THE IMPACT OF BIOFUEL AND GREENHOUSE GAS POLICIES ON LAND MANAGEMENT, AGRICULTURAL PRODUCTION, AND ENVIRONMENTAL QUALITY

A Dissertation

by

JUSTIN SCOTT BAKER

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

May 2011

Major Subject: Agricultural Economics

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Approved by:

Chair of Committee, Bruce A. McCarl
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ABSTRACT

The Impact of Biofuel and Greenhouse Gas Policies on Land Management, Agricultural Production, and Environmental Quality. (May 2011)

Justin Scott Baker, B.S., Texas Tech University;
M.S., Texas Tech University
Chair of Advisory Committee: Dr. Bruce A. McCarl

This dissertation explores the combined effects of biofuel mandates and terrestrial greenhouse gas GHG mitigation incentives on land use, management intensity, commodity markets, welfare, and the full costs of GHG abatement through conceptual and empirical modeling. First, a simple conceptual model of land allocation and management is used to illustrate how bioenergy policies and GHG mitigation incentives could influence market prices, shift the land supply between alternative uses, alter management intensity, and boost equilibrium commodity prices.

Later, a major empirical modeling section uses the U.S. Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG) to simulate land use and production responses to various biofuel and climate policy scenarios. Simulations are performed to assess the effects of imposing biofuel mandates in the U.S. consistent with the Renewable Fuels Standard of the Energy Independence and Security Act of 2007 (RFS2). Simulations are run for several climate mitigation policy scenarios (with varying GHG (CO_2) prices and eligibility restrictions for GHG offset activities) with and without conservation land recultivation.

Important simulation outputs include time trajectories for land use, GHG emissions and mitigation, commodity prices, production, net exports, sectoral economic welfare, and shifts in management practices and intensity. Direct and indirect consequences of RFS2 and carbon policy are highlighted, including regional production shifts that can influence water consumption and nutrient use in regions already plagued by water scarcity and quality concerns. Results suggest that the potential magnitude of climate mitigation on commodity markets and exports is substantially higher than under biofuel expansion in isolation, raising concerns of international leakage and stimulating the “Food vs. Carbon” debate.

Finally, a reduced-form dynamic emissions trading model of the U.S. economy is developed using simulation output from FASOMGHG and the National Energy Modeling System to test the effect of biofuel mandate expansion and domestic offset eligibility restrictions on total economy-wide GHG abatement costs. Findings are that while the RFS2 raises the marginal costs of offsets, full abatement costs depend on a number of policy factors. GHG payment incentives for forest management and non-CO_2 agricultural offsets can increase full abatement costs by more than 20%.

DEDICATION

I dedicate this manuscript to my family, who always pushed me work hard, be original, and to continue learning, and to Nicole, who has been loving and supportive throughout this process.

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For their patience and guidance throughout my dissertation completion process, I am extremely grateful to Dr. Bruce McCarl (Texas A&M), Dr. Brian Murray (Duke

Univ.), and Dr. Robert Jackson (Duke Univ.). Dr. McCarl helped me to stay humble and pushed me to improve my programming and operations research skills, keeping me focused and grounded on dissertation topics, and for provided general research and career advice. Dr. Murray encouraged me to think about the welfare implications of my research and its relevance to the broader policy community, helped my research gain exposure in public forums and academic journals, and in general pushed me to be a better applied economist. Dr. Jackson welcomed me into his lab and provided me with unique collaborative opportunities with natural and physical scientists, while also helping me improve as a scientist and an academic writer and through comments on my work and lab meeting exercises.

Finally, I am grateful to all of the professors at Texas A&M who helped me develop a diverse and unique skill-set as an applied economist, and to Vicki Heard, for all of her help editing. I also acknowledge support and useful comments from other members of the FASOMGHG model development team (including Greg Latta, Dr. Eric White, and Dr. Darius Adams (Oregon State Univsersity), Dr. Ralph Alig (US Forest Service), Dr. Robert Beach (Research Triangle Institute) Dr. Steve Rose (Electric Power Research Institute), and Dr. Sara Bushey-Ohrel and Dr. Jared Creason (US Environmental Protection Agency).

NOMENCLATURE

$/tCO2e	CO2 price per ton CO2 equivalent
$15/tCO2e	Simulation scenario with a $15/tCO2e price and full offset eligibility
$15/tCO2e Full Offsets	Simulation scenario with a $15/tCO2e price and full offset eligibility
$15/tCO2e Lim Offsets	Simulation scenario with a $15/tCO2e price and limited offset eligibility
$15/tCO2e No Offsets	Simulation scenario with a $15/tCO2e price and no offset eligibility
$15/tCO2e with CRP	Simulation scenario with a $15/tCO2e price, full offset eligibility, and CRP reversion
$30/tCO2e	Simulation scenario with a $30/tCO2e price and full offset eligibility
$30/tCO2e Full Offsets	Simulation scenario with a $30/tCO2e price and full offset eligibility

$30/tCO2e Lim Offsets	Simulation scenario with a $30/tCO2e price and limited offset eligibility
$30/tCO2e No Offsets	Simulation scenario with a $30/tCO2e price and no offset eligibility
$30/tCO2e with CRP	Simulation scenario with a $30/tCO2e price, full offset eligibility, and CRP reversion
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$50/tCO2e No Offsets	Simulation scenario with a $50/tCO2e price and no offset eligibility
$50/tCO2e with CRP	Simulation scenario with a $50/tCO2e price, full offset eligibility, and CRP reversion
50% Adjusted Emissions	DUET simulation scenario where transportation emissions are adjusted by 50%

	of the expected biofuel replacement rate
Adjusted Emissions	DUET simulation scenario where transportation emissions are adjusted by the expected biofuel replacement rate
AEO 2009 Baseline	FASOMGHG baseline using AEO 2009 energy prices
Afforestation	CO2 flux from afforestation
Agriculture CH4	Methane emissions from agriculture
Baseline Emissions	DUET Baseline, unadjusted emissions scenario
Bioelectricity	CO2 offset from bioelectricity feedstock production
Commercial	U.S. commercial sector
Corn Belt	FASOMGHG region encompassing Illinois, Indiana, Iowa, Missouri, and Ohio
Crop Mgt. Fossil Fuels	CO2 emissions from agricultural fossil fuel use
Crop Mgt. N2O	N2O emissions from agricultural activities (converted to CO2e)

Crop Soil C	Soil carbon flux from cropland and pasture
Cropland	Land used for crop production
Cropland Pasture	Land used for grazing, transferrable to crops
CRP	Land in the Conservation Reserve Program
DUET	Duke University Emissions Trading Model
FASOMGHG	US Forest and Agricultural Sector Model with Greenhouse Gases
Forest	Land used for forestry
Forest Management	CO2 emissions from forest management practices
Forest Products	C stored in final wood products
Full Offset Eligibility with the RFS2	DUET mitigation scenarios with the RFS2
GHG	Greenhouse Gas
Grazed Forest (Private)	Privately held forestland used for grazing
Grazed Forest (Public)	Publicly held forestland used for grazing
Great Plains	FASOMGHG region encompassing Kansas,

	Nebraska, North Dakota, and South Dakota
Industrial	U.S. industrial sector
K	Potassium used in agriculture
K-B	Provisions consistent with the Kerry-Boxer bill
Lake States	FASOMGHG region encompassing Michigan, Minnesota, and Wisconsin
Lim Offset Eligibility with the RFS2	DUET mitigation scenarios with limited eligibility and the RFS2
Liquid Biofuels	CO2 emissions offset by biofuel production
MAC	Marginal abatement costs
N	Nitrogen fertilizer used
N Loss Subsurface	Nitrogen subsurface seepage from agricultural activities
NO3 Loss Runoff	Nitrate leeching from agricultural activities
Northeast	FASOMGHG region encompassing Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey,

	New York, Pennsylvania, Rhode Island, Vermont, and West Virginia
P	Phosphorous used in agriculture
Pac. Northwest	FASOMGHG region encompassing Oregon and Washington
Pac. Southwest	FASOMGHG region encompassing California
Pasture	All grazinglands used in FASOMGHG
Pasture N2O	N2O emissions from activities on pasture
PercolationNLoss	Nitrogen pollution through percolation
PLosswithRunoff	Phosphorous pollution from runoff
PLosswithSediment	Phosphorous pollution through sedimentation
Rangeland	Rangeland used for grazing in FASOMGHG
Refining	U.S. industrial refining sector
Residential	U.S. residential sector
RFS2	FASOMGHG simulation scenario where RFS2 biofuel mandates are imposed

RFS2 with CRP	FASOMGHG simulation scenario with the RFS2 and CRP reversion allowed
Rocky Mts.	FASOMGHG region encompassing Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming
South Central	FASOMGHG region encompassing Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Tennessee, and Eastern Texas
Southeast	FASOMGHG region encompassing Virginia, North Carolina, South Carolina, Georgia, and Florida
Southwest	FASOMGHG region encompassing Oklahoma and the rest of Texas
Transportation	U.S. transportation sector
W-M	Provisions consistent with the Waxman-Markey Bill

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CHAPTER I

INTRODUCTION

Over the last several years the global agricultural and forestry (AF) sectors have experienced a shift in economic conditions categorized by increased commodity price and energy input cost volatility, growing populations with changing food preferences, and a rapidly developing market for bioenergy. Efforts to reduce net anthropogenic greenhouse gas (GHG) emissions could provide new incentives for alternative AF activities.

The ties between emerging policy efforts and AF production decisions create strong linkages between climate change mitigation, energy, and natural resource usage. The U.S. Energy Independence and Security Act of 2007 established a Renewable Fuels Standard (commonly called RFS2) that, if followed, will drastically increase the production of biofuels from AF feedstocks, calling for a total of 30 billion gallons a year to be produced and used by 2022. Biofuels (and more broadly, bioenergy) can provide a reduced carbon alternative to fossil fuels that contribute to energy security goals. However, promoting bioenergy production can induce AF land use change and pressure scarce water resource supplies.

Meanwhile, comprehensive climate policy such as an economy-wide cap-and-trade or carbon tax will reinforce the demand for low carbon fossil fuel substitutes, and could provide incentives for AF producers to adopt management practices that provide

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

GHG emissions offsets (where offsets are defined as net GHG emissions reductions in non-capped sectors of the economy that can be purchased by capped entities for compliance purposes under a GHG cap-and-trade scheme). AF GHG mitigation options can have opposite directional effects on land use change when compared to biofuel mandates by internalizing the value of carbon stored in terrestrial sources, and can lead to local environmental co-benefits such as water quality improvements by reducing GHG emitting agricultural inputs like nitrogen (N) fertilizer (Greenhalgh and Sauer, 2003, Pattanayak et al., 2005).

The market and environmental consequences of combining biofuel mandates and terrestrial GHG mitigation incentives are not well understood at this time. However, since GHG offsets from AF sources are considered a low-cost source of GHG abatement (EPA, 2009; EPA, 2010b), it is important to consider how biofuel mandates that are highly consumptive of AF resources might impact the costs of supplying GHG offsets to capped sectors.

There is a strong need for policy analysis that considers the interrelationships between climate and energy policy, land conservation, and environmental quality. There is a prominent literature on the potential market inefficiencies and environmental consequences of biofuel mandates and climate mitigation efforts, reinforcing the need for policy design to minimize these impacts (Cui et al., 2010; de Gorter and Just, 2009, 2010; Fargione et al., 2008, McCarl and Gan, 2007; Moschini et al. 2009; Murray et al., 2004; Searchinger et al., 2008; Pattanayak et al., 2005).

The task facing AF landowners and policy makers is to use land and water resources effectively to provide sufficient food, fiber, energy, and GHG emissions offsets. It appears inevitable that competition for such resources will continue to grow given these competing demands. In addition, while the AF sectors could play a prominent role in economy-wide GHG abatement, few studies have considered the implications of biofuel mandates on the full costs of GHG abatement and vice versa. This dissertation uses conceptual and empirical modeling techniques to analyze economic and environmental trade-offs between AF bioenergy production and GHG mitigation.

1.1 Research Objectives and Procedures

The objective of this dissertation is to improve the understanding of how combined biofuel and climate mitigation policies might affect the domestic AF sectors. This will involve consideration of implications for land use, production patterns, management intensity, water usage, total production, prices and exports, along with consumer and producer welfare. To improve such understanding, several procedures are undertaken:

1. A conceptual model is developed of biofuel policies and terrestrial GHG mitigation incentives and is used to analytically examine the potential interactions, synergies, and trade-offs of such policies,
2. The policies are formally modeled in an empirical framework that allows examination of economic and environmental impacts, plus associated trade-offs, and

3. Additional modeling is used to assess the implications of biofuel mandates and GHG offset restrictions on the economy-wide costs of GHG abatement.

1.2 Overview of Dissertation

The dissertation is organized into nine chapters that will address the above objectives:

- Chapter II focuses on the current policy landscape by discussing major provisions of the EISA RFS2 and recent U.S. federal climate policy proposals;
- Chapter III presents a focused literature review examining bioenergy and AF carbon offset activities plus their interactions and impacts on AF sector performance and commodity prices, land use decisions, water resources, and net GHG emissions.
- Chapter IV presents an analytical model of agricultural land management decisions and explores the consequences of policies.
- Chapter V lays out an empirical modeling framework for the policy simulation.
- Chapter VI uses the empirical framework to examine biofuel policy.
- Chapter VII uses the empirical framework to examine GHG mitigation policy.
- Chapter VIII unifies the results of chapters VI and VII in an analysis of the impact of biofuel mandates and domestic (U.S.) offset eligibility, and
- Chapter IX provides general conclusions for this dissertation and directions for future research efforts.

CHAPTER II

RESOURCE TRENDS AND POLICY BACKGROUND

This chapter provides a general policy and institutional background for this research by discussing current trends in the AF sectors and drivers of land use competition and water use, and through a brief discussion of emerging or possible polices toward bioenergy and GHG mitigation.

2.1 Trends in the AF Sectors and Land Resource Use

Land resources will be pressured by the growing demand for food and fiber. World population growth is projected to grow beyond 9 billion by 2050and global food demand could grow 59-99% from 2000 levels by 2050 (Southgate et al., 2007, Southgate 2009). In addition, income-driven changing diet preferences in rapidly developing economies such as Brazil, India, and China, have expanded global meat demand in recent years. Projections indicate that meat demand could more than double in India and China by 2020 (Delgado et al., 1999). Recent literature has shown that growth in the livestock industry has contributed to land use change and deforestation in many regions of the world (Trostle, 2008). Continued population growth and the diversion of grains previously used for feed or human consumption could exacerbate this trend of deforestation for livestock grazing[1]. Technological growth and improvements in yield

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[1] For a comprehensive review of expected global livestock production trends, see Dickson-Hoyle, and Reenberg, 2009.

productivity could alleviate deforestation and keep commodity prices in line with historical trends, but ultimately natural resource use will be affected by growing demands for food.

