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Texas AM University, Kasetsart University, Columbia University, Oregon State University, Texas AM University

2011

Chapter 09

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Abstract: Land use is majorly involved with climate change concerns and this chapter discusses and reviews the interrelationships between the vulnerability, adaptation and mitigation aspects of land use and climate change. We review a number of key studies on climate change issues regarding land productivity, land use and land management (LPLULM), identifying key findings, pointing out research needs, and raising economic/policy questions to ponder. Overall, this chapter goes beyond previous reviews and simultaneously treats the troika of vulnerability, mitigation and adaptation aspects of the issue, which will provide readers with a more comprehensive, multifaceted grasp of the spectrum of current issues regarding LPLULM and climate change.

Keywords: Land productivity, land use and management, climate change, vulnerability, adaptation and mitigation

Introduction

The climate change issue raises a number of risks and decision making opportunities. The decision/risk space involves three dimensions :(1) Societal vulnerability; where the effects of climate change influence current and future productivity.;(2) Societal adaptation; where adaptation actions are pursued to that reduce the productivity effects of climate change. These actions involve changes in operations accompanied by investments of resources.;(3) Societal mitigation; where actions are undertaken to reduce the net emissions of GHGs with the aim of reducing the future atmospheric concentrations of GHGs and the consequent effects of climate change. This also involves modification in operations plus potential investments.

Land use is majorly involved with these climate change concerns. Land productivity, land use and land management (LPLULM) decisions are relevant. Land productivity is affected by climate change which in turn alters the returns to enterprises using land (representing vulnerability to climate change). Also LPLULM decisions can alter net greenhouse gas (GHG) emissions and contribute to reducing the future extent of climate change (mitigation). Finally, LPLULM provides possible mechanisms for altering management or changing enterprise mix to enhance productivity in the face of climate change (pursuing adaptation).

In this chapter, we discuss and review interrelationships between the vulnerability, adaptation and mitigation aspects of land use and climate change. We do this based on the literature. A number of studies have addressed such issues and contain findings in terms of vulnerability, mitigation, and adaptation. We review key research on climate change issues regarding LPLULM, identifying key findings, pointing out research needs, and raising economic questions to ponder. In doing this we go beyond previous reviews and simultaneously treat the troika of vulnerability, mitigation and adaptation aspects of the issue. Hopefully this will provide readers with a more comprehensive, multifaceted grasp of the spectrum of current issues regarding LPLULM and climate change.

1 Land Use and Climate Change Interrelationships

As stated above, LPLULM is involved with all three aspects of the climate change issue. In terms of vulnerability, LPLULM productivity is sensitive to changes in climate. IPCC (2007) documents that the climate is changing by presenting data on increases in temperature, extreme events, heat waves, droughts, and alterations in rainfall incidence intensity. In additions, hydrological cycles, incidence of pests and diseases, and forest fire are also being affected.

In terms of mitigation, land cover change has been a major historical contributor to atmospheric GHG accumulation and is potentially reversible. Houghton (2003) and Golub et al. (2009) estimate that since 1850 a third of the total anthropogenic emissions of carbon have come from land use change. In contemporary terms, the IPCC (2001) finds the current share of total anthropogenic emissions from LPLULM related sources to be 18% from forestry and 14% from agriculture. These emissions are mainly from: (1) deforestation where forests are converted into cropland, pasture land, and developed uses; and (2) grassland conversion where land use is changed into cropland from pasture or range. Furthermore, agriculture is estimated to account for 52% and 84% of global anthropogenic methane and nitrous oxide emissions, respectively (Smith et al. 2008; IPCC 2001; WRI 2005). These emissions are mainly from land based crop and livestock production. In the face of this, authors like Lal, Follett, and Kimble 2003; Smith et al. 2007; Fri et al, 2010 argue that LPLULM actions may enhance sequestration or reduce emissions reducing future atmospheric concentrations.

LPLULM can also be used to adapt to a changing climate. Land use can be shifted among enterprises by changing crops, tree, or livestock species and also changing uses between cropping, pasture, grazing, and forests to exploit relative changes in productivity. One can also alter land management involving practices for crops, livestock, and forest production to better accommodate a changed climate. Now given this overview we delve individually into the vulnerability, mitigation and adaptation topics.

1.1 *Climate Change Vulnerability and Land Use Change*

Agriculture and forestry (AF) are decidedly vulnerable to climate change. Land use economists have widely addressed this vulnerability examining effects on direct AF productivity, disturbances, land values and water resources.

1.2 *Climate Change and AF Productivity*

IPCC (2007b) indicates that we have observed increases in temperature, changes in rainfall patterns, increased climate variability, and greater frequency of extreme events. These effects will differentially alter productivity across various types of crops, livestock, and trees and across regions. In addition, atmospheric CO_2 concentration increases enhance yields of some crops, grasses, and tree species. Findings on implications for major categories are reviewed below. Here we limit coverage to findings using observed data but not that IPCC 2007 reviews studies from simulation models.

1.2.1 *Observed Crop Yields*

A wide variety of studies have addressed climate change effects on crop yields. Deschenes and Greenstone (2007) find that yields of corn and soybeans are negatively correlated to growing degree days. Schlenker and Roberts (2009) and Huang and Khanna (2010) find similar results and reveal a non-linear effect of temperature on yields of corn, soybeans. Attavanich and McCarl (2011) and McCarl, Villavicencio, and Wu (2008) find that the effect of temperature on U.S. state yields depends on location with beneficial consequences to colder (Northern) areas and detrimental outcomes to the hotter (Southern) areas. Collectively these and other studies show that climate change will likely decrease yields in areas where heat stress is a factor and increase it in areas where cold is a key factor.

