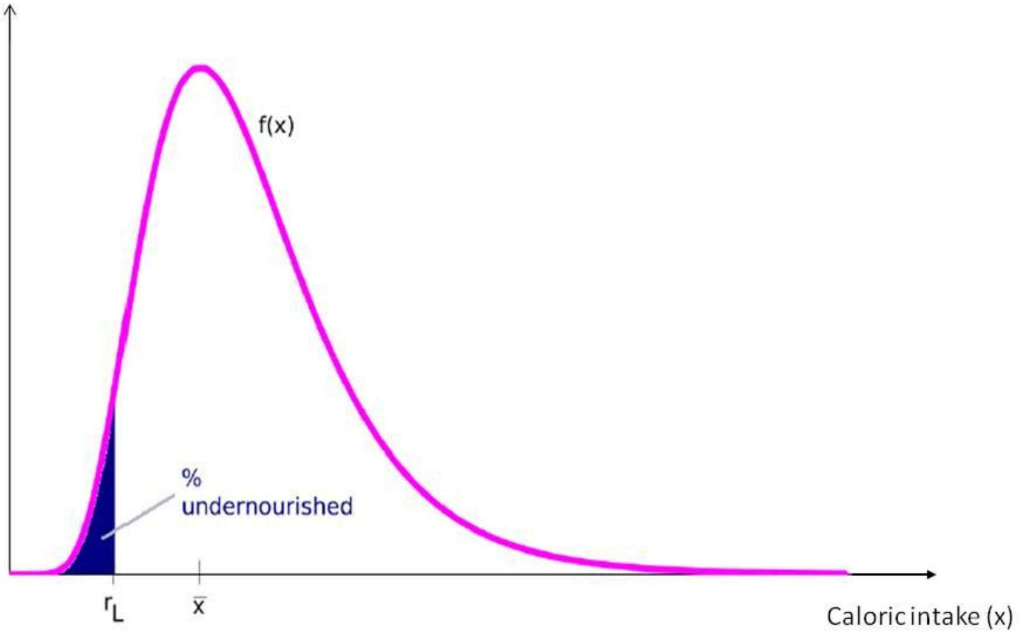


Figure 4-2. FAO method of calculating the number of undernourished people in a region

The frequency distribution curve f(x) depicts the proportion of the population corresponding to different per capita dietary energy consumption levels (x) represented by the horizontal line. The cumulative proportion of the population up to the cutoff point,

r_L (minimum per capita dietary energy requirement), on the horizontal line represents the proportion of the population undernourished. r_L is derived by aggregating the estimated gender and age-specific minimum dietary energy requirements, using the relative proportions of a population in the corresponding sex-age group as weights. In fact, as the sex-age distribution of the population changes over time, the cutoff point has to be adjusted over time. In our study, we simply assume it is constant in the future. The mean $\bar{x}$ refers to the energy available for human consumption, expressed in kilo-calories (kcal) per person. It is derived from the food balance sheets (FBS) compiled by FAO on the basis of data on the production and trade of food commodities.

Because the methodology and concepts applied in the household surveys are not sufficiently precise to provide an accurate estimate of the f(x) distribution, FAO employs a theoretical distribution by assuming f(x) to be log-normal. In this context, the log-normal distribution with its short lower tail and long upper tail is considered to reflect better the fact that wastages, food feed to pets, etc. are likely to be confined to the upper tail representing the richer and more affluent households (Naiken 2002). The log-normal distribution can be specified by two parameters, the coefficient of variations (CV(x)) and the mean ($\bar{x}$). If climate change may induce some changes on the representative household food consumption, the corresponding value of mean will change, and therefore generate a new distribution of f(x).

Finally, note that FAO provides caloric intake distributions for a much larger number of countries than are featured in the CGE model. We therefore adopted Monte

Carlo simulation method to randomly draw 65,500 trails for each aggregate region to estimate its empirical aggregated caloric intake distribution f(x) (Bryant et al. 2011). Similarly, the cutoff point r_L is aggregated with population weights of the countries within the specific regions.

4.4 Data

4.4.1 Climate Change Scenarios

The climate change scenarios used in this paper are derived from experiments conducted with the third generation Global Climate Model (GCM) developed by the UK Hadley Center (HadCM3) (Hulme et al. 1999). It runs with four (Special Report on Emissions Scenarios) SRES emissions scenarios:

- A1: Very rapid economic growth with increasing globalization, global population that peaks in mid-century and declines thereafter, rapid technological change, an increase in general wealth, with convergence between regions and reduced differences in regional per capita income, and fossil intensive. Three variants within this family that are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). Note that we only considered A1FI in this analysis.
- A2: Very heterogeneous, market-led world, with more rapid population growth but less rapid economic growth than A1. The underlying theme is self-reliance and preservation of local identities. Economic development is primarily regionally oriented, and hence both income growth and technological change are

regionally diverse. Fertility patterns across regions converge slowly, resulting in high population growth.

- B1: Globalization, same low population growth as A1, but development takes a much more environmentally sustainable pathway with global-scale cooperation and regulation. Clean and efficient technologies are introduced. The emphasis is on global solutions to achieving economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.
- B2: Regionalization, population increases at a lower rate than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1. The emphasis is on local solutions to economic, social, and environmental sustainability.

Table 4-1 outlines socio-economic characteristics of four SRES scenarios. Table 4-2 and 4-3 present the simulations of global mean temperature changes (relative to the pre-industrial reference mean), CO_2 emission levels and sea level rise projections for different SRES scenarios drawn from IPCC (2007a). It is noticeable that the A1FI scenario has the largest increases in global temperatures and highest level of CO_2 emission, while B1 is the coolest scenario with lower CO_2 emission.

To measure the food insecure population in this study, we quantify the global population growth under alternative scenarios based on world population projections developed by the United Nations/Population Division (Figure 4-3). We assume that B2 world with the medium population increase follows the same change as this. In the A1 and B1 worlds where there is relative low population growth, the growth rate is assumed to be one half as in the B2 world, whereas in the A2 world with high population growth, the increasing rate is therefore assumed to be twice as in the B2 world.

Table 4-1. Social-economic characters under alternative SRES scenarios (Source: IPCC 2007a)

Climate Scenario	A1	A2	B1	B2
	A1FI	A2	B1	B2
Population growth	low	high	low	medium
GDP growth	very high	medium	high	medium
Energy use	very high	high	low	medium
Land-Use Changes	low-medium	medium	high	medium
Resource availability	high	low	low	medium
Pace of technological change	rapid	slow	medium	medium
Direction of technological change	fossil intensive	regional	efficiency and dematerialization	dynamic as usual

Table 4-2. HadCM3 simulations of global mean temperature changes (relative to the pre-industrial reference mean) and CO_2 emission levels for different SRES scenarios (Source: IPCC 2007a)

Climate	A1	A2	B1	B2
scenario	A1FI	A2	B1	B2
Temperature(ºC)				
2020	1.29	1.16	1.14	1.21
2050	2.56	2.22	1.86	1.96
CO_2 (GtC/yr)				
2020	12.1	11.0	10.5	10.0
2050	23.1	15.5	11.7	11.2

Table 4-3. The projected sea level rise at the end of the 21st century under alternative SRES scenarios (Source: IPCC 2007a)

Climate scenario	A1 A1FI	A2 A2	B1 B1	B2 B2
Sea Level Rise (m at 2090-2099 relative to 1980-1999)	0.26-0.59	0.23-0.51	0.18-0.38	0.20-0.43

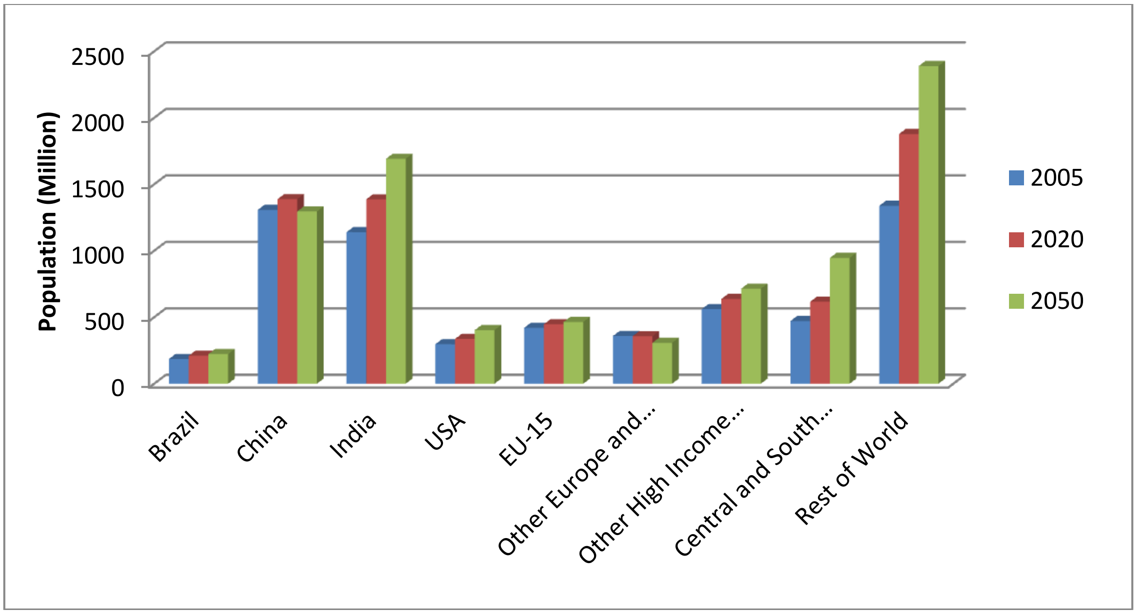


Figure 4-3. Projection of population in 2005, 2020 and 2050 over nine regions (Source: UN, Department of Economic and Social Affairs)

4.4.2 Crop Yield Responses

4.4.2.1 The reference case—no climate change

Assuming a future with no climate change and continued advances in agricultural technology worldwide, crop yields are set to increase. A 2006 FAO report presents estimates of crop yields for cereals and oilseeds over the next forty years (FAO 2006). As presented in Table 4-4, the 2000-2030 world increase rate of cereals (oilseeds) is 1.2% (1.9%) annually. Looking beyond 2030, a decline in the world growth rates are found in cereal and oilseed yields, which are 0.6% and 1.5% per year respectively. At the regional level, the growth rate of cereal and oilseed yields in developing countries are projected to be higher than those in developed and transition countries. In this study, we assume the estimated growth rate in FAO (2006) is corresponding to A1FI case which has a rapid technological change (Table 4-4). The one half and one fourth of A1FI growth rate are assumed under B1/B2 (medium technological change) and A2 (slow technological change) scenario, respectively (Table 4-5, 4-6).