Urban development pressures will also drive competition for scarce land resources. In the U.S., total cropland acreage (cultivated and non-cultivated) dropped from greater than 420 million acres in 1982 to approximately 368 million acres in 2003, a net decrease of 12% (Natural Resource Inventory, 2003), with a great deal of that land converting to alternative uses. Non-federal grazing lands also dropped steeply, falling from 611 million acres to 576 million acres over the same time frame (Natural Resource Inventory, 2003). This decline is expected to continue as rural farm and grazing lands are converted to developed uses. In the U.S., it is estimated that in 2020, an annual average of 348,000 acres a year of dedicated cropland will be developed for residential use. An average of 240,000 and 108,000 acres of pasture and rangeland could accompany this shift to development as well (Alig et al., 2010). In the U.S., deforestation for residential and commercial development is expected to occur at 1.4 million acres per year (Alig and Butler, 2010). In general, these development trends indicate that the total stock of land available for productive AF uses in the U.S. will decline over time under business as usual conditions, increasing competition for land resources further.

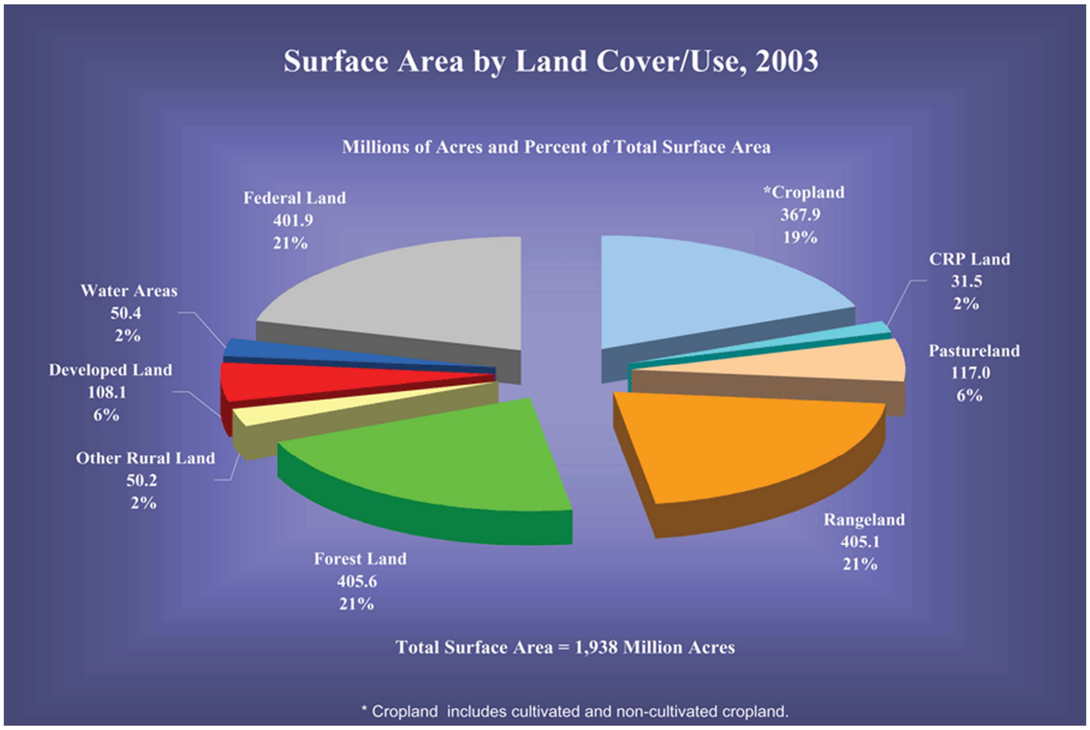
2.1.1 Current Resource Pressures

Biofuel mandates and carbon reduction policies could require a significant area of U.S. agricultural lands. As a relevant example, Table 1 displays the direct land use requirements for two biofuels (corn ethanol and soybean biodiesel), comparing crop yields (using 2009 NASS state averages) in two important agricultural states with significantly different yield productivity, Texas and Iowa. These data show that at current yield levels, massive amounts of land will be required to satisfy the RFS2 mandatory levels of soybean biodiesel (1 BGY) and corn ethanol (15 BGY). Taking the midpoint of each fuel type, results show that approximately 61 million acres would need to be dedicated to corn and soybean production purely for biofuel feedstock production, representing 15-20% of the current cropland base in production. The implication of this table is that even some of the most productive lands in the world require a large allocation of land to produce a significant amount of liquid transportation fuels (though a billion gallons of gasoline equivalent is less than 0.5% of the current U.S. transportation fuel consumption). As land productivity is not homogeneous, the share of land allocated to bioenergy feedstocks will vary significantly by region.

Table 1: Land Requirements for Corn Ethanol and Soybean Biodiesel under Alternative Yields

	Using TEXAS yields	**Using IOWA yields**	**Using TEXAS yields**	**Using IOWA yields**
	Corn Ethanol	**Corn Ethanol**	**Soybean Biodiesel**	**Soybean Biodiesel**
Crop Yield (Bushel/Acre)	120	200	25	48
Fuel Yield (Gallons/Bushel)	2.77	2.77	1.31	1.31
Fuel Land Use (Gallons/Acre)	332	554	32.8	63
Acres per 1 Billion Gallons	3.01Million	1.81 Million	30.48 Million	20.83 Million
Acres per 15 Billion Gallons	45.12 Million	27.08 Million	-----------------	-------------------

Where will this land come from? As of 2003, the total stock of non-federal land in the U.S. amounted to approximately 1.4 billion acres. Figure 1 displays the distribution of nonfederal land by type from the 2003 Natural Resource Inventory (NRI)[2]. Generally there are about 400 million acres of non-federal forest lands, between 300 and 400 million acres of dedicated cropland, with remaining lands falling into various rangeland and pasture categories, though the productive land base has decreased over time due primarily to development pressures[3].


Surface Area by Land Cover/Use, 2003

Millions of Acres and Percent of Total Surface Area

Total Surface Area = 1,938 Million Acres

* Cropland includes cultivated and non-cultivated cropland.

Figure 1: NRI land use distribution for the U.S. (source: NRI, 2003)

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[2] Non-federal lands include those that are privately owned, state or locally owned lands, and tribal and trust lands.

[3] Differences in land use data and our empirical depiction of U.S. land use are discussed in a subsequent chapter.

Water resources will also be pressured by policies that affect land management decisions. In the absence of U.S. biofuel mandates, it was estimated that global water use for irrigation could increase by 17% by 2025 over 2000 levels to satisfy growing agricultural demands (de Fraiture et al., 2001). Arid and semi-arid countries will be forced to rely more heavily on imported food products, as irrigation supplies could be inadequate to support increased levels of production, even without biofuel expansion.

In addition to managing dwindling supplies, water quality degradation from agricultural production activities is pervasive in many parts of the world. Increased use of nitrogen (N) fertilizer or other agricultural chemicals stimulated by bioenergy development or land use intensification presents serious environmental concerns, as potentially harmful N constituents can enter the atmospheric and aquatic environment in many forms. In some regions nitrogen runoff from agriculture is the predominant source of water pollution, and the problem is worsening (Aneja et al., 2008, S. Greenhalgh and A. Sauer, 2003). In the United States, Gulf of Mexico hypoxia, caused primarily by upstream agricultural runoff, threatens aquatic ecosystems and critical food supplies (Robertson andVitousek, 2009). Globally, this problem is acute in a number of regions; more than 400 hypoxic zones have been identified, and hypoxic activity has increased exponentially since the 1960s (Robert J. Diaz and Rutger Rosenberg, 2008). Nitrate contamination in surface- and groundwater systems poses a serious and diverse set of health risks, and is another environmental cost of agricultural N use (Alan R. Townsend et al., 2003). Thus, higher water use stimulated by bioenergy expansion is not the only concern; higher levels of agricultural input use will degrade water quality.

2.2 Bioenergy Expansion Policies

Both liquid biofuels and bioelectricity from AF biomass will likely play a key role in our energy future, though several pervasive issues remain. First, I describe some basic definitions of bioenergy and current socioeconomic concerns that have been raised. Liquid biofuels typically fall into three main categories:

1. *Grain or Sugar Based Ethanol*- Typically derived from a wet or dry mill fermentation process where the actual grain, or food-stuff is used to process the fuel—competes with food and fiber production
2. *Cellulosic Ethanol*- Ethanol is produced from lignocellulosic materials available in all forms of AF biomass, but requires a more involved, much higher cost conversion process than grain ethanol
3. *Biodiesel*- Diesel fuel processed out of corn and soybean oil, animal fats, or a number of industrial and municipal wastes (including yellow grease).

Bioelectricity is the replacement of coal-fired electricity using AF biomass. Bioenergy expansion policies have been designed in part to increase energy independence and reduce GHG emissions from fossil fuel combustion. In general, the term bioenergy can be broken down into two main categories: 1) biofuels, and 2) bioelectricity. Policy efforts are currently in place or under debate that will drive expansion of both. As a relatively high-cost substitute for fossil fuels, biofuel processors and distributors have relied on a number of policy mechanisms that boost the economic viability of their fuels, including production tax credits, blending requirements with gasoline and motor diesel, and CAFE standards (e.g., lower CAFE standards for flex-fuel vehicles that use a higher biofuel mix, or "flex fuels").

Biofuel mandates currently represent the most effective measure for increasing production. Mandates can be imposed via blending requirements, low carbon fuel standards (LCFS), or production quotas. Blending requirements mandate that a consistent volumetric portion of motor gasoline be blended with the biofuel ethanol. Blending ethanol in gasoline stimulates the demand for ethanol and has the environmental advantage of replacing another gasoline additive, Methyl Tertiary Butyl Ether (MTBE), which can pollute surface and groundwater systems. LCFS are difficult to implement and enforce, as the overall carbon content of biofuels can be difficult to quantify.

While many policies and institutions have pushed for biofuel expansion, no greater incentive exists than the national Renewable Fuels Standard established under the Energy Independence and Security Act of 2007; henceforth referred to as RFS2. The RFS2 includes stringent production mandates on multiple types of biofuels. Mandates for total renewable biofuels increase out to 2022 then the policy requires a minimum of 30 billion gallon per year (BGY) of biofuels be produced domestically from AF products for consumption in the transportation sector. EISA-RFS2 follows the original Renewable Fuels Standard of the Energy Policy Act of 2005 (RFS1), which imposed mandatory production levels of ethanol, biodiesel, and cellulosic ethanol, while extending tax incentives for those fuels. However, these production mandates were miniscule in comparison to those imposed by the RFS2 (EPA, 2010a).

EISA-RFS2 dictates different volumes of biofuels by type (grain/starch ethanol, cellulosic ethanol, and biodiesel), from a variety of AF feedstocks, establishes specific mandates for the use of "advanced" biofuels (e.g., cellulosic ethanol), and adds GHG emission reduction thresholds (or the full life cycle GHG emissions of a unit of biofuel derived energy relative to an energy equivalent amount of fossil energy) for several classes of biofuels. A maximum of 15 BGY of corn ethanol will be eligible for compliance under the RFS2, with the remaining coming from AF by-products and residues. The latter, denoted "advanced biofuels" are anticipated to come primarily from cellulosic ethanol processed from a variety of AF biomass sources.

Already, the RFS2 and high energy prices are significantly affecting AF development and production decisions (and hence land use), commodity prices, and net farm income in the U.S. and elsewhere (Biomass Research and Development Board BRDB, 2009). Bioelectricity is another form of renewable energy from AF feedstocks being driven by current policy efforts. Recent climate and energy legislation has called for a Renewable Electricity or Renewable Portfolio Standards, which will mandate that a proportion of U.S. electricity generation come from renewable resources such as forest biomass, agricultural residues, or municipal and industrial wastes. RPS related policies are also supported by recent climate mitigation incentives (H.R. 2454 and S. 1733). As the next chapter will discuss, biofuel expansion has the potential to raise food prices and impose significant natural resource costs. Continued policy-driven expansion will continue to raise important questions regarding the social and environmental trade-offs of cultivated biofuels.

2.3 GHG Mitigation Policy

Multiple policies to reduce U.S. GHG emissions are either in place, being developed, or being debated. Thirty-four states have enacted GHG emissions reduction efforts, including the Western Climate Initiative, the Regional Greenhouse Gas Initiative in the northeast, and the Midwest Greenhouse Gas Reduction Accord (Baker et al., 2010). A comprehensive federal cap-and-trade initiative was approved in June 2009 by the U.S. House of Representatives and is being considered in the U.S. Senate. The House bill is known formally as HR 2454 “American Clean Energy and Security Act” (ACES) and informally as the Waxman-Markey climate bill after its chief sponsors. Under ACES, the agricultural sector is excluded from a GHG emissions cap, but would be primarily affected through changes in energy prices, stimulated bioenergy demand, and the creation of a market for the sale of GHG emission offsets. Offsets are GHG mitigation activities in uncapped sectors (such as agriculture) that can be purchased by capped entities to offset emissions. As mentioned previously, HR 2454 and other recent climate mitigation bills have also proposed establishing a Renewable Portfolio Energy Standard (RPS) that would mandate a certain percentage of U.S. electrical power from renewable sources.

Climate legislation, if adopted, will likely affect the AF sectors in three primary ways: (1) by directly raising the costs of fossil-fuel intensive inputs and nitrogen fertilizer, through allowing GHG offsets from uncapped sectors such as AF, and by raising the price of fossil energy and indirectly stimulating the demand for biofuels and biomass for bioelectricity generation.

H.R. 254 Waxman-Markey, 2009, and similar bills such as S 2191 Lieberman-Warner, 2008 have all included significant provision of domestic and international offsets. Offsets are activities outside of capped economic sectors (or entities) that can either reduce emissions or increase the carbon uptake of terrestrial ecosystems. Capped entities might purchase offsets if the market price for offsets falls below the costs of abating the same amount of emissions.

Through domestic offset provisions, AF landowners could receive incentives for an array of activities, including:

- Divert agricultural land to forests and grasslands,
- Reduce use of histosols,
- Modify existing forest management to increase carbon sequestration,
- Reduce methane emissions from livestock, manure handling, and rice cultivation,
- Sequester carbon through cropland tillage change or set-asides, and
- Reduce nitrous oxide emissions from fertilizer use and manure/livestock operations.