Regarding the effect of precipitation, Chen, McCarl, and Schimmelpfennig (2004), Isik and Devadoss (2006), and McCarl, Villavicencio, and Wu (2008) find that increased precipitation enhances yields of corn, cotton, soybeans, winter wheat, and sorghum, while it has a negative impact on wheat. An inverted-U shape relationship between corn and soybean yield and precipitation is found in Schlenker and Roberts (2009) and Huang and Khanna (2010).

Attavanich and McCarl (2011) show heterogeneity in projected climate change effects, identifying negative effects over the currently wetter U.S. Central and Northeast regions and positive effects for the drier North Plains regions where precipitation gains are projected.

Climate variability and extreme events are addressed in a number of studies. McCarl, Villavicencio, and Wu (2008) find that increased temperature variation negatively impacts yields of all crops, and Huang and Khanna (2010) also found this result for corn and soybeans. McCarl, Villavicencio, and Wu (2008) and Attavanich and McCarl (2011) find that an increase in precipitation intensity decreases crop yields, while an increase in the Palmer drought index has a differential effect across crops. Chen and McCarl (2009) examine the effects of hurricane incidence and find yield reductions ranging from 0.20-12.90% with the U.S. Gulf coast and the southern Atlantic coastal regions being the most vulnerable areas.

Crop yields are also affected by atmospheric CO_2 concentration. C3 crops are found to be more responsive to CO_2 than are C4 crops under the ample water conditions (Ainsworth and Long 2005; Long et al. 2006; Kimball 2006; Attavanich and McCarl 2011)[1]. Leakey (2009) finds that C4 crops only benefit from elevated CO_2 in times and places of drought stress as do Attavanich and McCarl (2011). Farmers in developing countries have been found to be highly vulnerable to climate change. Butt et al. (2005) combine biophysical and economic models to investigate implications of climate change in Mali. They find that, under climate change, crop farmers are severely affected and overall food insecurity almost doubles.

1.2.2 *Forests*

Boisvenue and Running (2006) review previous literature related to climate change impacts on forest productivity. They find that climatic change has a generally positive impact on forest productivity when water is not limiting. McMahon, Parker, and Miller (2010) estimate that the Northeast U.S forest is growing at a much faster rate than expected and attribute this to rising levels of atmospheric CO_2, higher temperatures and longer growing seasons. Foster et al. (2010) argues to the contrary that past tree mortality could explain the difference in rates. Recent studies from the free-air CO_2 enrichment (FACE) experiments[2] suggest that direct CO_2 effects on tree growth may need to be revised downward (Norby et al. 2005; Karnosky and Pregitzer 2005; McCarthy et al. 2010). Allen et al. (2010) review studies and indicate that climate change may enhance tree mortality due to drought and heat in forests worldwide. Sohngen, Mendelsohn, and Sedjo (1999) in their global study on forest effects find a market and productivity induced shift to subtropical areas.

1.2.3 *Grasslands*

Changes in rainfall, temperature, and CO_2 concentrations affect the productivity of grasslands, an important fodder source for livestock production. IPCC (2007a) indicates projected declines in rainfall in some major grassland and rangeland areas (e.g., South America, South and North Africa, western Asia, Australia and southern Europe). They state that grass production tends to increase in humid temperate regions, but that it would likely see decreases in arid and semiarid regions (IPCC 2007b). In Australia, Cullen et al. (2009) predict an increase in grass production in subtropical and sub-humid regions of eastern Australia, while in southern Australia they predict slight increases as of 2030 but decreases of up to 19% in 2070.

Wang et al. (2007) projects that the net primary productivity of *grasslands*[3] in China will increase 7-21% under 2.7-3.9 °C increases in temperature, and 10% increases in precipitation coupled with doubled CO_2. However, they predict a drop of 24% when there are only increases in temperature. Mu, McCarl and Wein (2012) find in many regions land use shifts from cropland use to grasslands under predicted climate change. IPCC (2007b) indicates that CO_2 fertilization enhances grass growth with C3 pasture grasses and legumes positively responding exhibiting about 10% and 20% productivity increases, respectively (Ainsworth and Long 2005; Nowak et al. 2004). Shifts in forage quality are also expected (Polley et al. 2012).

1.2.4 *Livestock*

Climate change affects livestock productivity. Warming climates can increase thermal stress reducing livestock productivity, conception rates, and survival rates. Increased climate variability and droughts may lead to livestock production reductions (IPCC 2007b; Thornton et al. 2009). Stocking rates may also decline as gross growth is reduced. For example, Mu, McCarl and Wein (2012) find an inverted-U shape between summer precipitation and US cattle stocking rates and that cattle stocking rates decrease with increases in the summer temperature and humidity index (THI). Mader et al. (2009) find that under increased CO_2 concentration scenarios, the west side of the U.S. Corn Belt encounters productivity losses for swine of as much as 22.4%, while in the east side, losses of over 70% occur. For beef, they find increasing temperature is beneficial to beef producers in the western Corn Belt but not in the northwest and southeast regions. Finally, dairy production is projected to decrease from 1.0-7.2% depending on location.

Livestock in developing countries are highly vulnerable. Sirohi and Michaelowa (2007) state that the livestock impacts could be large and devastating for low-income rural areas. Seo and Mendelsohn (2008a) find that net revenue of beef cattle is lower in warmer places, but that sheep net revenue is lower in wetter places. They also indicate the expected profit from African livestock management will fall as early as 2020. Moreover, they show that climate change as predicted would cause considerable reductions in the net incomes of large livestock farms. Seo et al. (2009) find that a hot and dry climate results in a greater incidence of livestock compared with crop production. Butt et al. (2005) indicate that, under climate change, livestock weights are projected to decrease by 14-16%.