Table 4-4. Assumed annually average growth rate of crop yields under scenario A1 (Unit: %) (Corresponds to FAO 2006)

	Cereals (wheat, rice, maize)		**Oilseeds**	
	2000-2030	**2030-2050**	**2000-2030**	**2030-2050**
World	1.2	0.6	1.9	1.5
Developing Countries	1.4	0.7	2.1	1.6
Developed Countries	0.9	0.5	1.6	1.4
Transition Countries	0.8	0.4	1.8	1.4

Table 4-5. Assumed annually average growth rate of crop yields under scenario B1/B2 (Unit: %)

	Cereals (wheat, rice, maize)		**Oilseeds**	
	2000-2030	**2030-2050**	**2000-2030**	**2030-2050**
World	0.6	0.3	0.95	0.75
Developing Countries	0.7	0.35	1.05	0.8
Developed Countries	0.45	0.25	0.8	0.7
Transition Countries	0.4	0.2	0.9	0.7

Table 4-6. Assumed annually average growth rate of crop yields under scenario A2 (Unit: %)

	Cereals (wheat, rice, maize)		Oilseeds	
	2000-2030	2030-2050	2000-2030	2030-2050
World	0.3	0.15	0.48	0.38
Developing Countries	0.35	0.18	0.53	0.40
Developed Countries	0.23	0.13	0.40	0.35
Transition Countries	0.2	0.1	0.45	0.35

4.4.2.2 The future with climate change

The data of yields responses of wheat, rice and maize under four climate change scenarios based on HadCM3 model output along with GHG concentrations from SRES are taken from estimation by Iglesias and Rosenzweig (2009) (oilseeds data is taken from Parry et al. 2004). The dataset assesses the implications of temperature and precipitation changes for world crop yields taking into account uncertainty in the level of climate change expected and physiological effects of carbon dioxide on plant growth. The consequent crop yields estimates incorporate four major features: 1) weighting of model site results by contribution to regional and national and rain fed and irrigated production; 2) quantitative estimation of physiological CO_2 fertilization effects on crop yields is applied; 3) adaptation is explicitly considered, and the adapted yields are evaluated in each country as a fraction of the potential yields (the weighting factor combines the ratio of current yields to current yield potential and the economic limitation of the economic country’s agricultural systems. Therefore, the changes in regional crop yields are the result of the interactions among temperature and precipitation effects, direct physiological effects of increased CO_2 level and effectiveness and availability of adaptations.

Table 4-7~4-10 present the (percentage) change of crop yields of wheat, rice, maize and oilseeds respectively in nine regions relative to the base year (2005) case under alternative climate change scenarios in 2020 and 2050. It is noticeable that each HadCM3 climate change scenario alters the future path for global crop yields. Generally, four scenarios result in crop yield decreases in developing countries and yields increases in developed countries. The change scale is smaller in the 2020s than that in the 2050s. More specifically, in the A1FI scenario with its largest increase in global temperatures, decreases in the crop yields are especially significant in Africa and parts of Asia with expected losses up to 25%. In these regions, negative effects of temperature and precipitation changes on crop yields are beyond the beneficial direct effects of elevated atmospheric CO_2 concentrations. In Europe, North America, and Far East, the effects of CO_2 fertilization result in 2-5% increase in crop yields. The responses of the major crops to climate change in A2 are similar to that of the A1FI in the 2020s. In 2050s, the decrease in crop yields in Africa, parts of Asia and Central/South America is smaller than that in the A1FI world, which may be due to the relative moderate temperature increases. B1 is the coolest of the future SRES worlds. However, the overall impacts on cereal yields as a result of climate change are not significantly smaller or even greater than in the other scenarios. The possible reason is the small benefits from CO_2

fertilization as concentrations are only half that experienced under A1FI. In the B2 world, crop yields changes are moderate for the 2020s, which is mainly dominated by the influence of natural variability. By 2050s, with the medium CO_2 concentration, the negative effects witnessed especially in South America and Africa are reduced. The overall impacts on cereal yields in B2 world generally fall between those experienced in the A1FI/A2 and B1worlds.

Table 4-7. Oilseeds yield change (%) from base year (2005) in 2020 and 2050 under HadCM3 climate change scenario (Source: Parry et al. 2004)

	2020	2050
Brazil	-5.00	-8.00
China	-5.00	-3.00
EU-15	3.33	8.46
Other Europe	-9.87	-9.85
India	-4.00	-1.00
Other High Income	3.27	5.63
Rest of South America	-4.48	-4.42
USA	1.00	-4.00
Rest of World	-1.37	5.63

Table 4-8. Wheat yield change (%) from base year (2005) under alternative scenarios with climate change (Source: Iglesias and Rosenzweig 2009)

	2020				2050			
Region	**A1FI**	**A2**	**B1**	**B2**	**A1FI**	**A2**	**B1**	**B2**
Brazil	-3.43	-3.14	-6.88	-5.02	-0.81	-3.98	-5.85	-6.19
China	-0.22	-1.17	3.32	0.75	6.10	7.26	5.62	4.23
EU-15	4.39	4.79	1.58	2.96	7.73	8.66	4.83	4.70
Other Europe	-2.83	-3.27	-5.52	-5.92	-3.04	-2.52	-3.33	-4.15
India	-4.10	-2.23	-1.68	-4.62	-1.97	-3.27	-2.14	-5.63
Other high Income	2.66	1.53	-0.13	5.35	6.15	9.95	3.41	3.22
Rest of South America	2.32	7.15	1.02	2.10	-1.03	6.97	2.67	5.58
USA	4.08	4.63	1.05	1.46	-0.73	4.60	-0.17	0.94
Rest of World	-0.43	0.37	-0.95	2.10	7.67	0.75	-0.42	-1.67

Table 4-9. Rice yield change (%) from base year (2005) under alternative scenarios with climate change (Source: Iglesias and Rosenzweig 2009)

	2020				2050			
Region	**A1FI**	**A2**	**B1**	**B2**	**A1FI**	**A2**	**B1**	**B2**
Brazil	-5.43	-5.14	-8.88	-7.02	-5.76	-3.24	-2.68	-5.26
China	-0.92	-1.18	-0.67	-1.68	2.19	6.45	3.44	3.50
EU-15	2.16	3.62	-0.41	2.26	-1.84	-4.04	-4.40	-5.25
Other Europe	-3.04	-3.24	-6.22	-5.71	-4.18	-6.07	-6.06	-6.77
India	-6.10	-4.23	-3.68	-6.62	-2.98	-2.26	-1.60	-3.58
Other high Income	-0.37	0.38	-0.92	-0.72	-5.81	-5.55	-4.60	-6.17
Rest of South America	-1.71	-3.12	-7.62	-5.56	2.76	2.46	0.92	0.30
USA	2.08	2.63	-0.95	-0.54	-5.07	-3.84	-1.87	-2.80
Rest of World	-0.48	-1.08	-1.76	-2.53	-0.13	-0.68	-1.45	-2.16

Table 4-10. Maize yield change (%) from base year (2005) under alternative scenarios with climate change (Source: Iglesias and Rosenzweig 2009)

	2020				2050			
Region	**A1FI**	**A2**	**B1**	**B2**	**A1FI**	**A2**	**B1**	**B2**
Brazil	0.32	-0.18	-2.37	-2.23	1.43	-0.14	-1.84	-1.50
China	-3.30	-5.05	-3.35	-5.56	-5.97	-6.96	-6.62	-7.46
EU-15	-1.38	-0.93	-1.67	-2.24	-0.63	-0.68	-2.36	-2.69
Other Europe	-7.72	-8.02	-9.82	-8.33	-12.4	-11.8	-10.1	-11.1
India	-7.10	-5.23	-4.68	-5.93	-8.97	-10.3	-7.14	-10.6
Other High Income	-3.03	-2.35	-3.34	-3.54	-6.42	-5.37	-5.69	-5.45
Rest of South America	-4.81	-5.13	-5.33	-6.32	-8.18	-7.55	-7.87	-8.36
USA	0.62	1.37	-0.32	0.21	-5.01	-1.78	-3.61	-3.24
Rest of World	-5.24	-5.17	-4.90	-5.81	-12.3	-9.58	-8.10	-10.4

4.5 Procedure for Implementing Crop Yields Change

In this section, we will show the procedure of incorporating crop yields change into the original production function. CES production function is employed in the CGE model. This function takes on the following form:

(4-1) $$\mathrm{Q} = \phi\left(\sum_i a_i^{\frac{1}{\sigma}} x_i^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$$

where Q is total output; x (i=1,2,…) includes factors of production (e.g. labor, capital, natural resources, etc.); scale parameter ϕ represents productivity factor; α_i is the weight parameter for i-th factor; σ is the elasticity of substitution. The nested CES functions are calibrated against 2004 GTAP dataset, which details each entity's receipts and payments made to all inputs.

In the context of nested CES food production function, we implement climate change as a Hicks neutral technical change through modifying the value of scale parameter ϕ. Practically, new production quantity (Q_{new}) for rice, wheat, maize and oilseeds in each region is calculated through the following two equations:

(4-2) $$\mathrm{Q}_{\mathrm{new}} = \phi_{new}\left(\sum_i a_i^{\frac{1}{\sigma}} x_i^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$$

(4-3) $$\phi_{new} = \mathrm{r} * \phi$$

where r is the change rate of crop yields corresponding to the technical development or climate change factor. In this way, new quantity of food supply under alternative climate change is solved in the model.

4.6 Results

4.6.1 Technology Development

We first run the model without climate change but with technology development. Figure 4-4 and 4-5 show the percentage of food insecure population over nine regions under alternative SRES in 2020 and 2050 respectively. The percentage of the population in each region that is food insecure are determined by the magnitude of mean caloric intake per capita, namely the interaction effects of each region's household total food consumption (in calorie) and total population. The consequent food insecurity varies among different regions and SRES scenarios. Generally, in the short run (by year 2020), under A1FI and B1scenario, the percentage of food insecure population is less than that in the base year (2005), whereas a larger percentage of undernourished population is projected under A2 and B2 scenario. The explanation for this is that SRES scenarios of a relative higher technology development and lower population growth world (A1FI and B1) lead to the increase of daily calorie intake per capita. While in a more regionalized world (A2 and B2), where there is less rapid technological development but higher rate of population growth, the slow-medium production increase cannot keep up with the rapid rising demand. Therefore more percentage of people will be in risk of hunger.