2.4 Conjunctive Bioenergy Expansion and GHG Mitigation

It is unclear how bioenergy expansion efforts and GHG mitigation policy efforts might perform if enacted independently Biofuel mandates under the RFS2 or other regional efforts (such as the California Low Carbon Fuels Standard) have GHG reduction thresholds that certain fuels must meet to be eligible. For the RFS2 legislation, conventional ethanol and cellulosic must meet GHG reduction thresholds of 20% and 60% relative to energy equivalent sources of fossil energy. Criteria are in place for measuring the full life-cycle GHG reductions of such biofuels, including discounts for indirect LUC emissions.

Recent analysis argues indirect emissions (that is, emissions that fall outside of the production system boundaries—such as land use change emissions in response to a commodity price surge stimulated by biofuels) are prevalent in fossil fuels, not just biofuels, and that a more comprehensive GHG accounting methodology that compares final “system-wide” GHG responses to cap-and-trade and biofuel consumption is an improvement over life-cycle analysis that has systematic bounds and is thus unable to truly measure all emissions (or emissions reductions) associated with renewable energy consumption (DeCicco, 2009). The argument in Decicco, 2009 is that the cap itself should dictate the role of alternative energy supplies in the transportation sector, and that allowances (or allowable GHG emissions under an economy-wide GHG cap) should cover only the carbon content of the final fuel use on an energy equivalent basis.

This dissertation addresses a gap in the research on synergies and conflicts between renewable energy mandates and climate mitigation incentives. Renewable energy mandates are the most effective means for ensuring that biofuels play a principal role in our energy portfolio, but are inefficient at promoting GHG reductions because of the potential for leakage (both in terms of land use change emissions, and the rebound effect of higher fossil energy consumption). Additionally, mandates impose certainty into the market place by dictating fuel sources. To avoid indirect market consequences of biofuel expansion, Decicco (2009) proposes a “Land Protection Fund” by which international forest offset credits would be purchased in an effort to buy-back those emissions that occurred as an indirect consequence of U.S. biofuel expansion.

However, RFS2 mandates create two problems for economy-wide GHG mitigation goals. First, mandates might be more efficient than other distortionary biofuel expansion incentives, but they can induce higher levels of fuel consumption and potentially increase emissions in the transportation sector (de Gorter and Just, 2009). This occurs because mandates can lower the demand for fossil energy in market equilibrium initially, leading to a lower market price. At this lower price, more transportation fuels will be consumed, leading to new fuel market equilibriums and higher net emissions. Obviously, such a shift would be inconsistent with mitigation efforts, and could increase the costs of a cap-and-trade scheme by placing more pressure on the rest of the system to achieve reductions. Also, the RFS2 would require valuable land resources that could otherwise be used for carbon offsets. This raises the costs of domestic (and international) offsets and hence total compliance costs under cap-and-trade. The extent to which biofuel policies affect mitigation costs in AF is discussed in later chapters.

CHAPTER III

REVIEW OF THE LITERATURE

This chapter discusses how unintended market impacts of bioenergy and AF GHG mitigation activities together could devalue the benefits of the each policy mechanism. This chapter begins with a discussion of global AF's role in a low carbon economy, reviews recent literature regarding the economics of bioenergy and terrestrial GHG mitigation, then provides a discussion of the emerging relationship between AF commodity and energy markets. This growing market interdependency is particularly important for this dissertation; policies that effectively raise the price of fossil energy can affect production decisions and the economic viability of bioenergy. Understanding this correlation helps evaluate the manner in which national policies can affect production and land use decisions at local and aggregate scales.

Then, this review continues by highlighting important social trade-offs to consider in the pursuit of terrestrial GHG mitigation and bioenergy, including "Food vs. Fuel"—or potentially "Food vs. Carbon", socioeconomic equity concerns, and the potential implications of such measures on land and water resources. The latter is the primary empirical focus of the remainder of this dissertation, but results herein can provide insight into potential commodity market shifts that help inform the Food vs. Fuel vs. Carbon debate.

3.1 Greenhouse Gas Mitigation in Agriculture and Forestry

Agriculture currently accounts for 7-8 percent of GHG emissions in the United States and 10- 12 percent globally (Intergovernmental Panel on Climate Change, 2007) so the sector emissions can play an important role in global climate policy. More importantly, altering AF practices can boost the terrestrial carbon stock and provide a significant source of GHG offsets to entities seeking to reduce their individual carbon footprint. In addition to lowering GHG emissions, mitigation activities in agriculture can generally enhance ecosystem services on agricultural soils. Previous studies of U.S. and global AF GHG mitigation potential have shown that AF offset activities and bioenergy can play a vital role in overall GHG emissions reduction (McCarl and Schneider, 2001, Murray et al., 2005, Schneider and Kumar, 2008, Pete Smith et al., 2008).

Globally, deforestation is responsible for 15-20% of total GHG emissions, representing a higher proportion of net emissions than the global transportation sector (IPCC, 2007). Tropical deforestation represents overwhelming majority of emissions in Brazil and Indonesia, which are the world's third and fourth highest emitters (Olander et al., 2009, van der Werf et al., 2009). Reduced Emissions from Deforestation and Degradation (REDD) is an incentive mechanism currently being discussed in global climate mitigation talks. REDD proposes paying landowners in developing countries for the carbon value of their lands to keep forests intact and maintain forest carbon stocks. Additionally, domestic and international policy incentives that alter forest management strategies to improve carbon sequestration potential of forest stands can be an effective means of offsetting GHG emissions (Galik et al., 2009b, Murray et al., 2005).

Briefly, this chapter discusses two broad categories of AF activities that could contribute to low carbon policies: (1) Direct net emissions reduction, and (2) Bioenergy. Each option presents a number of institutional complications and can introduce new market or non-market externalities into the system, which is the focus of the empirical chapters of this dissertation.

3.1.1 Net Emissions Reduction

Options for directly reducing net emissions from AF include altering crop mix strategies to those that emit less in the production process, direct reductions in fossil fuel and input use, altering livestock production practices (through alternative feed blends, managing manure systems for reduced emissions, decreased rice cultivation, and avoided deforestation[4]. Direct emissions reduction involves production responses and altered crop mix decisions as a result of changing economic conditions as GHG intensive input costs increase. An example would be reduced emissions from lower N fertilizer use as the price of such inputs increases. A switch from dryland to irrigated production under elevated energy costs also qualifies as an indirect mitigation activity. Such actions can indirectly (or under the right incentive structure, directly) reduce emissions from AF practices, and it is important to account for shifts within a full GHG accounting framework.

Direct emissions reduction from shifting practices can also occur as a direct response to a policy lever that influences AF practices (for instance, an offset payment

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[4] Avoided deforestation can also be considered a traditional "offset" activity, though I categorize it as direct emissions reduction under the assumption that deforestation emissions would occur under business as usual conditions.

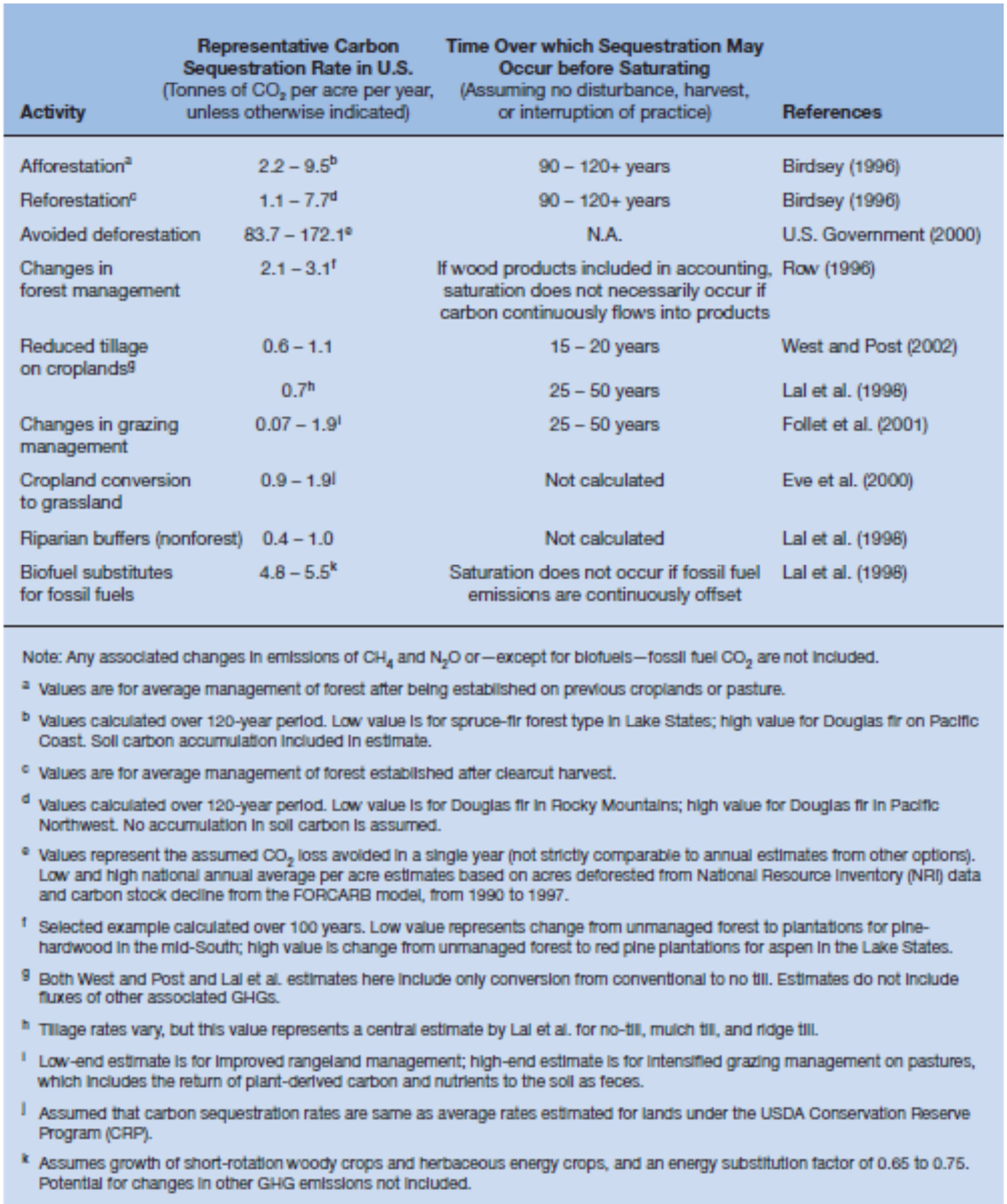
that would subsidize the landowner for carbon sequestration or emissions reductions beyond baseline practices. Some examples of offsets include the following.

3.1.1.1 Soil Carbon Management

The soil carbon stock is an extremely important global carbon account. As soils are intensively managed, soil carbon is lost to the atmosphere. For crop production, alternative tillage practices can boost the agricultural soil carbon account by eliminating soil disturbances that release CO_2 as land is tilled between planting seasons. There is a variety of conservation tillage method practices possible, including ceased use of tillage, strip-tilling (where planted rows exist between strips of untilled soil), or ridge till (where crops are planted on top of ridges—the base remains undisturbed).

Other options for managing soil carbon include the use of cover crops in the non-growing season to improve soil nutrient content, or increased residue retention by which crop residues are allowed to remain on the ground, and ultimately contribute to the soil organic carbon stock. Previous research has praised conservation tillage methods for its potential to offset ~10% of global fossil fuel emissions, while enhancing the quality of degraded soils and boosting yields on marginal croplands (Lal, 2004). However, the Lal, 2004 results are not consistent across all regions and cropping systems, and more contemporary estimates by Lal, 2004 and others have painted a more pessimistic picture of soil carbon sequestrations ability to contribute to economy-wide abatement goals.

The net carbon gains to conservation and no-till production practices are relatively small (0.6-1.1 tCO_2e $acre^{-1}$ $year^{-1}$), and the system will ultimately become saturated and unable to store additional carbon (Murray et al., 2005). The relatively small per-acre carbon gains means many landowners would be needed to create a meaningful mitigation contract, which would require significant high transaction costs. Additionally, reduced tillage practices are typically seen as economically viable mitigation strategies at lower CO_2 prices, but are less so as the carbon price increases; bioenergy and forest offset opportunities dominate the mitigation portfolio at higher CO_2 prices (McCarl and Schneider, 2001, Murray et al., 2005). Figure 2, taken from the EPA 2005 assessment of U.S. GHG mitigation potential in agriculture and forestry, illustrates the potential difference in per-acre GHG offset potential among various forms of AF carbon sequestration. Notice that changing tillage practices only competes with forestry offsets from a pure GHG standpoint (specifically, reforestation) at 1.1 tCO_2e, which is the high end estimate for no-till carbon gains.



Activity	Representative Carbon Sequestration Rate in U.S. (Tonnes of CO_2 per acre per year, unless otherwise indicated)	Time Over which Sequestration May Occur before Saturating (Assuming no disturbance, harvest, or interruption of practice)	References
Afforestation[a]	2.2 – 9.5[b]	90 – 120+ years	Birdsey (1996)
Reforestation[c]	1.1 – 7.7[d]	90 – 120+ years	Birdsey (1996)
Avoided deforestation	83.7 – 172.1[e]	N.A.	U.S. Government (2000)
Changes in forest management	2.1 – 3.1[f]	If wood products included in accounting, saturation does not necessarily occur if carbon continuously flows into products	Row (1996)
Reduced tillage on croplands[g]	0.6 – 1.1	15 – 20 years	West and Post (2002)
	0.7[h]	25 – 50 years	Lal et al. (1998)
Changes in grazing management	0.07 – 1.9[i]	25 – 50 years	Follet et al. (2001)
Cropland conversion to grassland	0.9 – 1.9[j]	Not calculated	Eve et al. (2000)
Riparian buffers (nonforest)	0.4 – 1.0	Not calculated	Lal et al. (1998)
Biofuel substitutes for fossil fuels	4.8 – 5.5[k]	Saturation does not occur if fossil fuel emissions are continuously offset	Lal et al. (1998)

Note: Any associated changes in emissions of CH_4 and N_2O or—except for biofuels—fossil fuel CO_2 are not included.

[a] Values are for average management of forest after being established on previous croplands or pasture.