1.3 *Disturbances*

Climate change can increase disturbances in the form of increased incidence of pest and diseases and fires. Numerous studies find that increases in temperature affect pest populations and migrations. Rising temperatures are also predicted to increase forest pests, crop pesticide usage costs, and wildfire risk (e.g., Chen and McCarl 2001; Williams and Liebhold 2002; Taylor et al. 2007; Hicke and Jenkins 2008; Robinet and Roques 2010; Walther et al. 2009; Gan 2004, 2005).

In a review of forestry studies, Taylor et al. (2007) find that the current outbreak of the mountain pine beetle in British Columbia is an order of magnitude larger in area and severity than all previous recorded outbreaks. Williams and Liebhold (2002) project that outbreak areas for southern pine beetles increase with higher temperatures and generally shift northward, while the projected outbreak areas for mountain pine beetle shifts towards higher elevations. Hicke and Jenkins (2008) map climate change effects on lodgepole pine stand susceptibility to mountain pine beetle attack, concluding that forests in the southern Rocky Mountains have the highest level of susceptibility.

Patriquin, Wellstead, and White (2007) find negative long-term economic implications of mountain pine beetle infestations in British Columbia. Schwab et al. (2009) predict a significant medium-term timber supply shortage, reduced stumpage revenues, and increased cost competition among primary wood-products manufacturers. Williams et al. (2010) estimate that about 7.6% of U.S. southwestern forest and woodland area experienced mortality associated with pine bark beetles between 1997 and 2008.

In terms of agriculture, crops are negatively affected by insect and disease pest outbreaks. Chen and McCarl (2001) find that increases in rainfall raise pesticide usage costs for corn, cotton, potatoes, soybeans, and wheat, while hotter weather increases pesticide costs for all crops except wheat. Rosenzweig et al. (2001) review studies on agricultural chemical use and conclude that in a warmer climate pests may become more active and may expand their geographical range, resulting in increased use of pesticides with accompanying health, ecological, and economic costs. Shakhramanyan, Schneider, and McCarl (2012) find that climate change causes significant increases in pesticide use and external costs.

For animal diseases, Purse et al. (2005) explore climate-induced shifts in bluetongue virus incidence in Europe and find that strains have spread across 12 countries and 800 kilometers further north due to climate change since 1998. Saegerman, Berkvens, and Mellor (2008) find similar results. Mu, McCarl, and Wu (2011) show that climate change may have caused part of the current increase in avian influenza incidence and is likely to further stimulate disease spread in the future.

Climate change also affects fire risk. Westerling et al. (2006) find argue that climate change has caused wildfire risk to increase particularly since the mid-1980s with the greatest increases occurred in mid-elevation Northern Rockies forests. Williams et al. (2010) find that about 2.7% of U.S. southwestern forest and woodland area experienced substantial mortality due to wildfires between 1984 and 2006. Moriondo et al. (2006) find an increase in fire risk in the EU Mediterranean countries, especially in the Alps region of Italy, the Pyrenees of Spain, and the Balkan mountains. Brown, Hall, and Westerling (2004) argue that climate change will exacerbate forest fires, and that new fire and fuels management strategies may be needed. The Montgomery chapter in this Handbook provides additional material on fire and land use change.

1.4 *Land Values*

Climate change affects LPLULM, which in turn impacts land values. Overall, the effect is mixed in developed countries, but negative in developing countries. Mendelsohn, Nordhaus, and Shaw (1994) find that higher temperatures in all seasons except autumn reduce average U.S. farm values, while more precipitation outside of autumn increases farm values. They estimate that a climate change induced loss in U.S. farmland value ranging from -$141 to $34.8 billion. Schlenker, Hanemann, and Fisher (2005) do a similar study and find an annual loss in U.S. farmland value in the range of $5-$5.3 billion for dryland non-urban counties. Mendelsohn and Reinsborogh (2007) find that U.S. farms are much more sensitive to higher temperature than Canadian farms and but are less sensitive to precipitation increases. Deschenes and Greenstone (2007) find that climate change will lead to a long run increase of $1.3 billion (2002$) in agricultural land values. They indicate that land values in California, Nebraska, and North Carolina will be lowered substantially by climate change, while South Dakota and Georgia will have the biggest increases.

For developing countries, Seo and Mendelsohn (2008b) find that in South America climate change will decrease farmland values except for irrigated farms. Moreover, they find small farms are more vulnerable to the increase in temperature, while large farms are more vulnerable to increases in precipitation. Mendelsohn, Arellano-Gonzalez, and Christensen (2010) project that, on average, higher temperatures decrease Mexican land values by 4 to 6 thousand pesos per degree Celsius amounting to cropland value reductions of 42-54% by 2100. Wang et al. (2009) find that in China an increase in temperature is likely to harm rain-fed farms but benefit irrigated farms. A small value loss is found in the Southeast China farms, while the largest damage is discovered in the Northeast and Northwest farms (Wang et al. 2009).

1.5 *Water Supply*

Climate change has important consequences for the hydrological cycle and water availability (IPCC 2007b; Bates et al. 2008). Land use patterns are affected by this change via the availability of irrigation water and the suitability of land for rain fed production.

Regions where the majority of water supply comes from snow or glaciers are vulnerable to climate change because higher temperatures cause a reduction in mountain storage of water and seasonality of water availability (Barnett et al. 2005; Gleick and Adams 2000). Such regions include South American river basins along the Andes, the Greater Himalayas, and much of the US west including California (Coudrian, Francou, and Kundzewicz 2005; Xu et al. 2009).

Climate change also poses water supply threats in Africa because much of the population relies on local rivers. De Wit and Stankiewicz (2006) project that a 10% decrease in precipitation in regions receiving about one meter of precipitation per year could reduce runoff into rivers by 17%, while in regions receiving 0.5 meters that runoff could be reduced by 50%. Furthermore, they predict that by the end of this century, surface water access will be reduced across 25% of Africa. Paeth et al. (2009) find climate change would cause a weakening of the hydrological cycle over most of tropical Africa, resulting in enhanced heat stress and extended dry spells. Additionally, on a global basis, the Mediterranean Basin, Central America, and sub-tropical Australia are projected to encounter declines in water availability (Bates et al. 2008) as is the Southwestern U.S. (Seager et al. 2008).