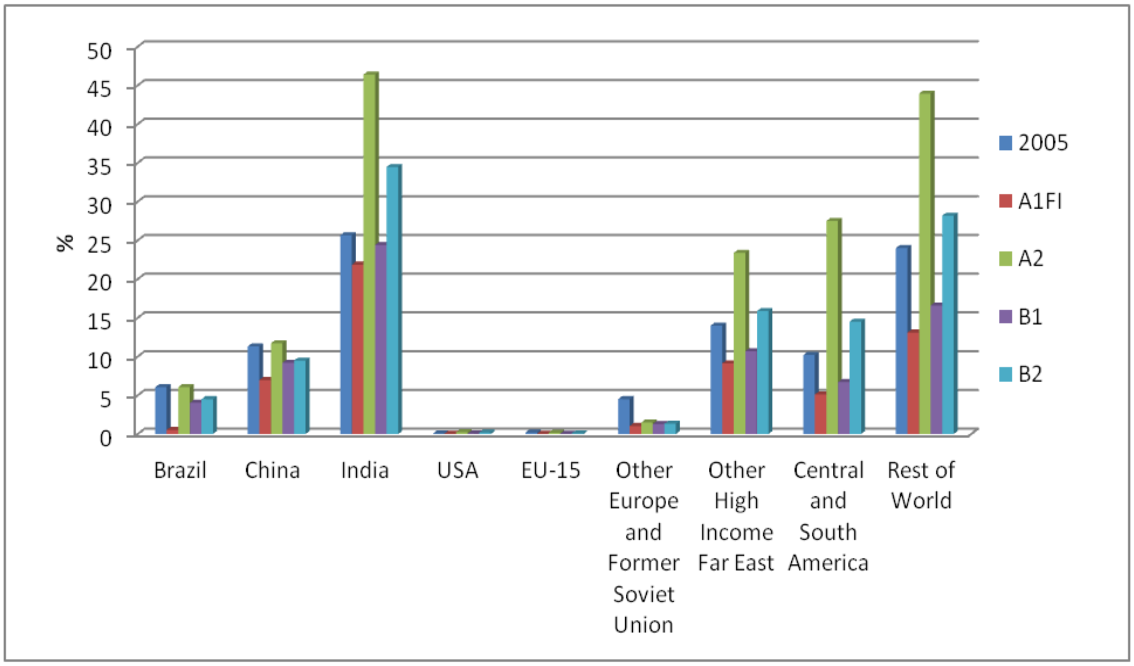


Figure 4-4. Percentage of populations that are food insecure under alternative scenarios, 2020

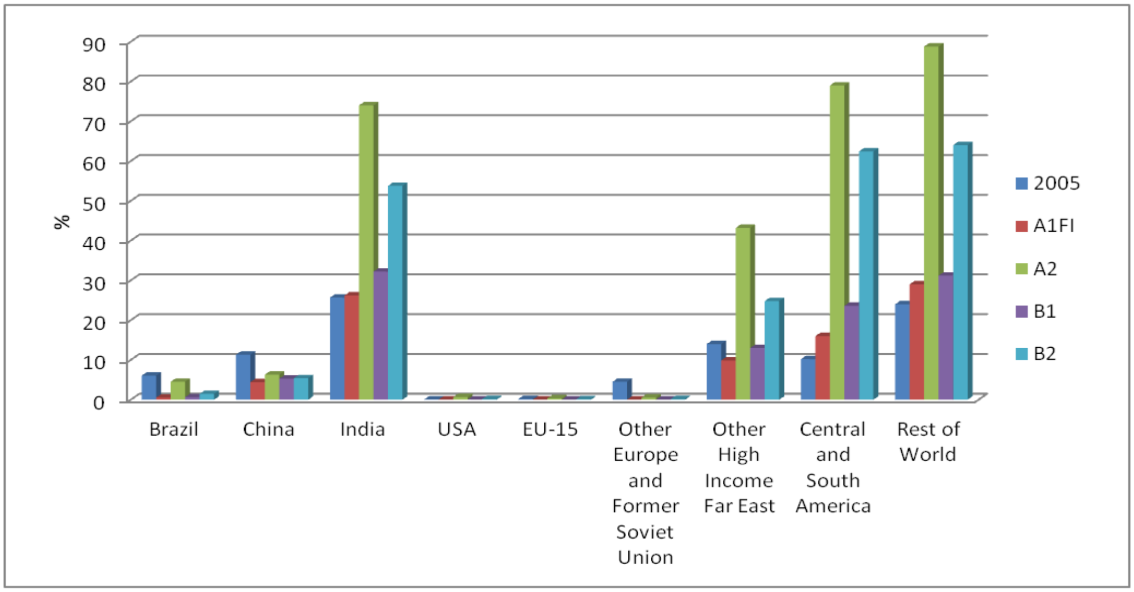


Figure 4-5. Percentage of populations that are food insecure under alternative scenarios, 2050

Regional differences in crop production and population growth lead to different food insecurity estimation among nine regions. However, such spatial differences are moderate by year 2020 due to the combined effects of production changes and population changes. The largest increase in the percentage of food insecure population is found in the A2 scenario over all regions except in EU-15, where there is less population as predicted by 2020. There are 54.8% and 67.5% more food insecure people in developed (excluding EU-15) and developing countries under the A2 scenario, respectively when compared with the 2005 base case. Under the A1FI and B1 scenarios, the benefits from the predicted high increase rate of technology development in the developing countries make them able to feed the increasing population in the short run. The estimated percentage food insecure population declines by 52.8% and 34.3% in relative to the base year case by 2020 under A1FI and B1, respectively. In the developed countries, even though the technology development rate is about 35.1% lower than that in the developing countries, much lower population growth rate (averagely 60.0% lower relative to the growth rate in the developing countries in 2020) leads to the larger declines of (percentage) food insecure population, which are 68.9% and 59.9% under A1FI and B1 scenario, respectively.

In the long run (by year 2050), the proportion of the food insecure population under alternative scenarios is larger than that in 2020. Also, the difference in the estimated food insecure population between developed and developing countries is greater. The predicted percentage of food insecure population increases under all scenarios in the developing countries. The significant change is found in A1 scenario:

the percentage of food insecure population goes up to 88.5%, 79.1% and 74.3% by 2050 in the Africa, Central/South America (excluding Brazil), and South Asia respectively. This is probably due to the decreasing rate of technology development and the much higher growth rate in population after year 2030. However, the change shows a contrary trend in the transition countries (e.g. Brazil and China) and developed countries. The estimated percentage of insecure population decreases under all scenarios in these regions. The insecure population is 1.8%, 5.3% and 1.4% in Brazil, China, and EU-15 respectively, which is 70.2%, 47.2% and 28.2% lower relative to the base year condition, respectively. The possible reason is the lower rate of population growth particularly after year 2030 in these regions.

In general, the technology development effect on global food security varies with SRES scenarios, regions and time periods. In the short run, A1FI and B1 lead to decreases in the percentage of food insecure population in most regions, whereas a larger food insecure population share is predicted under the A2 and B2 scenarios. In the longer run, greater differences arise in the projections of food insecure population between the developed/transition and developing countries. A larger percentage increase in the food insecure population is found in the developing countries under all SRES scenarios. By contrast, the decline is found in the developed and transition countries such as Brazil and China.

4.6.2 Climate Change Impacts

In this section, projected crop yields under the HadCM3 climate change scenario produced by four different SRES emissions scenarios are incorporated into the production functions in the CGE model. Technology development is assumed to take place in the future crop production in the world. Figure 4-6 and 4-7 show the changes in the percentages of food insecure people relative to the no climate change case under alternative climate change scenarios in year 2020 and 2050 respectively. It is noticeable that climate change-induced regional differences in crop production lead to a different regional effects, especially under scenarios of greater inequality (A1FI and A2). Production in the developed nations generally benefits from climate change, resulting in the decline in the food insecure population share. While the increase in the percentage of food insecure people in Africa, South Asia and Central/South America are likely due to the negative effects of crop yields from climate change.

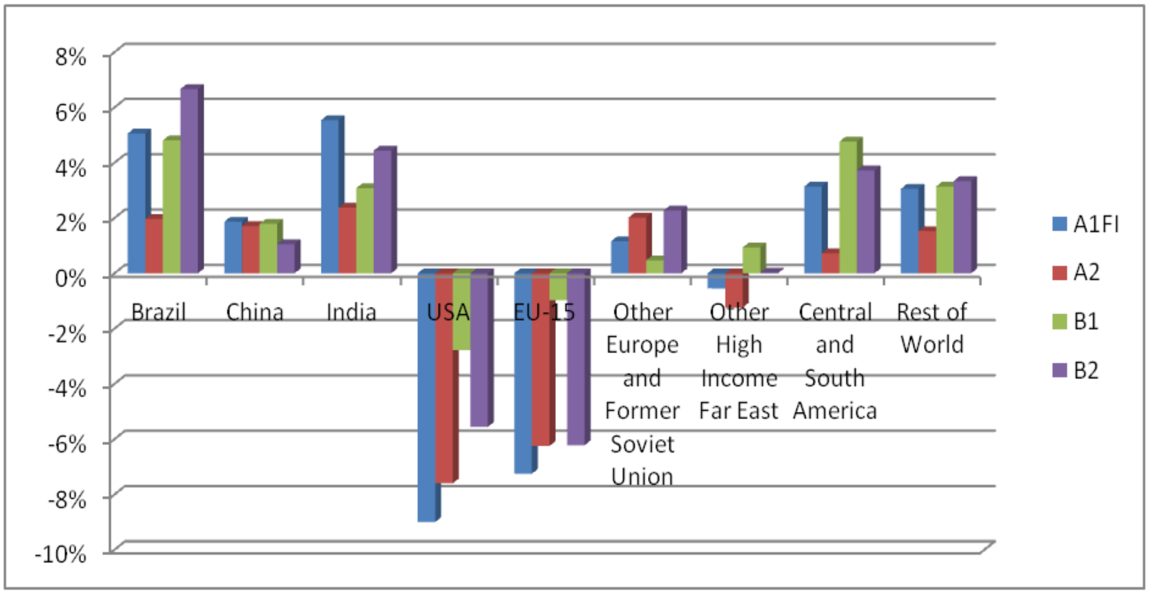


Figure 4-6. (Percentage) changes in the percentage of food insecure population relative to the no climate change case under alternative climate change scenarios, 2020