[b] Values calculated over 120-year period. Low value is for spruce-fir forest type in Lake States; high value for Douglas fir on Pacific Coast. Soil carbon accumulation included in estimate.

[c] Values are for average management of forest established after clearcut harvest.

[d] Values calculated over 120-year period. Low value is for Douglas fir in Rocky Mountains; high value for Douglas fir in Pacific Northwest. No accumulation in soil carbon is assumed.

[e] Values represent the assumed CO_2 loss avoided in a single year (not strictly comparable to annual estimates from other options). Low and high national annual average per acre estimates based on acres deforested from National Resource Inventory (NRI) data and carbon stock decline from the FORCARB model, from 1990 to 1997.

[f] Selected example calculated over 100 years. Low value represents change from unmanaged forest to plantations for pine-hardwood in the mid-South; high value is change from unmanaged forest to red pine plantations for aspen in the Lake States.

[g] Both West and Post and Lal et al. estimates here include only conversion from conventional to no till. Estimates do not include fluxes of other associated GHGs.

[h] Tillage rates vary, but this value represents a central estimate by Lal et al. for no-till, mulch till, and ridge till.

[i] Low-end estimate is for improved rangeland management; high-end estimate is for intensified grazing management on pastures, which includes the return of plant-derived carbon and nutrients to the soil as feces.

[j] Assumed that carbon sequestration rates are same as average rates estimated for lands under the USDA Conservation Reserve Program (CRP).

[k] Assumes growth of short-rotation woody crops and herbaceous energy crops, and an energy substitution factor of 0.65 to 0.75. Potential for changes in other GHG emissions not included.

Figure 2: Estimated carbon sequestration potential from Murray et al. (2005)

Another problem with pursuing soil carbon offset activities is that reduced tillage offsets will likely conflict with goals of the RFS2 where agricultural residues will be a marketable feedstock for energy production. Residue removal is often a requisite of no-till farming, making no-till an attractive management option under an RFS2 regime. Thus, under and RFS2 baseline, "additionality" would be a concern as the market for soil carbon offsets is likely limited by the existence of the RFS2, which pushes the demand for AF residues and dedicated energy crop. For a comprehensive review of other issues associated with soil carbon management and tillage offsets, see Murray et al., 2007.

3.1.1.2 Land Set-Asides

Incentives for fallowing or setting aside land currently in production are another option for directly reducing emissions. Land conservation programs akin to the CRP can directly reduce emissions from intense agricultural production while boosting soil carbon stocks, and allowing direct participation of CRP lands in a GHG offset market is a potential policy option for involving conservation lands into current climate mitigation efforts.

Although the CRP was not designed for carbon storage and sequestration, CRP contracts include land cover maintenance and restricted biomass removal, which enhances above- and below-ground carbon sequestration (FAPRI 2007). In particular, organic carbon levels in CRP lands can be significantly greater than in cropland; studies have shown that only five years after restoration of a perennial grass cover, 21% of the soil carbon lost during decades of intensive tillage had been replaced (Gebhart et al., 1994). A recent comprehensive review of soil carbon with the CRP estimates that soil organic carbon increases at the rate of 2.1 metric tCO_2 equivalent (e) per hectare per year (Piñeiro et al. 2009). These increases in soil carbon storage can be negated by recultivation; a global review found there is an average loss of 30% soil carbon from soil layers of less than 150cm deep following recultivation of conservation lands (Davidson and Ackerman, 1993). For more on the CRP in a low-carbon economy, see (Baker and Galik, 2009).

3.1.1.3 Reducing N_2O Emissions from Crop Management

As nitrogen fertilizer is applied to cropping systems to boost yields, direct and indirect sources of N_2O emissions come as a byproduct. Direct N_2O emissions are those N2O releases directly tied to the application of the N fertilizer. Indirect sources of N_2O occur as N leaches off-site then reverts to N_2O in a different location, or when nitrates volatilize in the form of N_2O as part of the nitrification process. To reduce N_2O emissions, offset incentives can subsidize farmers to decrease N use on farm. Given the potency of N_2O as a greenhouse gas (which has a global warming potential more than 300 times that of CO_2), and the other environmental benefits that come with reduced N use, this is a particularly popular offset mechanism in the environmental community. However, N fertilizers are a very important part of the production process, and even small decreases in N use can reduce crop yields.

3.1.1.4 Emissions Reduction from Livestock Management

First, consider direct agricultural GHG emissions reduction. Livestock production produces a significant source of global N_2O and CH_4 and CO_2 emissions. In the U.S., livestock emissions are a significant source of agricultural emissions accounting for 200 $TgCO_2e$, roughly 3% of total emissions (EPA, 2009). Globally, FAO (2006) estimates that net emissions from all livestock production and consumption activities are approximately 9% of global anthropogenic CO_2 emissions, 35-40% of global methane emissions, and 65% of N_2O global emissions[5] (FAO, 2006). Efforts to reduce livestock emissions include:

- *Improved enteric fermentation:* Reduced emissions through improved enteric fermentation are possible through alternative feed blends that improve rumen efficiency, and lead to fewer CH4 emissions per-unit of feed;
- *Manure management-* Anaerobic lagoon treatment for hog and dairy operations is a viable mitigation option; methane can be captured and potentially converted to energy for on-farm use, and
- *Altered management strategies:* including indirect management of CH4 emissions by increasing animal growth productivity[6], or by eliminating a stocker phase (and thereby decreasing the lifespan emissions of the livestock)
- *Reduced pasture emissions:* includes alternative management options for pasture land management to reduce emissions associated with grazing activities—again, an option could include eliminating the stocker phase of production.

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[5] Estimates include emissions from the cultivation of livestock feed, transportation and processing of meat products, and land use change emissions associated with livestock development.

[6] An option here is the application of bovine somotatrophin, a growth hormone that has raised other important environmental and human health issues (Outlaw et al., 2009).

Due to the amount of resources necessary for livestock production, a shift in food consumption habits to diets that contain a smaller proportion of meat can reduce anthropogenic emissions significantly. Recent analysis shows that a global shift to a "Healthy Diet" principally with less animal protein not only reduces the accumulation of CO2 in the atmosphere in 2050 by 30 parts per million (ppm)[7] (Stehfest et al., 2009). However, a reduction in global livestock production is unlikely as changing preferences are shifting the demand for meat in rapidly developing economies. In addition, if global demand for meat continues to rise, regional efforts to reduce herd size or alter diets could lead to leakage in the livestock sector (as production shifts elsewhere to satisfy global demand).

3.1.1.5 Emissions Reduction from Rice Cultivation

CH_4 emissions from rice cultivation account for a much smaller share of total U.S. emissions (~6 TgCO_2e, or <0.1% of total U.S. emissions) but comprise a larger share of global agricultural emissions (EPA, 2009). Global emissions from rice cultivation are estimated to be approximately 708 Tg CO_2-e for 2010 (US Environmental Protection Agency, 2006), 11% of global GHG emissions from the agricultural sector.

A direct response to reduce these emissions is to reduce rice cultivation altogether, forgoing methane emissions. Altering management strategies and species mix to one that reduces methane emissions is also an alternative. This includes use of iron silicate fertilizers (Ali et al., 2008a, Ali et al., 2008b)[8], which is a much more socially

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[7] The mitigation scenario analyzed was to stabilize GHG concentrations in the atmosphere at 450 ppm.

[8] Iron silicate fertilizers have been shown to boost yields from paddy rice cultivation in addition to reducing CH_4 emissions

palatable form of rice emissions reduction than a strict reduction in acreage, as approximately 370 million tons of rice are consumed for food (FAO, 2009). Mid-season drainage of rice paddy fields can significantly reduce methane emissions also but comes with the added cost of requiring additional water use.

3.1.1.6 Forestry Mitigation

Literature has shown that the greatest AF-GHG mitigation opportunities come from forest-based offset activities and bioenergy (Murray et al., 2005; Baker et al., 2009). A number of offset activities are available that potentially increase the carbon storage potential of forest stands, including:

3.1.1.6.1 Avoided Deforestation

Deforestation is a significant driver of anthropogenic greenhouse-gas emissions, accounting for roughly 12% of global emissions and comparable in size to the emissions from the global transportation sector (Olander et al., 2009). Deforestation accounts for an overwhelming portion of total emissions in Brazil and Indonesia, the world’s third and fourth largest emitters by volume (UNFCC 2009). Reducing deforestation rates and improving sustainable forest management is a challenge in a time of continuing population growth and agricultural expansion. Nevertheless, financial incentives and policy levers can be useful in this important task.

Reduced Emissions from Deforestation and Degradation (REDD) is an incentive mechanism that pays landowners to preserve forests as part of climate policy today (Miles and Kapos, 2008, Olander et al., 2009). Several recent studies have evaluated REDD incentives globally by comparing baseline land-use trajectories to other trajectories where carbon payments compensate landowners for keeping forests intact. Recent modeling efforts suggest that ~1.8 billion tCO_2e of global emissions can be eliminated for approximately \$10/tCO_2e; at \$20 and \$30/tCO_3e, mitigation estimates increase to 2.5 and 2.9 billion tCO_2e, respectively (Gullison et al., 2007, Kindermann et al., 2008, Murray et al., 2009). These greenhouse gas benefits could also be accompanied by a 50% reduction in global deforestation rates by 2030 (Kindermann et al., 2008). Avoided deforestation is thus likely a feasible, relatively cheap alternative for greenhouse gas mitigation that would produce many ecological co-benefits, including biodiversity conservation (Fearnside 2008) and additional net cooling from water recycling. The challenges with implementing REDD protocols include the method for distributing payments, the means of establishing a proper deforestation baseline, and leakage.

3.1.1.6.2 Forest Management

Forest management offsets are activities designed to increase the carbon sequestration potential of lands currently in timber production. A variety of options are available, including rotation extensions, altered species mix, partial thinning, and reforestation. Faster growing species can be planted in order to stimulate biomass growth and carbon accumulation, though this brings additional risks typical of introducing non-native species into vulnerable ecosystems (Jackson and Baker, 2010). Carbon sequestration rates vary significantly by region, topography, and other factors, but typically range 2.1-3.1t CO_2e $acre^{-1}year^{-1}$ (Row, 1996).

GHG mitigation protocols exist or are being developed within that explicitly state how land is to be managed, what is eligible, and how carbon payments should be discounted for landowners participating in forest management offset programs. Galik et al., 2009 shows that the break-even carbon price necessary for forest management activities to be economically feasible varies significantly by, region, species, policy design, and subsequent transaction costs (protocol) (Galik et al., 2009a, Galik et al., 2009b).

3.1.1.6.3 Afforestation

Afforestation is defined as the planting of managed forests in areas without trees for at least 50 years (or some other arbitrary length of time). In the U.S., afforestation has the potential to sequester ~100 Tg C yr^{-1}, depending on the price of carbon (SOCCR, 2007, Murray, et al., 2005). Globally, the combination of reforestation and afforestation activities could reduce atmospheric CO_2 concentrations significantly this century, by approximately 30 parts per million (ppm) (House et al., 2002). However, this potential mitigation may be limited by many factors. One is the vulnerability of forests to increased disturbances, including pathogens, fire, and storms (Galik and Jackson 2009). The mountain pine beetle is projected to convert 374,000 km^2 of pine forest from a small net carbon sink to a large carbon source in Alberta alone, liberating 270 Tg C to the atmosphere (Kurz et al. 2008).

A second potential limitation is landowner behavior, including decisions on what species to plant, how to manage forests, and direct opposition to planting trees on lands that have been in conventional agricultural production for generations. Much of the opposition to climate legislation echoed by the agricultural community stems from the supposition that farmers would never participate in an activity that would subsidize “tree planting” in lieu of business as usual operations.

3.1.1.7 Other Issues with Mitigation in Agriculture and Forestry

Landowner decisions will ultimately dictate the success of some climate-policy efforts. However, setting land aside for carbon sequestration purposes raises a number of relevant policy issues, including additionality, permanence, leakage, and transaction costs. These factors can confound the overall effectiveness of GHG offset activities, and it has been suggested that offset payments be discounted in light of these issues (Heng-Chi Lee et al., 2007).

- ***Additionality-*** For carbon offsets to be effective in offsetting emissions, the activity must be additional to the baseline, i.e., would not have occurred under business as usual conditions.
- ***Permanence-*** It is often difficult for AF activities to be considered permanent as carbon stored in soils and forest stands will ultimately reach a saturation point at which the system is no longer providing carbon benefits. In addition, there is increased risk of carbon reversal due to natural disturbances (fires, hurricanes, etc.) that make permanence a concern.
- ***Leakage-*** One of the recurring themes of this dissertation, if AF GHG mitigation activities lead to agricultural expansion or management intensification in another region which subsequently raises emissions, this is referred to as leakage.

- ***Transaction Costs-*** The true costs of carbon offset activities include the transaction costs of aggregating, monitoring, and enforcing carbon offset contracts. Transaction costs can vary by region, activity, management protocol, and can increase the break-even carbon price needed for the offset incentive to be economically viable (Galik et al., 2009a).

Each option detailed above presents challenges and opportunity costs to consider. However, direct and indirect environmental impacts are likely much greater for bioenergy production expansion than for carbon offset activities, an issue that is addressed in the following section.

3.1.2 Bioenergy- Social and Environmental Concerns

Prior to the establishment of the EISA-RFS, there was significant debate in the literature regarding the net energy balance of bioenergy, with many studies discounting biofuels as an effective source of renewable energy (Pimentel, 2003, Pimentel and Patzek, 2005). These concerns were alleviated to an extent by further work that have found positive energy balances for biofuels, and hence net GHG reduction potential (Dalgaard et al., 2006, Farrell et al., 2006, Hill et al., 2006, Wesseler, 2007).

Unfortunately, we currently lack the technology to support large-scale production of cellulosic ethanol, which would produce net GHG gains at the lowest environmental costs at this time (cellulosic ethanol from perennial grasses, wastes, agricultural residues, dedicated energy crops, and algae). During the economic downturn of 2008 and 2009 there was concern levied that EISA-RFS2 mandates were premature in mandating high proportions of cellulosic ethanol and they were relaxed for 2010. There is a great chance that the sector will be unable to meet these targets in the coming years.

In addition, bioenergy mandates and GHG mitigation policy raises a number of social issues that merit further policy consideration. Corn ethanol expansion has already boosted commodity prices and net farm income (Tyner et al. 1979; Biomass Research and Development Board, 2008; Fortenberry and Park, 2008; EPA 2009). In addition, second generation biofuels offer a source of revenue to producers and new opportunities for managing marginal lands by creating a market for agricultural residues or perennial energy crops. This can provide an additional revenue stream for producers in low-income countries as well, and can help productive regions realize greater levels of energy independence (Hunt, 2008).