In the U.S., climate change is projected to reduce California snow accumulation (Cayan et al. 2008). Barnett and Pierce (2009) find that climate change makes current levels of Colorado River water deliveries unsustainable into the future. Reilly et al. (2003) find that the U.S. irrigated agriculture needs for water are likely to decline approximately 5-10% and 30-40% for

2030 and 2090 due to increased precipitation and shortened crop-growing periods. McCarl (2008) finds that the U.S. Pacific Southwest gains the most under the climate change scenarios studied, while the U.S. Southern region encounters the largest losses.

1.6 *Vulnerability Research Needs*

Although many research studies have focused on the vulnerability of AF land use to climate change there are a number of pressing research needs. First, most studies have focused on developed countries. Thus, there is a need for future research in developing country settings, particularly those with the greatest projected climate change levels. Second, a number of issues related to LPLULM require more thorough research including: (1) increased incidence of extreme events including droughts, floods, and tropical storms; (2) analysis of multiple drivers acting at once including water supply/demand, pests, diseases, fires, sea level rise, and extremes; (3) effects of shifts in risks in terms of, for example, yield variability, pest outbreaks, droughts, and market prices; and (4) analysis of longer term decision making under uncertainty regarding long term phenomena like choice of tree species in the face of climate change uncertainty.

2 **Mitigation and Land Use Change**

LPLULM can alter net fluxes to the atmosphere through increases in sequestration or reductions in emissions (McCarl and Schneider 2000). Sequestration in the ecosystem can be increased through means like afforestation, forest management, grassland expansion, biochar, and reduced tillage intensity. Emissions can be limited through changes in land management and enterprise choice by means such as reducing fertilization, altering livestock feeding and numbers, providing less intensive emitting products like bioenergy, and reducing rice acreage. Here we elaborate discussing forestry and agriculture separately.

2.1 *Forestry Based Mitigation*

Forestry mitigation includes means such as: (1) reduction in emissions from deforestation and degradation ([4]REDD as discussed in Miles and Kapos 2008); (2) increase in forest carbon density through management; (3) afforestation (increasing forested land area); and (4) provision of substitutes for emission intensive products, particularly replacing fossil fuels, but also cement, steel, and other items (McCarl and Schneider 2000; Canadell and Raupach 2008).

Deforestation creates an estimated net emission of 1.5 billion tons carbon per year (Pg C $year^{-1}$) with carbon in standing trees, understory, and soils is released upon harvest and subsequent land use change (Canadell et al. 2007). The IPCC estimates that 17% of emissions come from forestry sources, largely from deforestation (IPCC 2001). Gullison et al. (2007) estimate that by reducing deforestation by 50% by 2050 and maintaining this level until 2010; society can avoid emissions equivalent to 50 billion tons of carbon.

Forest management offers another possibility for mitigation. Carbon density can be increased by thinning, protecting against disturbances (fires, diseases, pests), changing species mix, lengthening rotations, reducing harvest damage, accelerating replanting rates, and lengthening use life of harvested projects (Nabuurs et al. 2007). Afforestation can further reduce the net emissions. For example in China 24 million hectares of new forest were afforested to offset 21% of China's fossil fuel emissions in 2000 (Wang et al. 2007; Candell and Raupach 2008). Murray et al. (2005) show afforestation to be one of the large possible strategies for AF to participate in mitigation.

Bioenergy is commonly discussed as a means to mitigate climate change. In forestry various trees species plus logging residues and forest by products have been proposed for use as feedstocks for bioenergy to replace fossil fuels, and many of these use short rotation trees (Smith et al. 2008; Dias de Oliviera et al. 2005; Cerri et al. 2004). Kaul et al. (2010) show that significant carbon benefits can be obtained in the long run by using land for short rotation energy crops and substituting biomass for fossil fuels.

Finally in terms of forestry there is a dynamic issue involved when temporary/impermanent carbon sequestration and permanent emissions reductions are considered. In particular, the amount of carbon stock increase is limited by an approach to equilibrium. That is; as the tree grows to maturity and is subject to harvest, it reaches a point where carbon quantity reaches an equilibrium state with no further meaningful gains possible under a given management system (Birdsey 1996; Kim, McCarl, and Murray 2008). Furthermore the sequestration can be reversed in the future by changing practices, forest or other forces. In the face of this suppliers often propose to lease carbon sequestration in forests only for a limited time. This reduces the ultimate value of the carbon credits generated (Kim, McCarl, and Murray 2008).

2.2 *Agricultural Based Emissions*

Agriculture is a major emitter of GHGs but also has high potential to mitigate emissions using current technologies many of which can be implemented immediately. Mitigation options in agriculture mainly include: (1) enhancing carbon sequestration; (2) intensification and extensification in agricultural production and livestock management; and (3) substituting low emission products for higher emission products (bioenergy) and reducing emissions (McCarl and Schneider 2000; Schneider and Kumar 2008; Clemens and Ahlgrimm 2001; Smith et al. 2008).

Carbon sequestration enhancement involves increasing carbon stored in the ecosystem (Mendelsohn and Dinar 2009; Richard and Stokes 2004; Cacho et al. 2003). This is accomplished by some combination of increasing carbon inputs to the soil or reducing carbon decomposition. Reductions in tillage intensity embody a reduction in soil disturbance which in turn limits exposure of carbon to the atmosphere and the amount of oxidation, and increases sequestration (Smith et al. 2008; Cerri et al. 2004). Conversion of croplands to grasslands, forests, and perennials also reduces disturbance which leads to increased carbon in roots and in the soil. Global estimates have indicated that conversion of all cropland to conservation tillage could sequester 25 billion tons of carbon over the next 50 years (Pacala and Socolow 2004).