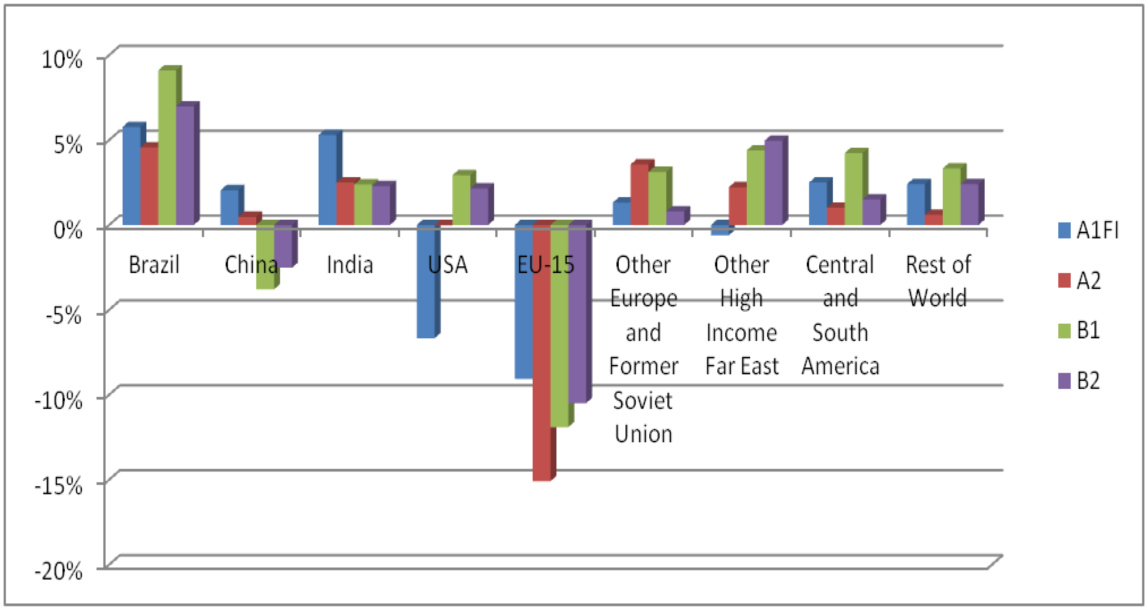


Figure 4-7. (Percentage) changes in the percentage of food insecure population relative to the no climate change case under alternative climate change scenarios, 2050

The number of additional food insecure people due to climate change effects (compared with the technology development only case) in year 2020 and 2050 is shown in Figure 4-8 and 4-9, respectively. Significant increases in food insecure population are mostly found in developing countries such as Africa and South Asia, whereas positive effects from climate change in reducing the undernourished people are shown in EU-15 and USA. Among four climate change scenarios, the number of additional insecure people is on average 34.8% lower in A2 than that in the other three scenarios. The possible reason is that there is larger CO_2 fertilization effect in A2 than in B1 and B2 plus lower projected temperature increases than in A1FI.

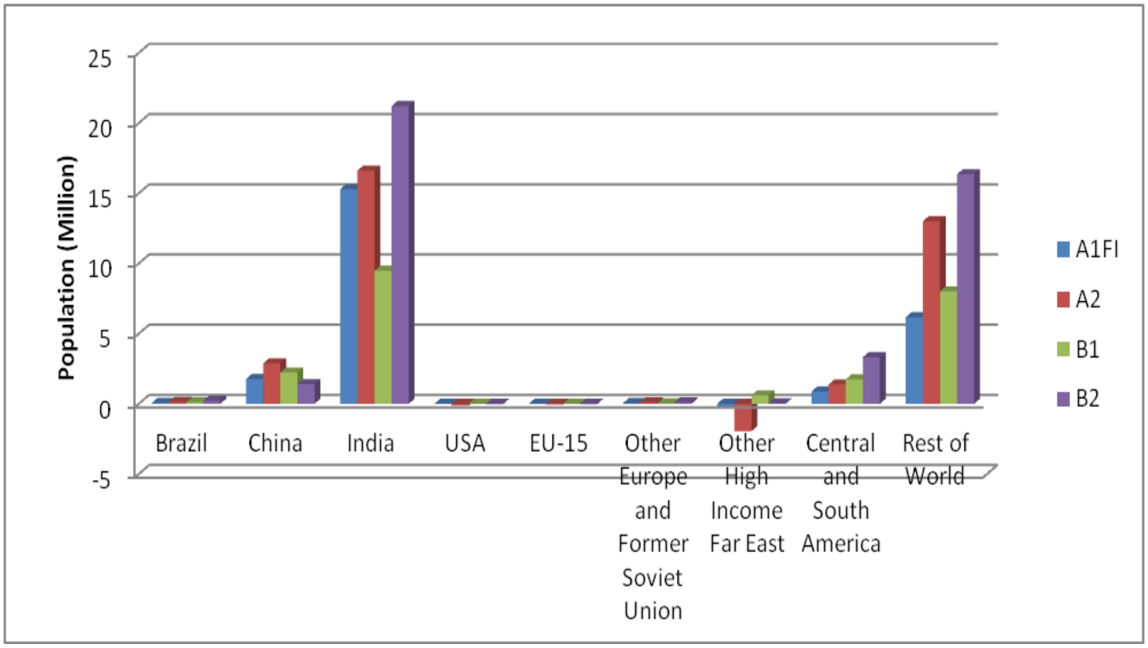


Figure 4-8. Additional millions of food insecure population under alternative climate change scenarios relative to the no climate change scenario, 2020

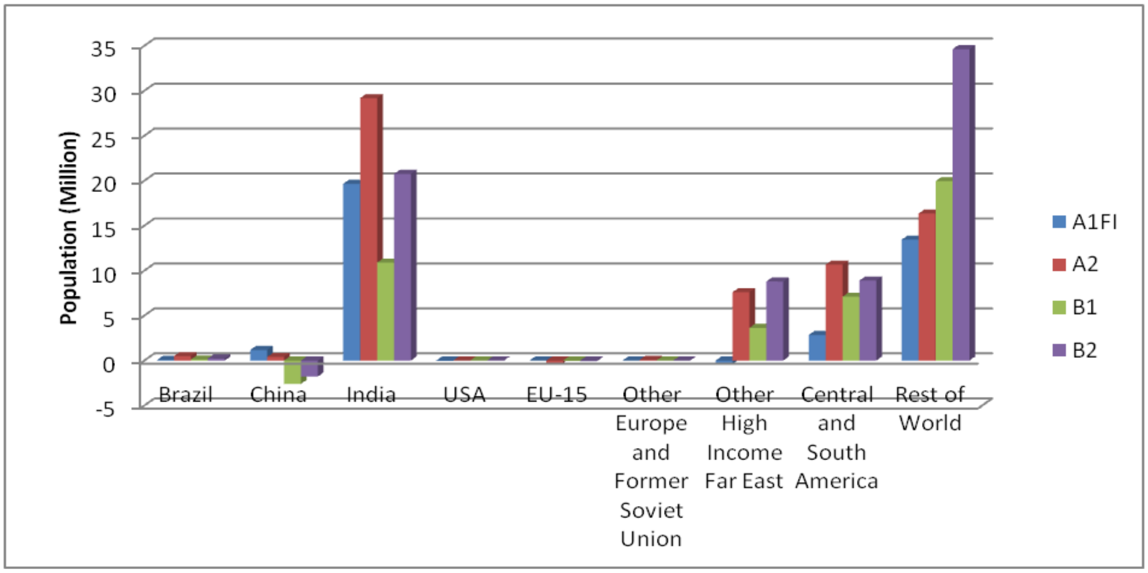


Figure 4-9. Additional millions of food insecure population under alternative climate change scenarios relative to the no climate change scenario, 2050

Table 4-11 and 4-12 show the food insecure population results under alternative scenarios in year 2020 and 2050 respectively. Notice that the measure of absolute number of food insecure population in the future is based on the combined effects of technological, climate and population change. In 2020, total insecure population decreases by 30.5% and 4.7% relative to that in the base year under A1FI and B1scenario respectively, while 137.2% and 56.4% increases are found in total insecure population under A2 and B2 scenario respectively. This is partly because of more global population projected in the A2 and B2 world. In the long run, by year 2050, the estimated results among four scenarios are more consistent than that in the short run case but with larger net changes. The global insecure population increases by 39.8%, 471.6%, 64.8% and 243.5% relative to the base year case in A1FI, A2, B1 and B2 world, respectively. However, the difference between developed/transition and developing countries is more pronounced than in the short run. Substantial increase in the food insecure population occurs in the Africa and South Asia, which is 224.1% and 232.5% (averaging over four scenarios) more than that in the base year case, respectively.

Table 4-11. Population that is food insecure under alternative scenarios with climate change, 2020 (Unit: Thousand)

	Base (2005)	**A1FI**	Change	**A2**	Change	**B1**	Change	**B2**	Change
Brazil	11234	1103	-90.18%	6912	-38.47%	2159	-80.78%	3363	-70.07%
China	135433	96251	-28.93%	171023	26.28%	126753	-6.41%	133636	-1.33%
India	246249	203989	-17.16%	716973	191.16%	317687	29.01%	499065	102.67%
USA	199	144	-27.69%	322	61.25%	188	-5.60%	287	43.69%
EU-15	656	161	-75.46%	691	5.38%	219	-66.59%	377	-42.43%
Other Europe and Former Soviet Union	16135	3748	-76.77%	5439	-66.29%	4618	-71.38%	4820	-70.13%
Other High Income Far East	78518	54328	-30.81%	155984	98.66%	64690	-17.61%	101073	28.73%
Central and South America	48121	28538	-40.70%	189488	293.77%	38195	-20.63%	92241	91.69%
Rest of World	321194	207773	-35.31%	787863	145.29%	263179	-18.06%	506457	57.68%
Total	857,739	596,034	-30.51%	2,034,694	137.22%	817,687	-4.67%	1,341,318	56.38%

Table 4-12. Population that is food insecure under alternative scenarios with climate change, 2050 (Unit: Thousand)

	Base (2005)	**A1FI**	Change	**A2**	Change	**B1**	Change	**B2**	Change
Brazil	11234	1124	-89.99%	11350	1.04%	1409	-87.45%	3480	-69.02%
China	135433	58422	-56.86%	82943	-38.76%	66099	-51.19%	68734	-49.25%
India	246249	390168	58.44%	1487519	504.07%	466081	89.27%	927826	276.78%
USA	599	539	-10.16%	1965	227.86%	180	-69.95%	654	9.13%
EU-15	656	137	-79.03%	1402	113.93%	203	-69.05%	511	-22.08%
Other Europe and Former Soviet Union	16135	65	-99.60%	1934	-88.01%	122	-99.25%	463	-97.13%
Other High Income Far East	78518	62620	-20.25%	349461	345.07%	86533	10.21%	185988	136.87%
Central and South America	48121	116288	141.66%	212825	342.27%	174432	262.49%	119887	149.14%
Rest of World	321194	570381	77.58%	2755656	757.94%	619142	92.76%	1640155	410.64%
Total	858,139	1,199,745	39.81%	4,905,055	471.59%	1,414,202	64.80%	2,947,699	243.50%

In general, the change of food insecure population is more stable in the developed countries than that in the developing countries under all climate change scenarios. Relative high growth rates of population plus more vulnerable agricultural production to changing climate results in increasing population at risk of food insecurity in Africa and South Asia, while developed countries with low rate of population growth are more resilient to climate change.