How will the agricultural sector will be able to supply human needs for food and fiber while supporting an expanding bioenergy industry? This dilemma has been characterized as the Food vs. Fuel debate (Daschle et al., 2007, Runge and Senauer, 2007). Typically, technological advancement and yield productivity growth have out-paced demand growth for food globally, discounting Malthusian concerns of feeding a growing world population. Nevertheless, U.S. and global bioenergy expansion could throw off this delicate balance by stimulating demand to the point that short-term supply shortages exacerbate hunger concerns in some regions of the world. This effect would be particularly acute especially during periods of adverse climatic conditions in the world's most productive regions.

Agricultural commodity prices contribute greatly to hunger and malnutrition globally (Senauer, 2008). One reason the Green Revolution was so successful in reducing malnourishment and global hunger is that advancements in productivity helped to stabilize world commodity markets, leading to declining real commodity prices in food markets over time. Recently, the number of malnourished people has risen sharply, and currently sits at more than 1 billion worldwide. While not completely driven by commodity prices, this trend is particularly troubling following the successes of the Green Revolution. Higher food prices can lead to social unrest as well, evidence by recent political protests and riots in Egypt, Guinea, Haiti, Indonesia, Mauritania, Mexico, Morocco, Senegal, the Philippines and Yemen (Senauer, 2008). Displacing the production of valuable food supplies with bioenergy will further contribute to this malnourishment trend as markets adjust to new conditions[9].

Also relevant are the environmental implications of an expanded bioenergy industry. Recent literature has outlined the potential environmental pitfalls of increased agricultural development. Environmental co-costs of bioenergy include direct or induced LUC, higher levels of agricultural input use, and water quality co-effects (discussed in sufficient detail in subsequent sections). Zah et al. 2007 compare total GHG emissions and the net environmental impacts of 26 different biofuels compared to conventional fossil fuels and results indicate that the majority of the biofuels evaluated (21 out of 26)

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[9] Commodity price concerns are not central to bioenergy expansion, however. As will be shown in the results chapters, GHG mitigation and offsets can pressure commodity markets even further.

are GHG reducing relative to fossil fuel equivalents, but often these fuels had a greater overall environmental impact[10].

Cellulosic ethanol from a variety of feedstocks presents an environmentally superior alternative to gain and sugar based biofuels as lingo-cellulosic materials often come from biomass that does not directly compete with food and fiber crops (e.g., residuals of crop or timber production). In addition, per acre energy output is higher for cellulosic ethanol as all biomass in the field is used in the fuel production process. Boosting per-acre energy output reduces land and resource requirements of the energy source, lowers environmental degradation, and provides greater life-cycle GHG benefits. Targeting sustainable bioenergy feedstocks or biofuels that negate socioeconomic or environmental impacts has been the focus of an emerging literature over the last few years. The subject of this literature has fallen into several categories. The first segment of this literature has focused on specific feedstocks or the life cycle impacts of particular bioenergy monocultures, providing estimates of full "well-to-wheel" energy potential and GHG reduction potential. Another portion has considered the social aspects of biofuel development as discussed. Then, the final segment has focused on the economic dimensions of biofuel policies, both in terms of resource consumption and net economic welfare of various policy levers. This dissertation will address aspects of all three areas.

The following sections discuss potential market outcomes of recent energy and climate policy initiatives, and how such policies enhance the linkages between energy

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[10] The net environmental impact in this study is an index value comprised of two main indicators, (1) Swiss environmental impact points- a measure of how much environmental impacts exceed legal limits, and (2) the European Eco-Indicator- which

and AF markets. This in turn influences natural resource management and consumption, AF input costs, output prices, and welfare feedbacks in the energy and transportation sectors.

3.2 Commodity Market Implications of Bioenergy and GHG Mitigation

As current policy drivers represent a fundamental shift in the US and global AF sectors, it is important to consider how energy, transportation, and AF markets are currently related and how policies strengthen such interdependencies and implies cross-sectoral welfare spillovers.

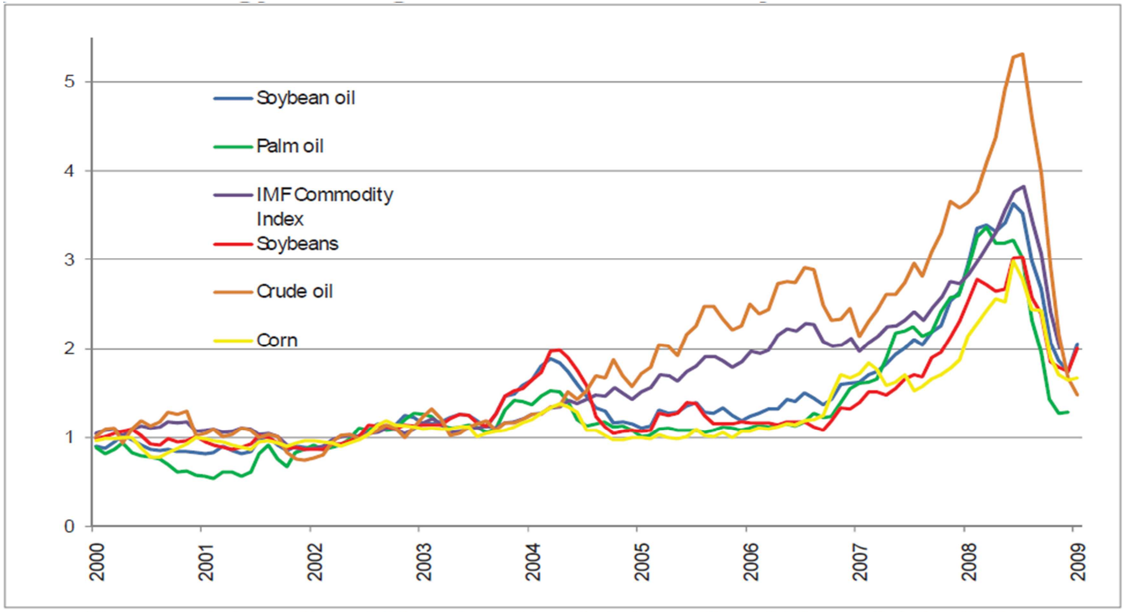
3.2.1 Increased Linkages between Energy and AF Markets

The relationship between energy and AF commodities has been established in the literature, but recent economic volatility and continued movement to an economy less dependent on fossil fuels will likely strengthen this connection. Data show that energy and commodity markets are closely related, exhibiting similar trends over time. Recent literature discusses these market interactions, pointing out that higher correlation between agricultural and energy markets could signal higher levels of volatility in important agricultural commodity prices (Du et al., 2009 , Irwin and Good, 2009). The relationship between agricultural and energy markets is important in several ways. First, if petroleum market volatility of 2008 is a sign of future market conditions, then the ethanol “boom” will continue to rise and fall with petroleum prices given the high correlation between agricultural and energy markets (Irwin and Good, 2009). There is a direct relationship between corn and petroleum prices for a dry mill corn ethanol plant to break even. For instance, to break even at \$5/bushel corn, petroleum price of \$80/barrel or greater would be needed. To obtain a 12% return on investment at \$5/bushel, a petroleum price of \$90/barrel or greater would be needed (Tiffany, 2007). As recent petroleum market fluctuations have shown, such price combinations are well within observed ranges, but volatility in petroleum markets and macroeconomic conditions mean that the economic viability of corn ethanol (in the absence of government intervention) will be cyclical (Figure 3).

Second, climate mitigation efforts will raise the price of conventional fossil fuels, thus directly affecting agricultural input costs, indirectly affecting output prices, and stimulating the demand for bioenergy even further as a low carbon fuel substitute (Baker et al., 2010). Currently, there is legitimate concern on the part of agricultural stake-holders that energy policies that raise the price fossil fuels place an undue burden on agricultural producers with low profit margins.

In general, data-trends show that producers were able to weather the storm of higher input prices in 2007 and 2008 through higher output prices. Also called “cost pass-through,” this phenomenon occurs when all producers in an industry or sector of the economy simultaneously face higher costs of production. Subsequent supply side responses force output prices upward as crop producers face higher energy input costs and limited budgets. Similarly, the recent economic downturn and subsequent fall in petroleum prices was accompanied by a fall in agricultural commodity prices as well. There are a number of studies that have statistically evaluated cost pass through and the interactions between energy price shocks and commodity market responses. Fertilizer processors and agricultural producers were able to pass through the highest proportion of oil price increases when compared to other economic agents (Baffes, 2007). Recent work has also found strong evidence of cost pass-through in the agricultural sector during the 2008 petroleum price spike (Kwon and Koo, 2009).

Other input costs, such as the price of fertilizer, were adversely impacted by the spike in petroleum prices as well. The production of fertilizer and other agricultural chemicals is fossil fuel intensive, and thus subject to price volatility in those markets. Additionally, the biofuels "boom" of 2007 and 2008 altered U.S. crop mix strategies to a more nitrogen intensive mix, more than doubling prices for nitrogen, potash, and phosphate fertilizers (Huang et al., 2009).



Source: International Monetary Fund, *International Financial Statistics*.
* Commodity prices and indices are normalized to equal 1.0, on average, for 2002.

Figure 3: Relationship between agricultural and energy markets

In general, higher energy prices are to be expected under low carbon policies, but will be accompanied by higher output prices. The extent of these output price effects is an important policy consideration that is evaluated in later chapters.

3.2.2 The Role of Biofuels during the Price Spike

Some critics of biofuel policies argue that that this food price rise was directly related to biofuel expansion in the U.S. and elsewhere, and this has imposed an unnecessary burden on the developing world. There is merit to this concern, as RFS mandates more closely tie commodity prices to energy prices (particularly corn and soybean) by effectively imposing a price floor under the agricultural feedstock (Babcock, 2009). A net increase in biofuel production in 2008 stimulated by the RFS certainly contributed to the commodity price spike. Studies suggest that a number of other factors were also partly responsible for the 2008 price spike, including increased production costs, adverse weather conditions, changing food preferences (and a greater demand for meat in rapidly developing economies), declining value of the U.S. dollar, and import/export policies in a number of important regions (Senauer, 2008, Trostle, 2008).

There is a growing correlation between energy and AF markets. Bioenergy expansion will likely reinforce this relationship and provide new revenue opportunities to AF producers by linking the demand for energy and transportation fuels to the demand for primary AF feedstocks.

3.2.3 Impacts of GHG Mitigation Policy on U.S. Agriculture

Putting it all together, policies that influence energy markets (renewable energy expansion or climate mitigation incentives) will influence agricultural commodity markets and natural resource use. This raises obvious questions regarding the economic welfare implications of such incentives. In terms of climate mitigation, this is especially cloudy. The net sectoral welfare effects of GHG policy are tied to a number of factors. First, climate legislation (either cap-and-trade or a carbon tax) directly raises the cost of fossil fuel intensive inputs (gasoline, natural gas, diesel, and electricity), and other inputs tied to fossil fuel prices (such as nitrogen fertilizer, which is highly correlated with natural gas and diesel markets). The U.S. Environmental Protection Agency (EPA) recently assessed HR 2454, and found that it could cause petroleum prices to rise 15% above baseline levels by 2050 (EPA, 2009). This analysis also shows electricity and natural gas prices rising 30 and 35%, respectively, by 2050. Figure 4 displays price index values relative to baseline trajectories for selective energy sources under EPA's projections of HR 2454:

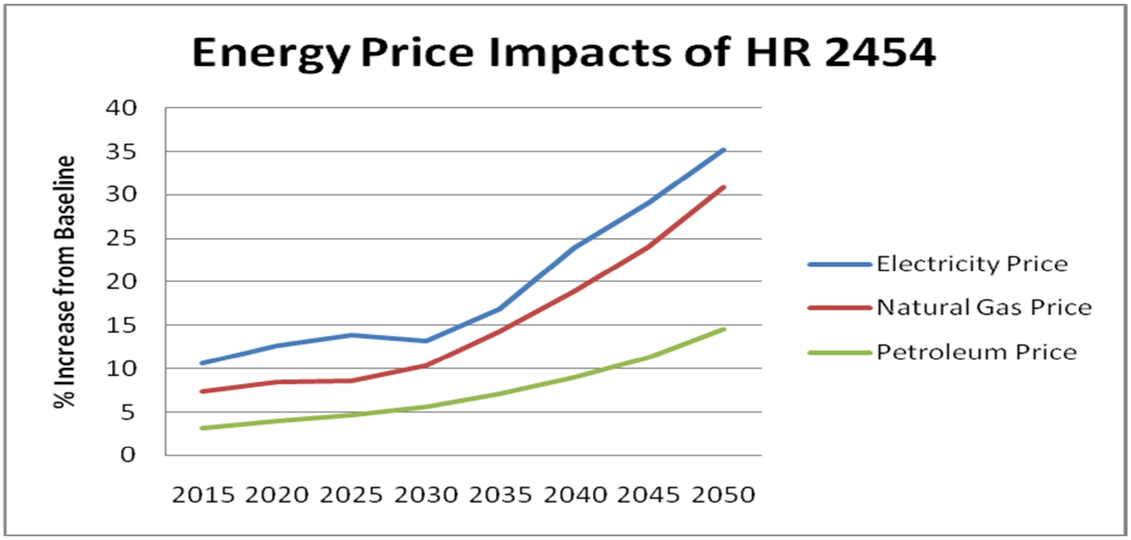


Figure 4: EPA energy price projections under HR 2454 (source: EPA 2009)

Potential cost-side impacts of climate legislation have led to staunch opposition to climate legislation by certain stakeholders in the agricultural community. Some studies have added to this concern by producing estimates of a substantial total cost burden imposed on the agricultural sector under cap-and-trade (Doane Advisory Committee, 2008; FAPRI, 2009). A recent USDA analysis uses EPA's estimates of energy price increases under the ACES, and found more modest operating costs in the short-term of less than 2%/acre, and relatively modest increases in the medium and long-terms of less than 4% and 10%/acre (USDA, 2009). Overall, the USDA analysis showed a net income loss to the agricultural sector over time, but did not account for changes in production practices over time, nor does it include potential offset and additional bioenergy revenue. It also ignored market effects caused by pursuit of GHG offsets that move land out of conventional agricultural production.