In terms of tillage or land use changes, one should note that the amount of carbon increase is limited by an approach to equilibrium as discussed under forestry above. Namely as the carbon quantity increases so does the decomposition rate and at a point the soil becomes saturated with no further meaningful gains possible under a given management system (West and Six 2007; Kim, McCarl, and Murray 2008). Furthermore that can occur in as few as 10 years (West and Post 2002).

Emissions can be reduced by lowering use of inputs like fertilizer, pesticides, and fossil fuels. In particular, reduced nitrogen fertilizer use limits N_2O emissions and also reduces CO_2 involved with nitrogen fertilizer manufacturing (Schlesinger 1999). Deintensification of tillage also reduces fossil fuel usage as does changes in other energy intensive operations like drying and irrigation (McCarl and Schneider 2000). Improved rice management can reduce methane emissions (Aulakh et al. 2001; Yan, Ohara, and Akimoto 2003, Smith and Cohen 2004; Smith et al. 2008).

Livestock are emissions sources through enteric fermentation and manure related emissions. Managing livestock using improved diets and feed additives aimed at suppressing methanogens is have been proposed to reduce emissions from enteric fermentation (Thornton and Geber 2010; Smith et al. 2007, 2008). Anaerobic digestion of waste from animals reduces methane emissions, while producing biogas (Gerber et al. 2008; Monteny et al. 2006). Lowering the number of animals can also reduce emissions. For example, a change in human diet from beef would likely reduce herd size and total methane emissions along with crop land needs and associated emissions (Schneider and Kumar 2008). Management changes, feed additives and animal breeding that raise animal growth and spread energy costs of maintenance across greater feed intake may reduce the methane output per kilogram of animal product (Smith et al. 2008; Boadi et al. 2004).

Mitigation can be achieved by substituting products that replace fossil fuels. In agriculture, production of bioenergy feedstocks may help achieve this. For example, an estimate of the percentage reduction in net GHG emissions by using corn-based ethanol is 17% relative to using gasoline (McCarl and Reilly 2007; McCarl 2008). However, one must be careful of market effects that may simulate land use change elsewhere as this can increase emissions (Murray, McCarl and Lee 2004; Searchinger et al. 2008; Fargione et al. 2008).

2.3 *Role of Markets and Policies in Climate Change Mitigation*

Cap and trade approaches have been implemented or contemplated as means of increasing mitigation by providing economic incentives. The Kyoto protocol suggests such trading and trading has been implemented in several forms and places such as Europe (Foxon 2010), and California. Theory indicates that market based incentives like carbon taxes or cap and trade are more economically efficient than regulatory approaches in controlling GHGs and are favored by most economists (Metcalf and Reilly 2008; Raymond and Shively 2008).

There are implementation issues concerning the wide range of GHGs and the global nature of climate change. Implementation issues mainly arise from: differential characteristics of additionality, permanence, uncertainty and leakage; transactions costs including measurement and monitoring costs and; and property rights. Each will be discussed below.

2.3.1 *Leakage*

Leakage is a major mitigation concern in that practices may reduce net emissions in one region, but lead to increased emissions elsewhere due to reduced supplies and market price signals. In particular actions that divert production in the mitigating area may well cause increases in production elsewhere with accompanying emissions increases (Murray et al. 2004). A number of authors have cautioned that this could well happen with expansion of biofuels or afforestation as such activities compete with traditional cropland and forest land can result in reduced production increased market prices stimulating other areas to expand production and in turn emissions and leakage (Murray et al. 2004; Searchinger et al. 2008; Fargione et al. 2008; Mendelson and Dinar 2009).

2.3.2 *Additionality*

Ideally policy desires to only pay for "additional" GHG net emission avoidance, not that which would have occurred under business as usual. This raises the issue of baseline establishment where a without policy baseline is compared to a with policy alternative and ideally only the additional contribution above the baseline would be eligible for market trading (Smith et al. 2004). Baseline projection is difficult and also implies that programs must be designed to anticipate future actions and not pay for actions that have not occurred under current circumstances but are projected to occur in the future in the absence of carbon markets. For example consider deforestation: most studies use the assumption that deforestation will continue (IPCC 2007b), but the extent of which is uncertain and there may be some changes in trends that portend less future deforestation (reductions in population growth and an increasingly renewable timber industry) as argued in Sohngen et al. (1999) and Mendelsohn and Dinar (2009). Policy makers may subsidize land holders to hold land in forests, but the question is will that forest have been cut down in the absence of policy and might we be paying for something that never would have happened.

2.3.3 *Permanence*

Permanence is another major issue particularly with carbon sequestration strategies in that carbon credits and offsets are not necessarily stored permanently or sold on a forever basis (Smith et al. 2007; Sands and McCarl 2005; Murray et al. 2004). The problem is that carbon may not be stored permanently (permanence) due to such things as possible future LPLULM changes, limited time of guaranteed storage (leasing), needs for maintenance fees, approach to equilibrium, fires, or extreme events. In turn this can lead to release of sequestered carbon and may merit significant price discounts accounting for non-permanent nature (Kim et al. 2008).

2.3.4 *Uncertainty*

Uncertainty is a complex implementation issue. Agriculture and forestry by their very nature are affected by climate and this means that both emissions reductions and sequestration amounts will be so affected and uncertain from year to year and over time. Uncertainty in estimating the magnitude of GHG emissions and sequestration rate has inhibited implementation of mitigation options in the AF sectors for example causing some to argue against inclusion of AF sequestration in trading schemes. There are also variations and correlations between years, seasons and locations that make estimation of the sequestration volume difficult. Kim et al. (2009) present a discounting procedure for taking this into account in trading while Mooney et al. (2004, 2007) dimension the size of the error and a sampling scheme.