4.7 Conclusions

This paper reports on a study of the potential impacts of climate change on the short- and long-term outlook for world food security. Four climate change scenarios (A1FI, A2, B1 and B2) are incorporated into the CGE model. The findings are

- In the reference case without climate change, high technology development and low population growth as in the A1FI and B1 worlds leads to a decrease in the percentage of food insecure population over the world in the next forty years. While in the A2 and B2 worlds, where there are relatively slow technology development and high population growth, large increases in the percentage of food insecure population are found in most developing and transition regions such as Africa, Far East, Central and South America and South Asia and grow stronger over time.
- Climate change-induced regional differences in crop production lead to a regionally differentiated effect on food insecure population.
- Substantial increase in the percentage of undernourished population is found amongst the poorer nations, especially under scenarios of greater inequality

(A1FI and A2). The crop production in the developed countries (e.g. US and EU-15), however, generally benefits from the climate change and therefore results in decreases in their food insecure population

- Under A1FI and B1scenarios, most of the world experiences a decrease in the absolute number of food insecure people relative to the base year (2005) condition in 2020. While in 2050, with combined effects of technological development and climate change, more people in the world appears to suffer food insecurity.

The results illustrate that the overall impact of climate change on world food security will differ across regions and over time and, most importantly, will highly depend on the overall social-economic status that a region/country has accomplished as the effects of climate change set in. Non-linearity in the technological change and population growth results in the variations in the estimated global food insecure population. Climate change is likely to increase the disparities in this measure between developed and developing countries. However, the magnitude of these impacts will be small compared with the impact of socio-economic development. It should also be noted that the impact range produced by the spatial-temporal variations evident between individual HadCM3 scenario members is significant. The future strategy of managing agricultural production and reducing food insecurity should take into account of both the social-economic and climate change effects plus spatial difference as well, which need to be borne in mind by policymakers. Appropriate international trade policy, innovative technical development and effective mitigation and adaptation strategies in the agricultural sector may be able to reduce the global risk of hunger and achieve food security for all regions in the future.

It should be noted that climate change takes impacts on all four dimensions of food security: availability, accessibility, stability and utilization (FAO 2008b). Besides food production, food distribution, economic access and nutrition security contribute to the accurate evaluation of food security. However, in this essay, we only focus on the availability dimension. Furthermore, labor endowments in the model do not change according to population changes, which may affect the consequent estimation of food insecurity level. Some key parameters like CES (Constant Elasticity of Substitution) of household consumption are calibrated without sensitivity analysis, which is another caveat. Bearing these in mind, we leave more comprehensive and precise analysis for our future work.

5. SUMMARY AND CONCLUSIONS

5.1 Summary

Climate is a primary determinant of agricultural productivity; in turn, food production is essential for human welfare. No other sector is more climate sensitive than agriculture, and as such climate change poses a challenge and will play an important role in maintaining a secure food supply. Examining agriculture vulnerability to the totality of climate change issue is a multi-faceted endeavor. In addition to the need to examine potential effects on agricultural productivity, one must also examine the impacts of adaptation and mitigation efforts. Adaptation of the agriculture sector to climate change is necessary for food security and maintenance of ecosystem services. By nature, agriculture is a carbon sink, which can contribute to mitigating climate change. Moreover, biofuels are estimated to offer potential to reduce greenhouse gas emissions by 10-90% relative to fossil fuels, depending on the feedstocks and technology. Variations in climate change impacts, adaptation and mitigation will occur simultaneously and interactively and introduce both challenges and opportunities in economic implications nationally and globally (IPCC 2007c). What are the synergies and tradeoffs in investment on adaptation and mitigation? To what extent climate change and bioenergy feedstock production will affect limited agricultural land and water allocation in the semi-arid area such as Texas High Plains Region? What effects will climate change have on world agricultural production and food security? To answer these questions, this dissertation investigates three aspects of climate change issues:

optimal allocation of investment in adaptation and mitigation, impacts on regional economy and global food production.

The first essay (section 2) focuses on examination of optimal financial investment and policy implications for adaptation and mitigation. To conduct the research, we extend the existing integrated assessment model – DICE (Dynamic Integrated Climate Economy) in two major ways: 1) both proactive and reactive adaptation levels and costs are incorporated 2) a more broadly based damage function is included that is based on economy wide possibilities drawing on the study by Parry et al. (2009). Such modification improves the original DICE model which has a rough assumption of residual climate change damages and adaptation strategy. The empirical results suggest that both adaptation and mitigation are simultaneously employed strategies in reducing climate change damages. Well planned adaptation is an economically effective complement to mitigation since the beginning. Additionally, there is a greater immediately role for adaptation with a longer run transition to mitigation.

The second essay (section 3) presents an integrated agro/hydrological based assessment that examines water depletion, agricultural production, climate change and regional economics. The analysis quantifies the extent to which climate change and bioenergy production may alter the short- and long-term outlook for regional food, agriculture and resource availability and how farmers may effectively adapt their production. To best understand the spatial-temporal interactions between climate change, biofuel feedstock production and limited natural resources (land and water), we developed a spatially based dynamic economic land allocation model which incorporates four sectors: agriculture, hydrology, climate change and biofuel feedstock. This model can determine optimal mixed land use of conventional crops (corn, cotton, wheat and sorghum) and energy crops (e.g. switchgrass and energy sorghum), while accounting for the spatial heterogeneity (sub-county level) in crop yields, production costs, land use patterns and groundwater availability within the Texas High Plains Region. Technically, it is a spatial-explicit, multi-sector nonlinear programming model depicting land transfers and water allocation among agricultural crops, livestock and biofuel feedstock production. In studying climate change impacts on agricultural land use in the next forty years, we find out that the effect varies among different crops and regions. As a result of changing yields and water use, optimal crop acreage allocation change as farmers switch crop patterns in response to changes in climate. While most climate change projections have positive effects on the net present value of agricultural production over the whole study region (Dallam, Hartley and Sherman), the sub-regions within a county with more water availability are more resilient to future climate change. Adopting of a water conserving crop mix is an effective strategy for farmers in adapting to climate change and continuing water depletion. In terms of biofuel feedstock production, we find that limited groundwater resource cannot sustain expanded corn-based ethanol production in the future. However, cellulosic feedstocks such as switchgrass and energy sorghum production as biofuel feedstocks are beneficial to enhance cropland value at the $60/dry ton market price and will play the leading role in the ethanol production. Water availability also has substantial impacts on feedstock mix. In the absence of energy sorghum, dryland switchgrass production is more favorable in water-scarce regions, which results in more dryland acreage converted from both irrigated cropland and grassland/pasture. The presence of energy sorghum alters the feedstock mix of biofuel productions, in which switchgrass is significantly reduced.

The third essay (section 4) turns to estimate potential impacts of climate change on world food insecurity. In the first stage, projected crop yields change (in 2020 and 2050) under a no climate change reference case and four SRES based climate change scenarios from the HadCM3 model are incorporated into a CGE model. In the second stage, outcomes of household food consumption are taken into a probability distribution framework to calculate the number of undernourished population. Essentially all quantitative assessments show that climate change impacts on food security will differ across regions and over time. Throughout all the SRES scenarios, the largest increase of additional food insecure population in relative to the reference case is found in Africa and South Asia, while we find agricultural production in the developed countries will benefit from climate change, which leads to the reduced percentage of food insecure population. More important, the absolute number of food insecure population is largely depending on the socio-economic development paths assumed for the different regions. The socio-economic environment is likely more important than the impacts that can be expected from the biophysical changes of climate.

5.2 Contributions

Compared with previous work, this dissertation makes a few contributions. First, better modeling of interrelationships between adaptation, mitigation and residual damages in an integrated assessment system is developed in Essay 1 and this could have important implications for climate policies (e.g. defining mitigation targets and planning adaptation activities globally or regionally).

Second, our GIS-based economic land allocation model is the first try to bring spatial-explicit ground water depletion into a land use change model, which is able to accurately simulate the spatial-temporal impacts of climate change and bioenergy policies on the regional natural resources allocation, environment and economy.

Third, we apply a recently released climate change-induced crop yield projection dataset incorporating both adaptation and CO_2 effects into a CGE model which has a highly disaggregated agriculture sector and detailed AEZ land use modeling relative to other CGE models. A comprehensive estimation of food security across different regions can provide useful information for designing food and trade policy as well as appropriate adaptation strategy.

5.3 Limitations and Future Work

In presenting the results and contributions above, several limitations must be noted. In the first essay, we applied the DICE model in studying optimal balances in adaptation and mitigation in a global scale. However, adaptation strategies are usually regional and unique in different sectors. More comprehensive estimation of synergies/tradeoffs between these two options in a regional modeling framework (e.g. RICE model) would have more significant implications. Moreover, we followed the original assumption of marginal abatement cost in original DICE/RICE model which is rough. For future research, with the reliable data availability, more accurate estimation of costs and benefits of adaptation, mitigation and residual damages across different sectors and regions/countries can be implemented into the integrated assessment model.

In the second essay, our model focused more on evaluating producer surplus. In the future work, regional demand can be added into the model which may result in a better understanding of social welfare changes.

In the third essay, our assessment of climate change impacts on food security focused more on the food availability and ignored effects on other economic sectors and food processes. In the future, a comprehensive research with sensitivity analysis with respect to some key parameters can be conducted across all four dimensions of food security plus on other sectors. It is also desirable to apply the model in addressing combined effects of climate change and adaptation and mitigation activities on food security issue.

REFERENCES

Acevedo, M.F. 2011. "Interdisciplinary Progress in Food Production, Food Security and Environment Research." *Environmental Conservation* 38(2):151-171.

Ackerman, F., E. A. Stanton, and R. Bueno. 2010. "Fat Tails, Exponents, Extreme Uncertainty: Simulating Catastrophe in DICE." *Ecological Economics*, 69:1657-1665.

Ackerman, F., E. A. Stanton, and R. Bueno. 2011. "CRED: A New Model of Climate and Development." *Ecological Economics:* in press.

Adams, R.M., C. Rosenzweig, R.M. Peart, J.T. Ritchie, B.A. McCarl, J.D. Glyer, R.B. Curry, J.W. Jones, K.J. Boote, and L.H. Allen. 1990. "Global Climate Change and U.S. Agriculture." *Nature* 345: 219-224.