An updated report put out by the USDA now shows net gains to the sector as a whole, piggy-backing on other empirical efforts that have evaluated the entire AF system, not just production cost impacts. Outlaw et al. evaluate a limited suite of offset activities and evaluate farm level economics of the ACES for 98 representative farms across the U.S. representing multiple regions and crop/livestock activities and found that 71 farms were worse off under the policy (Outlaw et al., 2009). Those that gained were concentrated mostly in the Midwest and Corn Belt regions.

Baker et al., 2010 take the cost/benefit issue of climate policy further by considering production and land use responses across a range of CO_2 equivalent prices and a full suite of mitigation opportunities, including offsets and bioenergy. Results suggest that AF producers could realize windfall gains under climate legislation from the sale of offsets, the emergence of bioenergy markets, and indirect revenues as stimulated by commodity market shifts, a key result highlighted in subsequent chapters (Baker et al., 2010). Similar results were found in de la Torre-Ugarte, et al., 2009, which also used sectoral economic modeling to evaluate multiple GHG offset provision options (de la Torre Ugarte et al., 2009).

In general, it appears that the net sectoral welfare gains to AF producers from offsets and bioenergy incentives could be substantial, and will more than offset any additional costs of climate and energy legislation. For livestock producers or AF producers of conventional commodities without the biophysical potential to participate in offset programs, indirect revenue flows through commodity price increases should provide adequate compensation. However, such economic gains might come at significant costs on natural resources as external environmental costs of change land management decisions are not completely internalized in this framework. The following sections discuss land and water resource concerns that arise under low carbon policies.

3.3 Land Resources in a Low Carbon Economy

One of the key themes of this dissertation is the effect of bioenergy and terrestrial GHG mitigation on land use decisions. As discussed, land resources will play a vital role in a low carbon economy, as a source of carbon offset potential, and by providing a resource necessary for cultivating the requisite feedstock for mandated bioenergy expansion. Low carbon policies can have deleterious impacts on land resources, as carbon-generating activities in one region can enhance land clearing, land management intensity, or raise the opportunity costs of land conservation in other regions.

3.3.1 Land Use and Bioenergy

Ultimately, biofuel policies will continue to influence land use decisions and LUC. In order to understand the full impact of the policy, it is important to distinguish between direct and indirect LUC. Direct LUC is defined as the conversion of lands from a prior use strictly for the purposes of bioenergy cultivation. Research has shown that direct land use changes for biofuel production in a number of ecosystems (including tropical rainforests or U.S. prairie grasslands) leads to significant payback periods, or the amount of time needed for the GHG benefits of non-stop biofuel cultivation to outweigh the carbon loss from the original land-clearing activity (Fargione et al., 2008, Gibbs et al., 2008, Pineiro et al., 2009). Table 2 summarizes carbon payback periods for various types of biofuel development, land categories, and regions. Notice there is significant variation in estimated carbon payback periods. This is due to differences in carbon stocks for different land types, disparity in global crop productivity, and the difference in life-cycle GHG emissions reduction potential for different biofuels.

There are several important implications of these studies. First, rapid development of viable "second generation" bioenergy feedstocks, such as cellulosic ethanol from crop residues, switchgrass, or woody biomass is critical. Dedicated cellulosic ethanol production can significantly or fully mitigate against lengthy carbon payback periods (Pineiro et al., 2009).

Also, these studies indicate a need for technological improvement, perhaps driven by policy incentives (Gibbs et al., 2008). Finally, the difference in regional carbon payback estimates illustrates the importance of supporting biofuel development on existing or abandoned cropland. Abandoned or idle cropland can be effective source of expandable land for bioenergy development, but keeping agricultural land set aside can be a better short-term climate investment (Hoogwijk et al., 2009, Pineiro et al., 2009).

Table 2: Estimated Carbon Payback Periods from Direct Land Use Change for Biofuels

Study	Land-use Type	Region	Biofuel	Carbon Payback Period
Fargione et al., 2008	Tropical or Peatland Rainforest	Indonesia/ Malaysia	Palm Biodiesel	86-423
Fargione et al., 2008	Tropical Rainforest	Brazil	Soybean Biodiesel	319
Fargione et al., 2008	Grassland	Brazil	Soybean Biodiesel	17-37
Fargione et al., 2008	Native Grassland	U.S.	Corn Ethanol	93
Fargione et al., 2008	Abandoned Cropland	U.S.	Corn Ethanol	48
Gibbs et al., 2008	Varying Grassland	Global	Sugar/Grain Ethanol	7-60
Gibbs et al., 2008	Varying Grassland	Global	Soybean Biodiesel	80-100
Gibbs et al., 2008	Varying Grassland	Global	Palm Biodiesel	0
Gibbs et al., 2008	Varying Forestland	Global	Sugar/Grain Ethanol	20-900
Gibbs et al., 2008	Varying Forestland	Global	Soybean Biodiesel	300-900
Gibbs et al., 2008	Varying Forestland	Global	Palm Biodiesel	5-120
Pineiro et al., 2009	CRP, Native Grassland	U.S.	Corn Ethanol	29-48
Pineiro et al., 2009	CRP, Native Grassland	U.S.	Cellulosic Ethanol	0

Indirect LUC (also referred to as induced LUC or leakage) from bioenergy cultivation is also of paramount concern. In this situation, the allocation of land for biofuel production in one region stimulates commodity markets and induces land use change in another region. The theory of induced land use change relies on the notion that a marginal increase in some land-clearing activity can be at least partly attributed to a price response brought on by production decisions in another region (McCarl, 2008).

Estimation of leakage is quite difficult, as it involves simulating agricultural development (or LUC) under a biofuel expansion scenario relative to a baseline trajectory. Assuming one has appropriate baseline assumptions of market conditions and economic behavior, modeling can be used to establish a baseline consistent with history. Then, to estimate induced LUC emissions, one must introduce the relevant policy shock into the economic system and see how markets and resource consumption decisions might adjust. If such a model adequately represents physical land stocks by region, LUC emissions can be calculated by comparing land use trajectories, and then calculating the emissions from land clearing activities that were not present in the baseline simulation. This requires spatially explicit biophysical data on land use and associated carbon stocks to fully capture net emissions. Typically, full structural economic modeling within systems that capture trade flows, spatial distributions of land types/use, and comprehensive GHG accounting are needed to conduct such analyses.

Recent work measured indirect land use responses to expanded ethanol production in the U.S., and has really stirred the debate surrounding the environmental effectiveness of bioenergy (Timothy Searchinger et al., 2008). Searchinger et al. find that LUC emissions resulting from domestic ethanol production will result in a 93% and 50% increase in emissions for corn biomass-derived ethanol, respectively, relative to an energy equivalent unit of gasoline (meaning every mile driven on corn ethanol emits approximately twice as much as a mile driven on gasoline). Put into the context of carbon payback periods, these results suggest that a payback period of 167 years of context biofuel production and consumption would be necessary to outweigh ILUC emissions.

Obviously, the implications of these studies contradict political ambitions of reducing GHG emissions by displacing fossil fuels with biofuels. However, some question the validity of the Searchinger analysis, and the inclusion of indirect LUC emissions in life cycle emissions calculation in general. Wang, 2008, questions assumptions regarding total reliance on corn ethanol (instead of cellulosic feedstock conversion), a lack of corn productivity growth, and general uncertainty not accounted for in the Searchinger analysis. Kim and Dale, 2009, point out that indirect LUC emissions depend on assumptions regarding social and environmental responsibilities taken by governments, and varying crop management practices, while also pointing out that fossil fuel consumption can also produce indirect emissions that are not accounted for (Kim and Dale, 2009).

Other recent studies show that indirect LUC trajectories depend on a number of factors; in particular, LUC is sensitive to assumptions regarding yield response to demand shocks (Keeney and Hertel, 2009). However, augmenting two simple assumptions (U.S. forest conversion, and constant yield) reduces this debt significantly. Holding U.S. forest use constant (whereas Searchinger assumes that 36% of new U.S. cropland entering production would come from forests) reduces the payback period to 141 years. Yield response plays an even larger role. A 1% increase in yield globally for the five major crop commodities (barley, corn, sorghum, soybeans, and wheat) would reduce the payback period to 31 years, reconfirming the yield response results in Keeney and Hertel, 2009.

An even more recent comprehensive analysis by Hertel et al. (2010) has attempted to replicate the Searchinger et al. (2008) results using a static computable general equilibrium model. This study found smaller net LUC emissions estimates from U.S. ethanol expansion (Hertel et al., 2010), including a net land use change response that is approximately 40% of the Searching estimates and a carbon payback period of approximately 30 years. The advantage of this study is that the sensitivity of LUC emissions to several key variables, including 1) resource constraints, 2) substitutability of crop co-products, 3) demand response for food, 4) yield responses to higher prices, and 5) lower productivity of cropland coming into production.[11] The paper illustrates that estimated ILUC emissions vary considerable for different base values of these key parameters.

It should be noted that the previous studies cited here relied on static economic models that inherently ignore the dynamics of land use decisions or commodity markets.[12] Additionally, biodiesel mandates, cellulosic ethanol, and other "advanced" biofuels produced in the U.S. are not modeled, and these studies have not measured ILUC on the economic margin, as the modeling approach exogenously "shocked" baseline conditions with a high level of corn ethanol. Also, cropland expansion in the

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[11] An *ad hoc* productivity factor of 0.66 is used to simulate reduced yields of new cropland. In general there is a real dearth of data that ties land productivity and production characteristics of lands considered "marginal" to regional average yields. Hertel et al. beseech the scientific community to fill this void. This sentiment is echoed in the concluding chapter of this dissertation.

[12] The authors are very clear that results of this comparative static approach should continue to be compared with those obtained from dynamic optimization approaches.

U.S. onto forested or grazing lands is highly is constrained in these studies using ad hoc assumptions or extremely inelastic elasticities of substitution for U.S. land uses. Greater flexibility in U.S. cropland expansion possibilities would presumably decrease these estimated losses further.

3.3.2 Land Use and GHG Mitigation

Induced LUC emissions are important in a climate mitigation context as well. Recent studies argue that not accounting for indirect LUC in life cycle analyses of bioenergy is a critical carbon accounting flaw in international climate policy legislation (Searchinger et al., 2009). Such models measure market responses to bioenergy expansion and subsequent land use decisions driven by the commodity market impact. Additionally, offsets that incentivize land set-asides on marginal or productive agricultural lands, while beneficial from carbon and wildlife habitat standpoints, can lead to alternative forms of development, including cropland deforestation and grassland conversion. This point is highlighted by unanticipated effects of the Conservation Reserve Program (CRP) that have been explored in a number of previous studies (Baker and Galik, 2009 ,Baker et al., 2008, Wu, 2000, 2005). While the program produces local environmental benefits, setting agricultural lands aside for conservation purposes can induce leakage other regions. Also, maintaining conservation lands in a period of high opportunity costs of conservation (i.e., arbitrarily high commodity prices or land rents) can lead to alternative forms of agricultural development in more sensitive ecosystems (Baker, et al., 2008).

Leakage is often thought of in a biofuels context, but pure climate mitigation activities can also lead to indirect land use changes. Several studies have evaluated leakage from forest conservation, forest management, and afforestation efforts (Gan and McCarl, 2007, Murray et al., 2004, Sun and Sohngen, 2009), and conclude that upward pressure on commodity markets induced by forest carbon sequestration incentives that lengthen rotations and alter forest management can shift timber production elsewhere, leading to diminished GHG gains to the mitigation effort. This effect can vary tremendously; Murray et al., show that leakage effects on net mitigation potential can range from less than 10% to more than 90%, depending on the region and mitigation activity undertaken.

In summary, managing land resources effectively under low-carbon policies such that the mitigation and renewable energy priorities are not undermined will prove to be a lofty goal. Shifting land resources away from conventional food and fiber production can boost agricultural development to the extensive margin. In the U.S., this could signal an increased propensity to deforest, cultivate natural grass or rangeland, or re-cultivate lands currently enrolled in conservation programs. Internationally, deforestation is of primary concern. External pressures on land resources illustrate the importance of international offsets, or programs designed to reduce deforestation rates internationally. If policies and production responses in the U.S. are primarily responsible for commodity price fluctuations, then U.S. support of policies that can alleviate land use change internationally is critical for comprehensive climate mitigation goals—a key result discussed in the concluding chapter of this dissertation.

However, land use change is not the only concern of environmental concern posed by bioenergy and climate mitigation policies, as water resources are also at risk. The next section discusses agricultural water resources in a low-carbon economy.

3.4 **Water Resources in a Low Carbon Economy**

To date, most studies within the climate/water paradigm have focused on the biophysical impacts of climate change on water resource systems, and implications for future water availability (Christensen et al., 2004, Jackson et al., 2001). The economics literature has examined water management institutions in a changing climate, or how agricultural production systems might respond to climate change (Chen et al., 2001, Döll, 2002, Fischer et al., 2007, Hatch et al., 1999, Mendelsohn and Dinar, 2003, Mendelsohn et al., 1994). These studies take an adaptation perspective, choosing to explain the economic consequences of changing temperatures and precipitation patterns with most highlighting the potential benefits of increased agricultural yields brought on by warmer temperatures, higher atmospheric CO_2 concentrations, and increased regional water availability.[13]

However, few studies have considered the impact of climate mitigation opportunities or renewable energy mandates on regional water resource systems. This is a growing area of concern, as highlighted by the most recent Assessment of the Intergovernmental Panel on Climate Change (Bates et al., 2008). Recent research

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[13] However, recent evidence by Roberts and Schlenker suggests that crop yields decline substantially beyond certain heat tolerance thresholds, suggesting that agriculture could experience substantial welfare losses under recent climate change projections (Roberts and Schlenker, *PNAS*, 2009).

indicates that world categorized by serious GHG reduction efforts would ease irrigation water requirements and improve water availability (Fischer et al., 2007).

The interactions of water, energy, and climate policy are critical, especially when climate mitigation efforts explicitly interact with AF by affecting both energy input costs and incentivizing alternative land uses. As climate mitigation schemes raise the cost of energy inputs, water managers in groundwater dependent regions will be forced into difficult decisions. In regions where scarcity is not a concern, increasing the marginal costs of water provision indirectly through GHG mitigation efforts raises equity concerns. Where scarcity and over-exploitation are prevalent, raising the marginal cost of water extraction could indirectly help sustain the lifetime of the aquifer. In addition, higher energy costs could lead farmers to switch to more energy and water efficient irrigation systems, such as the Low Energy Precision Application system.[14] Regardless of region, or relative water availability, climate mitigation incentives will be pervasive in water management decisions.