2.3.5 *Transactions Costs*

Conveyance of carbon credits in markets will likely result in cost wedges between buyers and sellers due to transaction costs. Kim (2011) separates such costs into a number of components as discussed below.

2.3.5.1 Assembly Costs

Carbon market purchases would likely need large quantities of offsets (with for example emissions of large power conglomerates in the 100s of millions of tons) compared to what a land user could produce. Typically it would not be economical for an offset purchaser in quest of 100,000 tons to deal with a single land user. An offset of 100,000 tons at an average sequestration rate of 0.25 tons carbon per acre (and average rate from West and Post 2002) would require 400,000 acres. Considering a rough average farm size of 400 acres (the average of U.S. farm was 418 acres in 2007), this offset would involve nearly 1,000 farmers. Thus, there would be a role for brokers or aggregators to assemble groups to create marketable quantities. Costs arise in such a process. Also there will be costs of keeping the group of farmers together and dispersing payments. The crop insurance case is like such a scheme and there transactions costs are about 25 percent for brokers.

2.3.5.2 Measurement, Monitoring and Certification

Market trading will also require measurement and monitoring to establish that offsets are being produced and continue to be produced. This requires the development of low cost measurement and monitoring approaches based on sampling with an integration of field level measurement, computer simulation, and remote sensing data (Mooney et al. 2004, 2007).

There may also be a need for certain bodies to certify offset quantity estimates or the effectiveness of practices and then monitor that the practice continues. For example under the Clean Development Mechanism (CDM) rules were established that indicates the number of offset credits from various practices. Such certification again introduces transactions costs.

2.3.5.3 Shortfalls, Enforcement and Liability

Compliance with carbon contacts will not always happen and an enforcement or liability mechanism may be needed. This may involve the setup and operation of shortfall insurance, an enforcement entity or a liability imposition mechanism. This again will introduce transactions costs.

2.3.5.4 Additional Adoption Cost Incentives

Market participation may involve education and training of agricultural producers on how to alter their practices so that they produce emission offsets most efficiently. Costs may be borne by agencies and this may also involve transactions costs.

2.3.6 *Property Rights*

A final issue involved in market design involves property rights. As argued in McCarl and Schneider (2001), embarking on the road toward enhanced carbon sequestration poses policy questions regarding private property rights. For example, if carbon programs involve land use conversion, there may be a need to insure that these movements are not offset by countervailing movements and this may limit the property rights of a number of land owners.

2.4 *Mitigation Research Needs*

There is wide literature that focuses on mitigation issues but there are still pending unresolved questions. Raymond and Shively (2008) pose the questions: Which methods are best used given transactions costs, regional variations and uncertainties? Which strategies should not be adopted by agriculture? In addition to the above questions we pose the following: How does one design mitigation strategies to address leakage, additionality, uncertainty and permanence all of which have been major obstacles? How do we expand coverage to an international setting to avoid leakage and unnecessary shifts in comparative advantage? What are the tradeoffs and synergies between sustainable development and mitigation? How can one design incentives to practically harness the implementation of AF mitigation?

3 Adaptation and Land Use Change

Climate is expected to change agriculture productivity and shift ecosystems over space (Zilberman et al. 2004; Mendelsohn and Dinar 2009). Adaptation is the least explored economic area to date. Adaptation involves the purposeful manipulation of LPLULM to increase productivity in the face of such shifts.

There are two types of adaptation: (1) actions undertaken by private decision makers in their own best interests (autonomous adaptation); and (2) actions undertaken by the public sector in the name of society (FAO 2007; IPCC 2007b). Prior authors have called the later planned adaptation but we prefer public adaptation as it generally addresses public goods characteristics of under investment in certain adaptation actions.

3.1 *A Conceptual View of Adaptation*

Following Zilberman et al. (2004) and Mendelsohn and Dinar (2009), a theoretical view of adaptation through AF land use change is illustrated in Figure 1. There suppose L depicts the total land available, which is assumed fixed. From right to left, the horizontal axis shows the land allocated to agriculture; while from left to right it shows land used for forest. The two sloped lines are the marginal returns to land allocated to agriculture and forestry. P_L is the land price. L_1 is current land allocated to agriculture. $L - L_1$ is current land allocated to forest. With climate change, the returns to agriculture and forest shift and are represented as dashed lines. The revised land allocation is then L_2, and $L - L_2$.

[Insert Figure 1 here]

This reflects substitution to adapt to climate change induced increases in productivity. The framework shows that users will autonomously adapt to improve their situation in response to climate change (Mendelsohn and Dinar 2009). However public investments may be needed to either make alternative actions available, such as, making crop varieties more heat tolerant, adapting infrastructure (changing the stock of roads, bridges, processing locations etc.), or providing information on heretofore unknown adaptation possibilities.

3.2 *LPLULM Adaptation Options*

There are a number of potential LPLULM adaptation options. These are often variations of existing climate risk management strategies (Howden et al. 2007). They include changes in enterprise choice, crop or livestock mix, moisture management, irrigation,soil, and water conservation, and management of natural areas among others (McCarl 2007).

A number of authors have examined observed or potential adaptations in AF sector. In national studies, Adams et al. (1990), Reilly et al. (2003), and McCarl (2011) examine changes in crop acreage and find northward shifts in crop mixes. Mu, McCarl, and Wein (2012) examine the ways climate change induced land use adaptation between crop and pasture in the U.S., and find that climate change causes shifts in land from crop to pasture and lowering of stocking rates. They estimate that projected climate change will decrease cropland by 6% and increase pasture land. Seo (2010a) finds that, in Africa, a hotter and wetter climate causes a shift from crops toward animals. In addition, Reilly et al. (2003) examine how crops have shifted over time, constructing the geographic centroid of production for corn and soybeans finding that between the early and later 1900s both U.S. corn and soybean production shifted northward by about 120 miles. Attavanich et al. (2011) update this, finding that U.S. corn and soybean production has shifted northward ranging from 100-150 miles between 1950 and 2010.