Adams, R.M., R.A. Fleming, C.C. Chang, B.A. McCarl, and C. Rosenzweig. 1995. "A Reassessment of the Economic Effects of Global Climate Change on US Agriculture." *Climatic Change* 30(2):147-167.

Adams, R. M., C.C. Chen, B.A. McCarl, and R.F. Weiher. 1999. "The Economic Consequences of ENSO Events for Agriculture." *Climate Research* 13: 165-172.

Adams, R. M., C.C. Chen, B.A. McCarl, and D.E. Schimmelpfenning. 2000. "Climate Variability and Climate Change: Implications for Agriculture. In The Long Term Economics of Climate Change." In D. Hall and R. Howarth, ed. *Advances in the Economics of Environmental Resources*.West Yorkshire, UK: Emerald Group Publishing Limited, pp.95-113.

Aggarwal, P.K., and V.K. Sivakumar. 2011. “Global Climate Change and Food Security in South Asia: An Adaptation and Mitigation Framework.” In R. Lal, ed. *Climate Change and Food Security in South Asia.* Dordrecht, The Netherlands: Springer Publisher, pp. 253-275

Almas, L.K., W.A. Colette, and S.C. Park. 2006. “Economic Optimization of Groundwater Resources in the Texas Panhandle.”Paper presented at Southern Agricultural Economics Association (SAEA) Annual Meetings, Orlando FL, 5-8 February.

Almas, L.K. 2008. “Economic Optimization Models to Project Income and Hydrological Changes : A Case of Groundwater Management in Texas.” Paper presented at the International Conference on Policy Modeling (EconMod 2008), Berlin Germany, 2-4 July.

Amosson, S., L. New, L. Almas, F. Bretz, and T. Marek. 2001. “Economics of Irrigation Systems.” Texas A&M University Agr. Exp. Sta. Res. Bull. No. B-6113, December.

Beach, R. H., C. Zhen, A. Thomson, R. M. Rejesus, P. Sinha, A. W. Lentz, D. V. Vedenov, and B. A. McCarl. 2009. *Climate Change Impacts on Crop Insurance.* Report prepared for USDA Risk Management Agency, Kansas City MO.

Beach, R.H., and B.A. McCarl. 2010. *U.S. Agricultural and Forestry Impacts of the Energy Independence and Security Act: FASOM Results and Model Description.* Report prepared for U.S. Environmental Protection Agency, Washington DC.

Bosello, F. 2008. “Adaptation, Mitigation and ‘Green’ R&D to Combat Global Climate Change: Insights From an Empirical Integrated Assessment Exercise” Working paper, Department of Economics, Business and Statistics, University of Milan.

Bosello F., C. Carraro, and E. de Cian. 2010. “Climate Policy and the Optimal Balance between Mitigation, Adaptation and Unavoided Damage.” *Climate Change Economics*, 1(2): 71-92.

Bryant, H.L., J. L. Campiche, and J. Lu. 2011. “A Static Computable General Equilibrium Model of World Energy and Agricultural Markets (WEAM).” Research paper, Agricultural and Food Policy Center, Texas A&M University.

Burton, I. 2004. “Climate Change and the Adaptation Deficit; in Climate Change: Building the Adaptive Capacity.” In A. Fenech, D. MacIver, H. Auld, R. Bing and Y. Yin, ed. *Environment Canada*. Toronto, Canada: Meteorological Service of Canada, pp.137-161.

Butt, T.A., B.A. McCarl, J. Angerer, P.T. Dyke, and J.W. Stuth. 2005. “The Economic and Food Security Implications of Climate Change in Mali.” *Climatic Change* 68(3):355-378.

Buttrey, E., B. Bean, F. McCollum, R. Brandon, Q. Xue, and T. Marek. 2011. “Yield, Water-Use Efficiency, and Nutritive Value of Six Warm-Season Perennial Grasses in Response to Irrigation Level.” *Forage and Grazinglands* 10:1-15.

Carter, T.L., M.L. Parry, S. Nishioka, and H. Harasawa. 1994. *Technical Guidelines for Assessing Climate Change Impacts and Adaptations*. Cambridge, UK: Cambridge University Press.

Chang, C.C. 2002. “The Potential Impact of Climate Change on Taiwan’s Agriculture.” *Agricultural Economics* 227: 51-64.

Chen, C. C. and B. A. McCarl. 2001. “Pesticide Usage as Influenced by Climate: A Statistical Investigation.” *Climatic Change* 50(1-2): 475-487.

Chen, C.C., B. A. McCarl and R. M. Adams. 2001. “Economic Implications of Potential ENSO Frequency Strength Shifts.” *Climatic Change* 49(1-2): 147-159.

Chen, C. C., B. A. McCarl and C.C. Chang. 2012. “Climate Change, Sea Level Rise and Rice: Global Market Implications.” *Climatic Change* 110(3-4): 543-560.

Cline, W. 2007. *Global Warming and Agriculture: Impact Estimates by Country.* Washington DC: Peterson Institute.

Conway, D., and E. F. Schipper. 2011. “Adaptation to Climate Change in Africa: Challenges and Opportunities Identified From Ethiopia.” *Global Environmental Change* 21(1): 227-237.

Darwin, R. F., M. Tsigas, J. Lewandrowski, and A. Raneses. 1995. *World Agriculture and Climate Change - Economic Adaptations*. Washington DC: U.S. Department of Agriculture, ESCS For. Agr. Econ. Rep. June.

Darwin, R. F. 1999. “A Farmer's View of the Ricardian Approach to Measuring Agricultural Effects of Climatic Change.” *Climatic Change* 41(3-4): 371-411.

Das, B. 2004. “Towards a Comprehensive Regional Water Policy Model for the Texas High Plains.” Paper presented at Southern Agricultural Economics Association Annual Meetings, Tulsa OK, 14-18 February.

Das, B.R., D.B. Willis, and J. Johnson. 2010. “Effectiveness of Two Water Conservation Policies: An Integrated Modeling Approach.” *Journal of Agricultural and Applied Economics* 42(4): 695-710.

de Bruin, K.C., R.B. Dellink, and R. S. J. Tol. 2009. “AD-DICE: An Implementation of Adaptation in the DICE Model.” *Climatic Change* 95(1-2): 63-81.

Deke, O., K. G. Hooss, C. Kasten, G. Klepper and K. Springer. 2001. “Economic Impact of Climate Change: Simulations with a Regionalized Climate-Economy Model.” Working paper, Kiel Institute of World Economics.

Dellal, I., and B.A. McCarl. 2010. “The Economic Impact of Drought on Agriculture: The Case of Turkey.” Paper presented at the Second International Conference on Drought Management, Istanbul Turkey, 4-6 March.

Easterling W.E. III, P. R. Crosson, N.J. Rosenberg, M.S. McKenney, L.A. Katz, and K.M. Lemon. 1993. “Agricultural Impacts of and Responses to Climate Change in the Missouri–Iowa–Nebraska–Kansas (MINK) Region.” *Climate Change* 24:23–61.

Fankhauser, S. 1994. “Protection vs. Retreat—the Economic Costs of Sea Level Rise.” *Environment and Planning A* 27(2):299–319.

Feng, S.J., A.D. Hagerman, B.H. Hurd, J.H. Mu, B.A. McCarl, and W.W. Wang. 2010. “Climate Change and Its Impact on Agriculture: Challenges for the 21st Century.” In J.M. Cossia, ed. *Global Warming in the 21st Century*. New York: Nova Science Publishers, pp. 1-40.

Feng, Y. 1992. “Optimal Intertemporal Allocation of Ground Water for Irrigation in the Texas High Plains.” PhD dissertation, Texas Tech University.

Fischer, G., K. Frohberg, M.L. Parry, and C. Rosenzweig. 1994. “Climate Change and World Food Supply, Demand and Trade: Who Benefits, Who Loses?” *Global Environmental Change* 4(1): 7-23

Food and Agriculture Organization (FAO). 2001. *The State of Food Insecurity in the World.* Rome.

Food and Agriculture Organization (FAO). 2006. *World Agriculture: Towards 2030/2050.* Rome.

Food and Agriculture Organization (FAO). 2008a. *FAO Methodology for the Measurement of Food Deprivation.* Rome.

Food and Agriculture Organization (FAO). 2008b. *Climate Change and Food Security: a Framework Document.* Rome.

Food and Agriculture Organization (FAO). 2009. *Climate Change and Bioenergy Challenges for Food and Agriculture.* Rome.

Food and Agriculture Organization (FAO). 2010. *Global Hunger Declining, But Still Unacceptably High.* Rome.

Füssel, H.M., and R.J.T. Klein. 2006. “Climate change vulnerability assessments: an evolution of conceptual thinking.” *Climatic Change* 75(3):301-329.

Gallagher, P. W., M. Dikeman, J. Fritz, E. Wailes, W. Gauthier, and H. Shapouri. 2003. “Supply and Social Cost Estimates for Biomass from Crop Residues in the United States.” *Environmental and Resource Economics* 24:335-358.

Gleick, P.H., G. Wolff, E.L. Chalecki, and R. Reyes. 2002. *The New Economy of Water-the Risk and Benefits of Globalization and Privatization of Fresh Water.* Oakland CA: Pacific Institute.

Grubb, H. W. 1966. *Importance of Irrigation Water to the Economy of the Texas High Plains.* Austin TX: Texas Water Development Board.

Guru, M.V., and J.E. Horne. 2000. *The Ogallala Aquifer*. Poteau OK: The Kerr Center for Sustainable Agriculture, Inc.

Hanemann, W.M. 2008. "What is the Economic Cost of Climate Change?" Working Paper, Department of Agricultural and Resource Economics and Policy, University of California-Berkeley.

Hertel, T.W. 1997. *Global Trade Analysis: Modeling and Applications*. Cambridge, UK: Cambridge University Press.

Hope, C.W., J. Anderson, and P. Wenman. 1993. "Policy Analysis of the Greenhouse Effect—an Application of the PAGE Model." *Energy Policy* 15:328–338

Hornbeck, R., and P. Keskin. 2011. "Farming the Ogallala Aquifer: Short-Run and Long-Run Impacts of Groundwater Access." Working paper, Department of Economics, Harvard University.

Howden, S.M., J.F. Soussana, F.N. Tubiello, N. Chhetri, M. Dunlop, and H. Meinke. 2007. "Adapting Agriculture to Climate Change."*Proceedings of the National Academy of Sciences* 104(50):19691-19696.

Hughes, W.S., and L.H. Wyatt. 1969. *Projected Economic Life of Water Resources, Subdivision Number 1, High Plains Underground Water Reservoir*. College Station TX: Texas Agricultural Experiment Station.