Policy makers should be careful in promoting carbon benefits at the expense of water resources; water quantity/quality trade-offs of renewable energy development should be carefully weighed.

3.4.1 Interactions with AF Mitigation Alternatives

In no way is the carbon/water trade-off more appropriate than with GHG mitigation incentives for agriculture and forestry. While previous research has suggested

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[14] Recent studies refute the claim that such systems actually promote water conservation (Peterson and Ding, 2005).

that climate mitigation in agriculture can directly benefit water resources (Greenhalgh and Sauer, 2003, Pattanayak et al., 2005), this dissertation will show that terrestrial mitigation can have largely ambiguous net effects on water consumption and quality

Much like land resources, one classify the policy induced impacts of bioenergy expansion and AF mitigation activities as having either direct or indirect effects on water resources. Direct, or local effects, are the accompanying responses in consumption, quality, and altered hydrologic flows associated with a mitigation activity (or cultivation of bioenergy feedstocks). Indirect responses occur when changing production practices or land uses in one region stimulate management intensity in another, thereby boosting irrigation rates or application of agricultural inputs that reduce water quality[15].

Biofuels present the most ostensible dilemma. There is valid concern that a global biofuel industry will increase use of irrigation water and degrade water quality through agricultural chemical application (National Research Council (U.S.), 2008, Rajagopal and Zilberman, 2007). However, some argue that the net impacts of biofuel development will be negligible at a global scale, but could have acute impacts locally, especially where water is scarce to begin with (Berndes, 2002, de Fraiture et al., 2008). In terms of quality, increased nitrogen runoff and leaching are likely; for surface water supplies this can lead to hypoxia in the Gulf Coast as well as other residual environmental impacts (Donner and Kucharik, 2008). If allocation of land to energy production in one region extends production in another, indirect impacts on water resources could negate any benefits in the conservation region. As an example, consider

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[15] I refer to this as "water leakage" from herein.

the case of an offset market that incentives land set-asides for carbon sequestration. If a unit of irrigated agricultural production leaves production in one region, then the indirect market outcome could shift water use in a region with existing scarcity concerns that lacks the biophysical capability to participate in an offsets market at a large scale (this case is explored conceptually in the following chapter).

The cultivation of dedicated energy crops or use of agricultural residues for bioelectricity could have less pronounced effects on water. Perennial biomass crops such as switchgrass, hybrid poplar, and willow can reduce agricultural input use and irrigation requirements relative to alternative biofuel crops such as corn and soybean (Scharlemann and Laurance, 2008, Zah et al., 2007). However, water leakage is still a concern if dedicated energy crops replace food production in areas with predominately non-irrigated production.

Agricultural mitigation activities will also affect water resources directly and indirectly. Consider land set-asides and soil sequestration through reduced tillage. The former will obviously reduce irrigation withdrawals and improve water quality locally as land is taken out of production. For instance, research indicates that CRP lands reduce water erosion, sedimentation and nutrient leaching (Davie and Lant, 1994; Randall et al., 1997). Conservation tillage is another option to increase the sequestration potential of agricultural lands (Lal, 2004). The advantage of conservation tillage is that it helps nutrient and water retention in agricultural soils, leading to decreased input use and long-term production sustainability. Conservation tillage also reduces soil erosion, which decreases sedimentation runoff (Lal, 2004, Pimentel et al., 1995). Regional studies have combined economic and biophysical modeling systems to simulate potential environmental co-benefits of conservation tillage, finding net water quality improvements (Feng et al., 2007, Kurkalova et al., 2004). However, reduced tillage is often accompanied by additional herbicide application, which can degrade water quality (Schneider and Kumar, 2008).

In many parts of the world nitrogen runoff from agriculture is the predominant source of water pollution and the problem is worsening (Aneja et al., 2008, Greenhalgh and Sauer, 2003). In the United States, Gulf of Mexico hypoxia, caused primarily by upstream agricultural runoff, threatens aquatic ecosystems and critical food supplies (Robertson and Vitousek, 2009). Globally, this problem is acute in a number of regions; more than 400 hypoxic zones have been identified, and hypoxic activity has increased exponentially since the 1960s (Diaz and Rosenberg, 2008). Nitrate contamination in surface and groundwater systems poses a serious and diverse set of health risks, and is another environmental cost of agricultural N use (Townsend et al., 2003). Thus, any effort to reduce on-farm nitrogen use--be it through nutrient trading or N use offsets, will aid in reducing the environmental costs of intense agriculture. Production function relationships between N and water inputs and yield effects will determine whether the extent to which N offsets affect water resources.

Forest offsets can also alter hydrologic flows, and indirectly impact water management outside of the system. Afforestation incentives can have indirect consequences on water via leakage, similar to the aforementioned options. Additionally, new forest stands could directly impact hydrologic systems by reducing stream flow and disrupting natural hydrologic processes (Jackson et al., 2005, Jackson et al., 2005, le Maitre and Versfeld, 1997). The extent of reduced runoff and water system disruption depends on the geographic location of afforested lands, and the species of vegetation planted (Farley et al., 2005). Depending on the geographic location of afforested land, impacts on the hydrologic cycle can be quite serious (Zomer et al., 2006). Avoided deforestation, can benefit ecosystems and water supplies by reducing run-off, preventing erosion and flooding, protecting fisheries, and lowering siltation of river systems (Chomitz and Kumari, 1996, Parrotta, 2002).

CHAPTER IV

A MODEL OF LAND ALLOCATION AND MANAGEMENT UNDER BIOENERGY AND GHG MITIGATION POLICIES

The purpose of this chapter is to develop a conceptual model that is consistent with the goals of renewable energy (implying cropland expansion) and GHG mitigation (which could refer to offset market participation, or some other price-mechanism incentivizes reductions in emissions or enhanced sequestration) on land management options on the intensive and extensive margins. This model shows how such policies can all lead to higher output prices.

4.1 Background

Several previous studies have addressed the welfare and commodity market implications of renewable energy mandates or GHG mitigation in the agricultural sector (Murray et al. 2007, Baker et al., 2010, Feng and Babcock, 2010). Feng and Babcock use comparative statics of a system in market equilibrium to show that biofuel mandates will lead to cropland expansion and management intensification in input use as farmers respond directly and indirectly to the new market conditions. Keeney and Hertel, 2009 use a global computable general equilibrium to simulate land use responses on the intensive and extensive margins. This study takes this methodology a step further by illustrating the effects of combined bioenergy mandates and mitigation efforts on land management decisions.

This chapter presents a simple model of the linkages between the production of food, bioenergy, and the provision of carbon from multiple land supplies. This model provides insight into the effect of renewable energy mandates, GHG intensity thresholds for bioenergy, and carbon offset incentives on land management decisions along the intensive and extensive margins. An extensive shift in agriculture requires that new land be brought into production (such as previously productive land that had been idled, or natural forests or grasslands that are cultivated for the first time). An intensive shift requires a change in management intensity (i.e. increased application of agricultural inputs). This chapter attempts to conceptually model the linkages between reduced carbon policy efforts, and how land management shifts can affect commodity prices as well as the potential and costs of GHG mitigation in the AF sectors. Innovations of this model compared to previous studies of biofuel mandates and land use include the addition of emissions intensity of production, mandates combined with GHG intensity thresholds (instead of a pure volume-based mandate), and a carbon offset market.

4.2 The Model

First, consider a system in which producers will make resource allocation and production decisions in a static fashion. Consider a supply of land (L) that can be used for three alternative purposes: production of conventional food (f), bioenergy (b), or carbon (c). The supply of c can more generally be thought of as the net emissions or mitigation emanating from the terrestrial systems. While there are many food and bioenergy cropping alternatives, this model assumes a very general commodity representation for simplicity. Conventional commodities are represented by the composite *f*, bioenergy is represented by the composite *b*, and GHG emissions, *c*. An aggregate production function (*Y*) captures the production possibilities of these goods as a function of land use, and an index of production intensity (a variable which includes soil management intensity, and the degree of agricultural input use), denoted by μ_j. The level of chosen management intensity is directly related to productivity and GHG emissions. While previous studies have explored the role of intensification in alleviating indirect LUC concerns of biofuel policies, no study has explored this variable in detail, or how resulting emissions can be altered by intensity of production in addition to land use changes. The form of μ_j can vary by region; depending on geographic and production characteristics of the land.

Before returning to management intensity, consider the total land supply function for this system.

(Equation 1)

$$L = L^c + L^f + L^b$$

L^c represents the land that is idle in a given time period and L^f is the land used for the production of food, and L^b is allocated to energy production. One can assume that land is idled for a combination of factors, including the non-market value of lands held in situ, or due to geographic factors limiting the production potential of lands (that is, not all idle land can be used for food or energy production). Alternatively, this could represent land that is actively managed for timber production. The interactions between production agriculture and forestry are handled in detail in subsequent chapters.

4.2.1 Food and Energy Supply Functions

For now, assume that food and energy are the only productive options on this land, and while this may come from the same feedstock, one can represent Y^f and Y^b with separate production specifications.[16] Production of food follows a relatively simplistic form that depends on the amount of land and intensity applied to the system, and the amount of land in production at any given time (which allows for declining productivity as additional land is brought into production. Let θ represent the total proportion of land in production, or $\left(L^f + L^b\right)\big/L$. The aggregate supply function for food becomes:

(Equation 2)

$$Y_f = \int_0^{L^{f*}} y_f(\mu_f, \theta) dL^{f*}$$

Land-based bioenergy production takes a similar form:

(Equation 3)

$$Y_b = \int_0^{L^{b*}} y_b(\mu_b, \theta) dL^{b*}$$

Following most agronomic relationships, assume that production of food and bioenergy is increasing and concave in input use, such that $\frac{\partial y_j}{\partial \mu_j} > 0$, and $\frac{\partial^2 y_j}{\partial \mu_j^2} < 0$.

Notice that the proportion of land dedicated to production activities also enters the production function $y_j()$. The implication here is that, *ceteris paribus*, marginal productivity will decline in this system as additional land is brought into production,

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[16] Note that this formulation makes assumes no overlapping between energy and conventional cropping systems (thus, no harvesting of residues on food systems for advanced biofuels production. While the Renewable Fuels Standard was designed to allow for biofuels produced from cropping residues and other agricultural by-products, I choose to model a generic form of this management decision.

thus $\frac{\partial y_j}{\partial \theta} < 0$ for $j=f,b$. This is the expansion effect on productivity. Assuming that landowners will use their most productive lands actively, any effort to expand total acreage will boost total productivity, but at a declining rate (holding intensity constant).

While this model can be applied to two distinct production functions for food and energy, this chapter makes the simplifying assumption that the composite food commodity and energy feedstock come from the same crop. Thus, one can substitute the production of food into that of energy using the same feedstock. Land shares and chosen production intensity for food and energy, respectively, will remain independent of the other. This is an important distinction. Since the production of each producers a different source of emissions on the margin, it is important to separate the two. For instance, lower production intensity for energy crops can produce additional GHG benefits on the margin as this is coupled with the carbon value of fossil-fuel replacement.

4.2.2 Carbon Supply Functions

The contribution of this model is the joint product supply function of *c*, either in the form of emissions or mitigation potential, from energy and food cropping systems. Previous analytical models of biofuels, climate, and land use have not captured the emissions and terrestrial carbon sequestration profiles of the land use system. The production of *c* is defined as the sum of all sources of GHG emissions and terrestrial carbon sequestration in the system. Again, the term "*c*" refers to all sources of GHG emissions within the system that contribute to the atmospheric concentration of GHGs. These include:

- CO_2 emissions from land shifts from idle to productive use (a loss in terrestrial carbon),
- CO_2 emissions tied to fossil fuel use captured by the intensity proxy (μ_j),
- CO_2 emissions offset in the general economy through bioenergy replacement of fossil fuels (τ),
- N_2O and other non-CO_2 emissions captured by the intensity proxy (μ_j),
- Emissions from energy consumed in transporting and processing the bioenergy feedstock per unit output (constant) is represented by ϕ_b (and the parameter ω is GHG emissions per-unit energy consumed)[17],
- C stored in productive soils managed under low-intensity regimes, and
- C sequestered in land moved over into conservation.

The net carbon supply function for this system is defined by Equation 4, which sums over all sources of emissions and sequestration from productive and non-productive activities.

(Equation 4) $$Y_C = cs \cdot L^C - L^f c_f(\mu_f) - L^b c_b(\mu_b) - \left(\omega\phi_b - \tau\right) Y^b$$

Production activities can produce a source of GHG emissions through energy and agricultural input use. Total emissions from food cultivation will depend on the amount of land in production, and the per-unit emissions from cultivation, which is a function of the chosen level of management intensity. Thus, the net contribution of *c*

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[17] This is a simplifying assumption. In reality, energy consumed in transporting biomass for bioenergy processing would depend on productivity per unit land and

from food production to Y^c is represented by $L^f c_f(\mu_f)$. However, bioenergy consumption replaces emissions from fossil fuel combustion, so the net contribution of *c* from bioenergy systems will include emissions from the cultivation process $L^b c_b(\mu_b)$, and emissions from transporting, processing, and combustion of the final biofuel, represented by $\left(\omega\phi_b - \tau\right)Y^b$. Thus, net emissions depend on production decisions on the intensive margin (μ_j) and the relative share of land in each use.

This model also assumes that non-productive land will sequester a constant amount of carbon, represented by the parameter *cs*. In this simple static representation, the carbon uptake from idle land is a function of the amount of land idled, so saturation of terrestrial carbon stocks does not happen (if this were a dynamic model, terrestrial carbon stocks would ultimately reach a saturation point, and the stock of carbon lost from land use changes would grow with the amount of time the land had been in a prior use). Any change in this stock will be met by an addition in annual carbon sequestration (from shifts out of production), or an instantaneous loss in carbon equal to the sequestration rate[18]. Any movement of land from production to idle use will generate a constant rate of carbon sequestration (*cs*). This relationship is illustrated by Figure 5:

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[18] A simplifying assumption as this is a static model. Accurate representation of terrestrial carbon fluxes requires comparative dynamics.