Studies also have shown that cropping system management adjustments can be used to adapt (Adams, McCarl, and Mearns 2003; Easterling, Chhetri, and Niu 2003; Butt et al. 2005; Travasso et al. 2006; Challinor et al. 2007). Reilly et al. (2002) show considerable potential to varietal adaptation but Schlenker and Roberts (2009) suggest limited historical adaptation of seed varieties or management practices to warmer temperatures. Jin et al. (1994) find that using new rice cultivars and changing planting dates in southern China can substantially adapt to climate change and increase rice yields. Kurukulasuriya and Mendelsohn (2008a; 2008b) find that, in Africa, farmers adapt by shifting toward more heat-tolerant crops as temperatures rises, and that farmers will also shift toward more heat-tolerant and water loving crops. In Greece, Kapetanaki and Rosenzweig (1997) find that changing planting dates and varieties of corn can increase yields by 10%. In Spain, Iglesias, Rosenzweig, and Pereira (2000) find that hybrid seeds and altered sowing dates can allow for double cropping of wheat and corn, thus increasing yields and reducing water use.

Within livestock systems many adaptation options are connected with maintaining the availability of fodder and feed and reducing heat stress from animal housing (Parry et al. 2009; McCarl 2007). McCarl and Reilly (2008) estimate changes in the size of the U.S. livestock herd under 2030 climate scenarios and find increased sheep, cow calf, dairy, turkey, hog and broiler numbers with less feedlot beef animals. In South America, Seo, McCarl, and Mendelsohn (2010) discover that livestock increase with warming but decrease when it becomes too wet. In Africa, Seo and Mendelsohn (2008a) find that a warming climate is harmful to commercial livestock but beneficial to small landowners. Seo et al. (2009) find climate change will likely decrease African dairy cattle but increase sheep and chickens although adaptation measures vary across agro-ecological zones.

Farmers can adapt to climate change by adjusting livestock numbers and species. Mu, McCarl, and Wein (2012) find that adaptation involves reductions in cattle stocking rates under projected climate change. Alternatively, farmers could switch breeds so that livestock can adapt to a warmer temperature and changes in precipitation. Zhang, Hagerman, and McCarl (2011) examine breed choices among cattle in Texas and find that heat-tolerant breeds like Brangus cattle are used as an adaptation strategy in a hot and humid environment.

Climate change is projected to have far-reaching impacts on ecosystems and supported species (Fischlin et al. 2007; Chopra et al. 2005; Lemieux and Scott 2005). Adaptation of managed forests could involve changes in tree species, harvesting patterns, pest control and location of managed woodland (McCarl 2007). Ecological models have predicted that forests will expand globally and become somewhat more productive and also that forest ecosystems would shift pole-ward and to higher elevations (Mendelsohn and Dinar 2009; Ziberman et al. 2004). Howden et al. (2007) argue that the forest sector can plant better adapted tree species and can reduce disturbance losses by harvesting high-risk stocks before they can be destroyed. Mendelsohn and Dinar (2009) indicate that climate change will alter land allocation between forest and wild lands. Sohngen et al. (2010) and Mendelsohn and Dinar (2009) show that forest adaptation is a dynamic process involving staged harvest decisions limiting ability to change large forest stocks quickly.

Parry et al. (2009) argue that complementary relationships between adaptation and mitigation can be exploited as adaptation actions can have positive or negative mitigation effects and vice versa. In forest sector, afforestation of degraded hill slopes is an example of a mitigation action with a positive adaptation affect which would not only sequester carbon, but also control soil erosion (IPCC 2007b).

3.3 *Completeness of Adaptation*

Adaptation has been found to improve welfare so it is therefore very likely that people will autonomously adapt (Butt et al. 2005; Mendelsohn and Dinar 2009). However, most impacts due to climate change are projected to continue to increase for some time (IPCC 2007b). This implies a need for continuing adaptation. Furthermore, some adaptation actions may not be practical due to costs or barriers. Therefore, it is likely some climate change impacts are unavoidable (Parry et al. 2009). The resolution of who is going to pay for adaptation is also a major issue.

3.4 *Adaptation and Development*

Social-economic development and adaptation are intimately linked (Parry et al. 2009). Technological sophistication and progress are important determinants of farm productivity and adaptation potential and also influences adaptation demand. In particular, if technological progress lags behind population growth, there will be increased competition among land uses including those for adaptation and mitigation (McCarl et al. 2012; Mendelsohn and Dinar 2009). Lobell et al. (2008) indicate that South Asia and Southern Africa are regions that, without sufficient adaptation measures, will likely suffer negative impacts on several crops important to large food-insecure human populations.

It is not clear what level of adaptation investment is appropriate because we have limited knowledge of climate change impacts as well as studies on the effectiveness and optimal level of adaptation (Parry et al. 2009). The United Nations Framework Convention on Climate Change (UNFCCC 2007; McCarl 2007) estimated the annual cost of AF adaptation ranged between \$11.3-12.6 billion for 2030 with developing counties needing \$7 billion dollars. With such levels of adaptation, about 80% of the costs of potential impacts might be avoided, but about 20% might not (Parry et al. 2009), and cost of adaptation may rise steeply after 2030 (IPCC 2007b).

3.5 *Adaptation Research Needs*

The choice of optimal adaptation levels is uncertain as information about future potential impacts and adaptation effectiveness is scarce (Parry et al. 2009), and this delays adaptation. Research efforts to narrow this uncertainty and identify robust adaptation are needed.