Hulme, M., J. Mitchell, W. J. Ingram, J.E. Lowe, T.C. Johns, M. New, and D. Viner. 1999. “Global Change Scenarios for Global Impact Studies.” *Global Environmental Change* 9: S3–S20.

Iglesias, A., and C. Rosenzweig. 2009. “Effects of Climate Change on Global Food Production under Special Report on Emissions Scenarios (SRES) Emissions and Socioeconomic Scenarios: Data from a Crop Modeling Study.” Working paper, Socioeconomic Data and Applications Center (SEDAC), Columbia University.

Intergovernmental Panel on Climate Change (IPCC). 2007a. *Climate Change 2007: The Physical Science Basis.* Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2007b. *Climate Change 2007: Impacts, Adaptation and Vulnerability.* Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2007c. *Climate Change 2007: Mitigation of Climate Change.* Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (IPCC). 2008. *Climate Change and Water*. Cambridge, UK: Cambridge University Press.

Johnson, J. W. 2003. “Regional Policy Alternatives in Response to Depletion of the Ogallala Aquifer.” PhD dissertation. Texas Tech University.

Khanna, M., X. Chen, H. Huang, and H. Önal. 2011. "Supply of Cellulosic Biofuel Feedstocks and Regional Production Patterns." *American Journal of Agricultural Economics* 93(2): 473-480.

Kumar, K.S.K., and J. Parikh. 1998. "Climate Change Impacts on Indian Agriculture: the Ricardian Approach." Working paper, World Bank.

Lal, M. 2011. "Implications of Climate Change in Sustained Agricultural Production in South Asia." *Regional Environmental Change* (11): S79-S94.

Lorite, I., L. Mateos, F. Orgaz, and E. Fereres. 2007. "Assessing Deficit Irrigation Strategies at the Level of an Irrigation District." *Agricultural Water Management* 91(1-3):51-60.

Marek, T., S. Amosson, F. Bretz, B. Guerrero, and R. Kotara. 2009. *2011 Panhandle Regional Water Plan, Task 2 Report: Agricultural Water Demand Projections A Water Planning Report.* Lubbock TX: Texas AgriLife Experiment Station.

Martin, F. 1988. "Food Security and Comparative Advantage in Senegal: a Micro-Macro Approach." PhD dissertation, Michigan State University.

Maxwell, S., and M. Smith. 1992. "Household Food Security: a Conceptual Review." In S. Maxwell and T. Frankenberger, ed. *Household Food Security: Concepts, Indicators, Measurements.* Rome and New York: IFAD and UNICEF, pp.1-72.

McCarl, B.A. 1982. "Cropping Activities in Agricultural Sector Models: a Methodological Proposal." *American Journal of Agricultural Economics* 64(4): 768-772.

McCarl, B.A., and H. Önal. 1989. “Aggregation of Heterogeneous Firms in Mathematical Programming Models.” *European Review of Agricultural Economics* 16 (4): 499-513.

McCarl, B.A., and H. Önal. 1991. “Exact Aggregation in Mathematical Programming Sector Models.” *Canadian Journal of Agricultural Economics/Revue Canadienned' Agroeconomie* 39 (2): 319-334.

McCarl, B. A., and J. M. Reilly.1999. “Water and the Agricultural Climate Change Assessment: Issues from the Standpoint of Agricultural Economists.” Paper presented at Proceedings of American Water Resources Association Special Conference on Potential Consequences of Climate Variability and Change to Water Resources, Atlanta GA, 4-8 August.

McCarl, B.A., D. Adams, R. Alig, and J. Chmelik. 2000. Competitiveness of Biomass-Fueled Electrical Power Plants. *Annals of Operations Research,* 94:37–55.

McCarl, B.A., X. Villavicencio, and X. Wu. 2008. "Climate Change and Future Analysis: Is Stationarity Dying?" *American Journal of Agricultural Economics* 90(5):1241-1247.

McDonald, S., S. Robinson, and K. Thierfelder. 2005. “A SAM Based Global CGE Model Using GTAP Data.” Working paper, Department of Economics, University of Sheffield.

McDonald, S., S. Robinson, and K. Thierfelder. 2006. “Impact of Switching Production to Bioenergy Crops: The Switchgrass Example.” *Energy Economics* 28:243-265.

McGuire, V.L., M.R. Johnson, R.L. Schieffer, J.S. Stanton, S.K. Sebree, and I.M. Verstraeten. 2003. *Water in Storage and Approaches to Groundwater Management, High Plains Aquifer, 2000*. Working paper, US Geological Survey.

McMichael, A.J., R.E. Woodruff., and S. Hales. 2006. "Climate Change and Human Health: Present and Future Risks." *The Lancet* 367(9513):859–869.

Mendelsohn, R., W. D. Nordhaus, and D. Shaw. 1994. “The Impact of Global Warming on Agriculture: A Ricardian Analysis.” *The American Economic Review* 84: 753-771.

Mendelsohn, R. O., W. D. Nordhaus, and D. Shaw. 1999. “The Impact of Climate Variation on U.S. Agriculture.” In R. O. Mendelsohn and J. E. Neumann, ed. *The Impact of Climate Change on the United States Economy*. Cambridge, UK: Cambridge University Press, pp. 55-74.

Mendelsohn, R. 2009. “Climate Change and Economic Growth.” Working paper, Yale School of Forestry and Environmental Studies, Yale University.

Mendelsohn, R., K. Emanuel, and S. Chonabayashi. 2009. *The Impact of Climate Change on Global Tropical Storm Damages.* Working paper, World Bank.

Naiken, L. 2002. “FAO Methodology for Estimating the Prevalence of Undernourishment.” Paper presented at the Proceedings of International Scientific Symposium on Measurement and Assessment of Food Deprivation and Undernourishment, Rome Italy, 26-28 June.

National Academy of Sciences (NAS). 2010a. *America’s Climate Choices: Advancing the Science of Climate Change.* Washington DC.

National Academy of Sciences (NAS). 2010b. *America's Climate Choices: Limiting the Magnitude of Climate Change.* Washington DC.

National Academy of Sciences (NAS). 2010c. *America's Climate Choices: Adapting to the Impacts of Climate Change.* Washington DC.

Nelson, G.C., M. W. Rosegrant, A. Palazzo, I. Gray, C. Ingersoll, R. Robertson, S. Tokgoz, T. Zhu,T. B. Sulser, C. Ringler, S. Msangi, and L. You. 2010. *Food Security, Farming and Climate Change to 2050, Scenarios, Results, Policy Options.* Working paper, International Food Policy Research Institute (IFPRI).

Nordhaus, W.D. 1994. *Managing the Global Commons: The Economics of the Greenhouse Effect.* Cambridge MA: MIT Press.

Nordhaus, W.D., and J. Boyer. 2000. *Warming the World: Economic Modeling of Global Warming*. Cambridge MA: MIT Press.

Nordhaus, W.D. 2007. "The Challenge of Global Warming: Economic Models and Environmental Policy." Working paper, Department of Economics, Yale University.

Nordhaus, W.D. 2008. *A Question of Balance: Economic Modeling of Global Warming.* New Haven CT: Yale University Press.

Nuthall, P.L. 1980. "A Survey of Methods for Determining a Planning Horizon." *Review of Marketing and Agricultural Economics* 48:21-36.

Parry, I.H., R. C. Williams III., and L.H. Goulder. 1999. "When Can Carbon Abatement Policies Increase Welfare? The Fundamental Role of Distorted Factor Markets." *Journal of Environmental Economics and Management* 37 (1), 52-84.

Parry, M.L., C. Rosenzweig, A. Iglesias, M. Livermore, and G. Fischer. 2004. “Effects of Climate Change on Global Food Production Under SRES Emissions and Socio-Economic Scenarios.” *Global Environmental Change* 14(1):53-67.

Parry, M., N., P. Arnell, D. Berry, D. Dodman, S. Fankhauser, C. Hope, S. Kovats, and R. Nicholls. 2009. “Assessing the Costs of Adaptation to Climate Change: A Review of the UNFCCC and Other Recent Estimates.” Working paper, International Institute for Environment and Development and Grantham Institute on Climate Change, Imperial College London.

Patt, A.G., D. van Vuuren, F. Berkhout, A. Aaheim, A.F. Hof, M. Isaac, and R. Mechler. 2010. “Adaptation in Integrated Assessment Modeling: Where Do We Stand?” *Climatic Change* 99(3-4):383-402.

Pearce, D., W. Cline, A. Achanta, S. Fankhauser, R. Pachauri, R. Tol, and P. Vellinga. 1996. “The Social Cost of Climate Change: Greenhouse Damage and the Benefits of Control.” In J.P. Bruce, H. Lee, and E.F. Haites ed. *Climate Change 1995: Economic and Social Dimensions of Climate Change.* Cambridge, UK: Cambridge University Press, pp. 179-224.

Peterson, J.M., T.L. Marsh, and J.R. Williams. 2003. “Conserving the Ogallala Aquifer: Efficiency, Equity, and Moral Motives.” *Choices* 1:15–18.

Pimentel, D., B. Berger, D. Filiberto, M. Newton, B. Wolfe, E. Karabinakis, S. Clark, E. Poon, E. Abbett, and S. Nandagopal. 2004. “Water Resources: Agricultural and Environmental Issues.” *BioScience* 54(10):909-918.

Reilly, J. M. 1994. “Crops and Climate Change.” *Nature* 367:118-119.

Reilly, J., W. Baethgen, F. Chege, S. van de Geijn, L. Erda, A. Iglesias, G. Kenny, D. Patterson, J. Rogasik, and R. Rotter. 1996. “Agriculture in a Changing Climate: Impacts and Adaptation.” In R.T.Watson, M.C. Zinyowera, R.H. Moss, ed. *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses.* Cambridge, UK: Cambridge University Press, pp. 429-467.

Ringler, C., T. Zhu, X. Cai, J. Koo, and D. Wang. 2010. “Climate Change Impacts on Food Security in Sub-Saharan Africa.” Working Paper, International Food Policy Research Institute (IFPRI).

Rose, S.K., and B.A. McCarl. 2008. “Greenhouse Gas Emissions, Stabilization and the Inevitability of Adaptation: Challenges for US Agriculture.” *Choices* 23(1): 15-18.

Rosenberg, N.J., D.J. Epstein, D. Wang, L. Vail, R. Srinivasan, and J.G. Arnold. 1999. “Possible Impacts of Global Warming on the Hydrology of the Ogallala Aquifer Region.” *Climatic Change* 42(4):677-692.