In addition, incorporating adaptation into integrated assessment models is needed as is inclusion of information on both autonomous and public adaptation cost. While global estimates of adaptation cost have emerged (e.g., UNFCCC 2007; Nelson 2009; Parry et al. 2009 and McCarl 2007 in a LPLULM sense), costs of adapting to varying amounts of climate change need analysis, thus providing a choice range for level of adaptation investment. There is also a need for analysis of the unavoidable impacts, and the resulting damage costs that we need to anticipate (Parry et al. 2009).

Adaptation plans may suffer from a maladaptation or leakage problems (Smith et al. 2000; Sathaye and Andrasko 2007; and Sohngen and Brown 2008), where actions in one region cause lower net adaptation in other locations. Furthermore, the roles of many non-climatic factors, such as changes of commodity prices, population growth, economy development, or farm programs, etc., that interact with climatic stimuli in influencing LPLULM adaptation decision-making are rarely substantively examined (Kandlikar and Risbey 2000; Schneider, Easterling, and Mearns 2000).

4 Interrelationships between Climate Change Effects, Mitigation and Adaptation

The total burden of climate change consists of three elements: (1) the costs of mitigation (reducing the extent of climate change); (2) the costs of adaptation (reducing the impact of change); and (3) the residual impacts that can be neither mitigated nor adapted to (Parry et al. 2009). Mitigation and adaptation both avoid climate change but are fundamentally different in timing with adaptation an immediate avoidance and mitigation a long term reduction in extent. Some studies have attempted to understand the interplay among impacts, adaptation, and mitigation. Yet, there are still many unanswered questions.

Bosello et al. (2009) indicate that welfare is greater when adaptation and mitigation are implemented jointly and both contribute to better control of climate damages. Estimations considering only single mitigation or adaptation actions are thereby likely to yield biased results.

The major climate change policy question is: *"What combination of emissions reduction and adaptation is appropriate in offsetting the impacts of climate change?"* In addressing this question one must realize that adaptation and mitigation can be both complementary and substitutes. The IPCC (2007b) reviews four major types of interrelationships between adaptation and mitigation as: (1) adaptation actions that have consequences for mitigation; (2) mitigation actions that have consequences for adaptation; (3) decisions that include trade-offs or synergies between adaptation and mitigation; and (4) processes that have consequences for both adaptation and mitigation.

Important implications arise from the interdependence between mitigation and adaptation. Lecocq and Shalizi (2007) point out the need for mitigation and adaptation policies to be analyzed and implemented jointly, not separately. Mata and Budhooram (2007) state that in a hypothetical world where all net costs are borne by a single global entity that choices would probably be driven by total cost minimization, rather than by aversion of "dangerous anthropogenic interference with the climate system." However, the complexities of costs and benefits and their widespread distribution make these assumptions implausible (Mata and Budhooram 2007). Rather society is saddled with the burden of optimally allocating resources subject to budget constraints and uncertainties. In addition, action should incorporate learning and irreversibility.

Some studies have tried to assess the optimal policy balance of mitigation and adaptation using cost-benefit frameworks based on integrated assessment models (IAMs) (IPCC 2007b). Temporal investment allocation results obtained using IAMs in de Bruin et al. (2009) and in Wang and McCarl (2012) showing that both adaptation and mitigation are simultaneously employed with adaptation prevailing initially then mitigation investment taking over in the long run as the damages from GHG emissions increase.

4.1 *Research Needs*

Most studies on climate change responses focus on single aspects of the adaptation-mitigation nexus, without considering their interplay. Hence, there are substantial research needs to address the optimal portfolio of adaptation and mitigation along with practical inquiries into the extent to which climate change vulnerability can be addressed. The IPCC (2007c) indicates that the relationship between development paths and adaptation-mitigation interrelationships requires further research. This is particularly important in developing-country settings.

5 Concluding Comments

LPLULM decision making is certainly affected by climate change and climate policy. Actions can certainly address adaptation or mitigation and there certainly will be climate change induced damages that are not mitigated or adapted to. In the future, we think substantial research will need to be devoted determine how land use decisions can facilitate adaptation and mitigation as well as the degree of vulnerability under alternative levels of action. We only hope that this review will inform researchers as to past efforts and potential productive future ones.

Acknowledgments

We thank the editors for comments. Seniority of authorship is shared among authors.

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[1] All plants must convert sunlight to energy by "fixing" carbon as part of photosynthesis. C3 crops are crops in which the CO_2 is first fixed into a compound containing three carbon atoms, while C4 crops are crops in which the CO_2 is first fixed into a compound containing four carbon atoms before entering the Cavin cycle of photosynthesis. In brief, C4 crops are better adapted than C3 crops in an environment with high daytime temperatures, intense sunlight, drought, or nitrogen or CO_2 limitation. Examples of C3 crops include soybeans, wheat, and cotton, while examples of C4 crops consist of corn and sorghum.

[2] In these experiments, air enriched with CO_2 is blown into the rings where crops are grown in the real field (not in the chamber). Then, a computer-control system uses the wind speed and CO_2 concentration information to adjust the CO_2 flow rates to maintain the desired CO_2 concentration. Finally, crop yield in the elevated CO_2 rings are compared to that in the control rings with non-elevated CO_2 environment.

[3] The Leymus chinensis meadow steppe is widely distributed in the east of the Eurasian region, and more than half of the steppe is located in China, especially in the northeastern China Plain and Inner Mongolian Plateau (Wang et al. 2007).

[4]The Reducing Emissions from Deforestation and Forest Degradation (REDD) is an initiative process to consider policy that reduces emission from deforestation and forest degradation initiated at the Eleventh Session of Conference Parties (COP 11) to the United Nations Framework Convention on Climate Change (UNFCC).