Rosenzweig, C. 1989. “Potential Effects of Climate Change on Agricultural Production in the Great Plains: a Simulation Study.” In J.B. Smith and D. Tirpak, ed. *The Potential Effects of Global Climate Change on the United States.* Washington DC: United States Environmental Protection Agency, pp. 353-401.

Rosenzweig, M. R., and H. P. Binswanger. 1993. “Wealth, Weather Risk and the Composition and Profitability of Agricultural Investments.” *The Economic Journal* 103: 56-78.

Sarofim, M.C., and J. M. Reilly. 2011. "Applications of Integrated Assessment Modeling to Climate Change." *Wiley Interdisciplinary Reviews: Climate Change* 2(1):27-44.

Schmidhuber, J., and F.N. Tubiello. 2007. "Global Food Security under Climate Change." *Proceedings of the National Academy of Sciences* 104:19703–19708.

Schneider, S.H. 1997. "Integrated Assessment Modeling of Global Climate Change: Transparent Rational Tool for Policy Making or Opaque Screen Hiding Value-laden Assumptions?" *Environmental Modeling and Assessment* 2: 229-248.

Seo, S.N., and R. Mendelsohn. 2008. "Measuring Impacts and Adaptations to Climate Change: A Structural Ricardian Model of African Livestock Management." *Agricultural Economics* 38(2):151-165.

Shoven J.B., and J. Whalley. 1999. *Applying General Equilibrium.* Cambridge, UK: Cambridge University Press.

Stanton, E.A., J. Cegan, R. Bueno, and F. Ackerman. 2011. "Estimating Regions' Relative Vulnerability to Climate Damages in the CRED Model." Working paper, Stockholm Environment Institute.

Stern, N. 2007. *The Economics of Climate Change: the Stern Review*. Cambridge, UK: Cambridge University Press.

Stone, K. C., P.G. Hunt, K.B. Cantrell, and K.S. Ro. 2009. "The Potential Impacts of Biomass Feedstock Production on Water Resource Availability." *Bioresource Technology* 101:2014-2015.

Terrell, B. 1998. “Economic Impacts of the Depletion of the Ogallala Aquifer: An Application to the Texas High Plains.” MS thesis, Texas Tech University.

Tol, R.S. J. 2005. “Adaptation and Mitigation: Trade-offs in Substance and Methods.” *Environmental Science and Policy* 8:572–578.

Tol, R.S. J. 2007. “The Double Trade-off between Adaptation and Mitigation for Sea Level Rise: an Application of FUND.” *Mitigation and Adaptation Strategies for Global Change*, 12(5):741–753.

Tol, R.S.J., and S, Fankhauser. 1998. “On the Representation of Impact in Integrated Assessment Models of Climate Change.” *Environmental Modeling and Assessment*, 3:63–74.

United States Climate Change Science Program (USCCSP). 2008. *The Effects of Climate Change on Agriculture, Land Resources, Water Resources, and Biodiversity in the United States.* Washington DC.

U.S. Department of Energy. 2011. *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry.* Washington DC.

United Nations Framework Convention on Climate Change (UNFCCC). 2010. *Report of the Ad Hoc Working Group on Long-term Cooperative Action under its Eighth Session.* Copenhagen, Denmark.

van Vuuren, D.P., and K. Riahi. 2008. “Do Recent Emission Trends Imply Higher Emissions Forever?” *Climatic Change* 91(3):237-248.

Viguier, L. 2003. “Defining Meaningful Participation of Developing Countries in Climate Change Mitigation.” Working paper, Department of Economics and Social Sciences, University of Geneva.

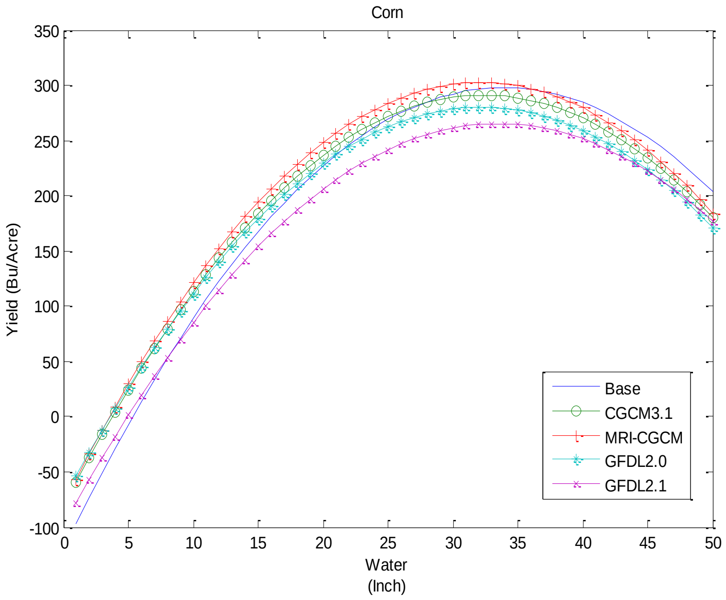
Willis, D.B., J. Stovall, J.W. Johnson, K. Rainwater, L.S. Barbato, K. Mulligan, and E.B. Fish. 2011. “The Impact of Spatial Heterogeneity in Land Use Practices and Aquifer Characteristics on Groundwater Conservation Policy Cost.” Paper presented at the Southern Agricultural Economics Association 43rd Annual Meetings, Corpus Christi TX, 5-8 February.

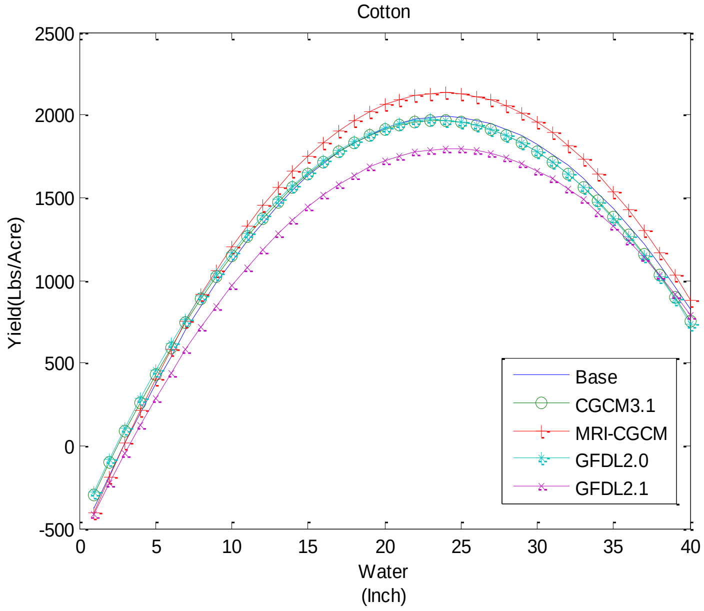
World Bank. 2010. *The Economics of Adaption to Climate Change.* Washington DC.

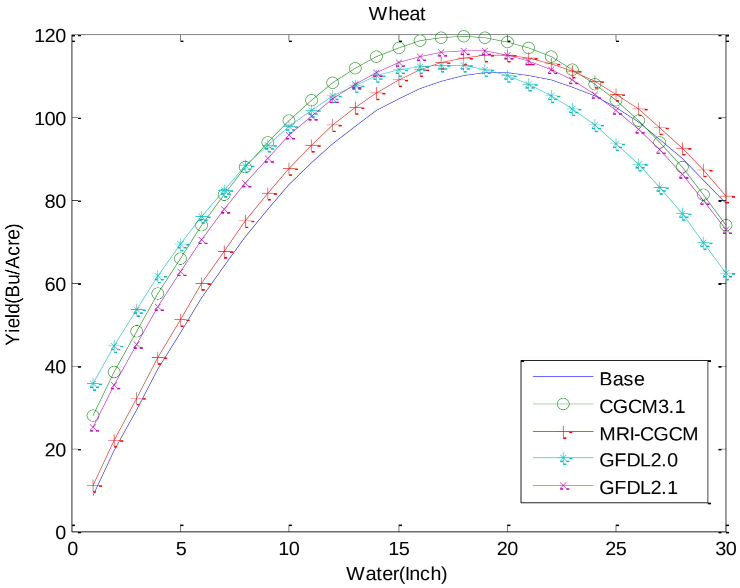
Yohe, G.W., J. Neumann, P. Marshall, and H. Ameden. 1996. “The Economic Costs of Sea Level Rise on US Coastal Properties.” *Climatic Change* 32(1): 387-410.

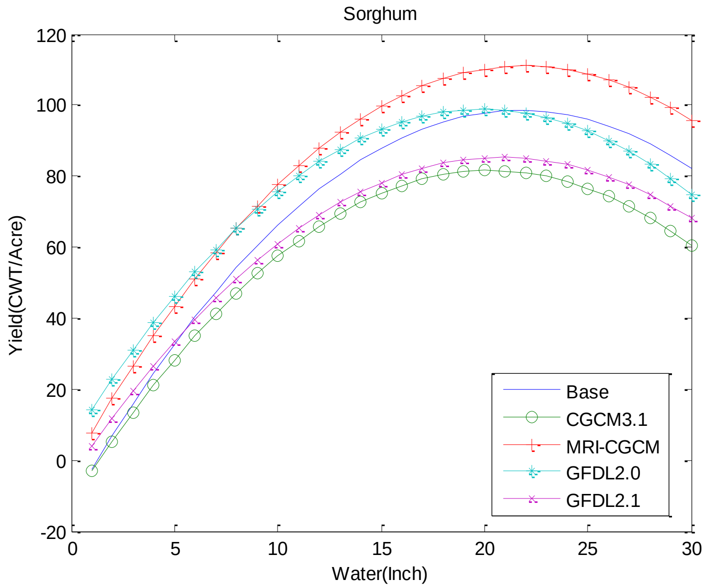
APPENDIX

Crop yields response to irrigation water use under base scenario and four climate change scenarios (CGCM3.1, MRI-CGCM, GFDL2.0, GFDL2.1). Baseline crop response is based on unpublished statistic regression data from NPWD (North Plains Water District) and personal communication. Crop response under each climate change projections are numerically calculated based on EPIC model predictions.









Energy use factor for electricity or natural gas (EF) is 0.164 KWH/feet of lift per acre-inch, irrigation system operating pressure (PSI) is 16.5 pounds per square inch, energy price (ENP) is assumed of $0.0633 per KWH and pumping engine efficiency (PE) is 50% and the factor 2.31 (feet) is the height of a column of water that will exert a pressure of 1 pound per square inch. Fixed cost of assumed Low Elevation Spray Application (LESA) irrigation system is $2.63/acre-inch of water, total variable cost is $14.55/acre-inch. Crop price are calculated using average prices between 2005 and 2010 and keep constant in the model.

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