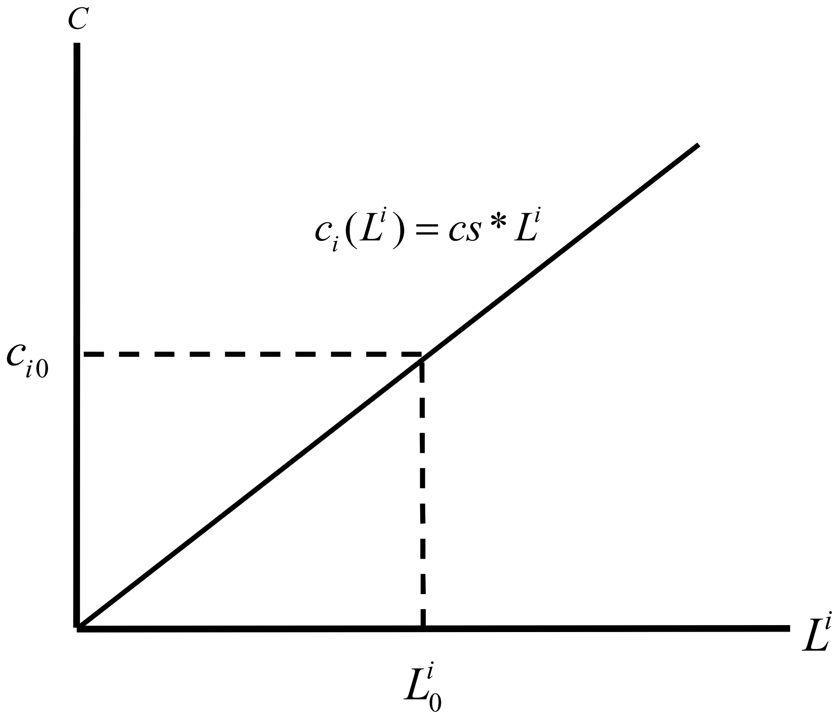


Figure 5: Carbon sequestration supply from idle land

Additional land moved into production will contribute a positive source of emissions, thereby reducing the total supply of *c*. The net effect of this source depends on the chosen management intensity level for food and energy production, and the proportion of each in the total productive land base, as discussed in the subsequent section. Equation 5 depicts the net emissions resulting from a unit shift of land into food and bioenergy respectively. Here, the system suffers a loss in carbon sequestration plus any subsequent cultivation emissions from a chosen level of management intensity.

(Equation 5)

$$\frac{\partial Y_C}{\partial L^f} = -cs + c_f(\mu_f^*) \qquad \text{if food expansion}$$

$$\frac{\partial Y_C}{\partial L^f} = -cs + c_b(\mu_b^*) - (\omega\phi_b \text{-} \tau) y_b(\mu_b^*) \qquad \text{if bioenergy expansion}$$

Emissions also vary with intensity of food and energy production (μ_j). To visualize GHG emissions at different levels of effort, and the relationship between yield productivity and emissions, consider Figure 6. Here, curves are drawn arbitrarily to depict concavity in production and increasing emissions per level of effort. Yield per unit area is represented by the vertical axis on the left side of the figure. Emissions per unit area are represented by the vertical axis on the right-hand side. The horizontal axis represents the chosen level of management intensity, $\mu_{j.}$ To reiterate, the intensity variable is defined as some functional relationship that captures the yield impacts of input use and soil management decisions. Simultaneously, the intensity proxy determines the emissions contribution of the production activity. As additional energy use increases emissions linearly, and increased N fertilizer can induce non-linear (increasing) emissions, emissions from food systems increase over the intensity horizon.

First, consider a value of $\mu_j = 0$. This would imply the absolute minimum intensity level required to produce some given level of base output, y_j^0. One could imagine this to be a labor-intensive system, perhaps with perennial crops, continuous no-till, and no fertilizer or chemical additives. The main source of capital inputs would be the energy and machinery required to initially plant the system and for harvest. Regional climate and plant growth conditions might affect productivity more than management decisions. Notice that at low levels of intensity (indicated by zone *A*), the system is producing a net GHG sink (hence, negative total emissions) such that that the carbon sequestered in productive soils outweighs the additional emissions produced form input and fossil fuel use in the system. This would likely imply a case of continuous no-till or conservation tillage practices, with limited fertilizer/chemical application, and limited fossil fuel use. Net emissions then increase quickly, such that the productive system becomes a net source at low to medium levels of μ_j. Thus, the emissions function from food production, $c_f(\mu_f)$, is increasing and convex in intensity such that:

$\partial c_f(\mu_f) \big/ \partial \mu_f > 0$, and $\partial^2 c_f(\mu_f) \big/ \partial \mu_f^2 > 0$. The implication here is that movement to the intensive margin from a low-intensity system defined by Zone A into a high-intensity system in Zone B will increase productivity, but at the expense of higher emissions. In a business-as-usual regime with no policy incentives to reduce emissions, a producer will choose the level of intensity that equilibrates the marginal costs of intensification with marginal returns. Incentives for emissions reductions, however, could cause a producer to relax management intensity if the GHG mitigation payment outweighed any expected loss in productivity from de-intensification.

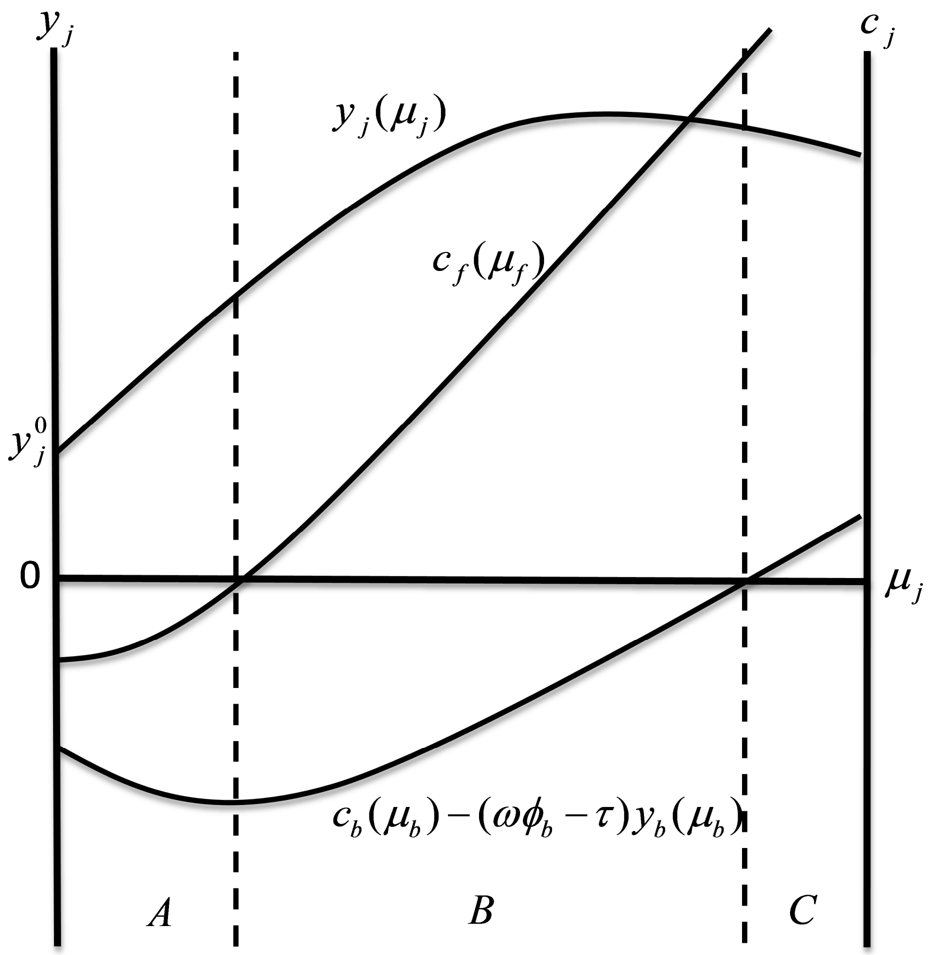


Figure 6: Emissions from productive activities

Emissions from bioenergy cropping systems take a slightly different form due to the emissions displacement effect of biofuels. Total emissions per unit area from bioenergy cropping are depicted by the bottom curve in Figure 6, and mathematically by Equation 6. Here, total emissions are a function of intensity as before, so $c_b(\mu_b)$ denotes the per-acre emissions of bioenergy cultivation. However, additional terms are needed to account for the full life-cycle emissions from bioenergy production from energy consumed for transporting and processing the biomass (defined by $\omega\phi_b$). Again, the term ϕ_b represents the energy consumed to transport and process the bioenergy (assumed constant in this model for simplicity—in reality this would vary regionally depending on processing technologies and hauling distances), while ω is a simple emissions factor for converting energy consumed to CO_2 (or similar GHG metric). The final term, τ, represents the emissions factor for an energy equivalent unit of fossil energy. Take the example of corn ethanol and gasoline. A gallon of gasoline has CO2 content equal to roughly 0.0088 tCO_2e, and ethanol is roughly 70% as efficient as gasoline on an energy equivalent basis, so τ in this case would be 0.7*0.0088 = 0.00616. Thus, in the case of corn ethanol, in addition to cultivation emissions, each unit of bioenergy produced in the system provides $\tau = 0.00616$ units of carbon through fossil fuel replacement in the transportation fuel market (assuming no leakage).

(Equation 6) $$Emit_b = c_b(\mu_b) - \left(\omega\phi_b - \tau\right) y_b(\mu_b,\theta)$$

This specification shows that increasing bioenergy crop yields will boost the supply of GHG benefits up to a point where $\partial c_b(\mu_b) / \partial\mu_b = (\omega\phi_b - \tau)\left(\partial y_b(\mu_b,\theta) / \partial\mu_b\right)$. Beyond this point, the emissions from increased intensity will outweigh the marginal GHG gains of higher energy yields. This is important for policies that impose GHG reduction thresholds on the full life-cycle GHG benefits of biofuels. While the production relationships of energy and food are considered identical, choosing alternative levels of intensity in both can affect net GHG emissions from the entire system (thus intensity in food and energy production are accounted for separately).

Consider a fixed proportion of land allocation between food and energy. Holding this proportion constant, the net GHG effect of a shift to the intensive and extensive margins is given by (Equation 7. The importance of this specification is that GHG emissions (or the supply of *c*) depend not only on the land clearing activity, but also on management responses on the intensive margins. To date, most analyses have focused on the former, but have ignored the latter.

(Equation 7)

$$\frac{\partial^2 Y_C}{\partial L^f \partial \mu_f} = \frac{\partial c_f()}{\partial \mu_f}$$

(Equation 8)

$$\frac{\partial^2 Y_C}{\partial L^b \partial \mu_b} = \frac{\partial c_b(\mu_b)}{\partial \mu_b} + \left(\omega\phi_b - \tau\right)\frac{\partial y_b(\mu_b)}{\partial \mu_b}$$

4.2.3 Profit Maximization in the Absence of Policy

Incorporating the supply of *c* directly into a land use optimization framework can illustrate analytically how policy-induced shifts to the intensive and extensive margins can impact net emissions from the system. A system with existing bioenergy mandates (or equivalent incentive) that wishes to pursue GHG mitigation might face higher abatement costs than under BAU conditions.

First, consider a simple profit maximization case in the absence of policy drivers. Here, land allocation and management intensity will depend on the relative land rents from energy feedstock, food production, and idle use. Assume that there is some implicit value on land not in L^f or L^b, which is depicted by $V_c(L^c)$. Let $w_j(\mu_j)$ represent the costs of input use for a given level of management intensity per unit land area, and let P_e

be the price of fossil energy used in transporting and processing bioenergy (processing biomass to energy requires additional cost components—previous studies have employed this component to describe the price difference between corn and ethanol). Now we can express the net returns function from land use activities in the following terms:

(Equation 9)

$$\pi = \max_{L^f, L^e, \mu_f, \mu_e} \sum_{j=1}^{J} \left(P_j Y^j - w_j(\mu_j) L_j - P_e \phi_j Y^j + V_j(L_j) \right) \quad \text{for } j = f, b$$

$$s.t. \qquad \sum_{j=1}^{J} L^j = L$$

$$\text{Where: } P_j, Y^j, w_j(\mu_j) = 0 \quad \text{for } j = c$$

$$\phi_j(\mu_j, L^j) = 0 \qquad \text{for } j = f, c$$

$$V_j(L_j) = 0 \qquad \text{for } j = f, b$$

The Langrangian for this system becomes:

(Equation 10) $L(...) = \sum_{j=1}^{J} \left(P_j Y^j - w_j(\mu_j) L_j - \phi_j(\mu_j, L^j) Y^j + V_j(L_j) \right) - \lambda \left(L - \sum_{j=1}^{J} L^j \right)$

First order conditions of this system are shown in the following equations, where a "*" is used to denote choice variables at optimality. Equations 11-13 ensure that the marginal value of land among alternative uses is equilibrated at the same shadow price (λ).

Land will be allocated such that these conditions hold on the margin; any change in the relative value one land holding will influence allocation among the other uses. For instance, a policy that increases the equilibrium commodity price of f or *b*, or mandates a greater supply of either commodity will bring more land into production (assuming no change in $V_c(L^c)$). (Equation **14** and (Equation 15 equate the marginal costs of an aggregate shift in management intensity with the marginal value of productivity gained by boosting intensity. Thus, an aforementioned policy driver could also manifest itself in higher average production intensity to enhance productivity per-unit area. Equation 16 ensures that the constraint on land allocation holds in equilibrium (that is, land cannot be created).

(Equation 11)

$$P_f y_f(\mu_f^*, \theta^*) = \lambda$$

(Equation 12)

$$P_b y_b(\mu_b^*, \theta^*) - \phi_b y_b(\mu_b^*, \theta^*) = \lambda$$

(Equation 13)

$$\frac{\partial V_c(L^{C*})}{\partial L^C} = \lambda$$

(Equation 14)

$$P_f \frac{\partial \int_0^{L^{f*}} y_f(\mu_f^*, \theta^*) dL^{f*}}{\partial \mu_f^*} = L^f \frac{\partial w_f(\mu_f^*)}{d\mu_f^*}$$

(Equation 15)

$$P_b \frac{\partial \int_0^{L^{b*}} y_b(\mu_b^*, \theta^*) dL^{b*}}{\partial \mu_b^*} = L^b \frac{\partial w_b(\mu_b^*)}{d\mu_b^*} + P_e \phi_b \frac{\partial \int_0^{L^{b*}} y_b(\mu_b^*, \theta^*) dL^{b*}}{\partial \mu_b^*}$$

(Equation 16)

$$\sum_{j=1}^{J} L^j = L$$

Assuming all second order conditions hold for this system, one can use optimality conditions to express the optimal land use totals and the intensity proxy as a function of own price, cross price, and supply of the other good. The implication is that policies that influence commodity prices, mandate the production of bioenergy, or incentivize GHG emissions reductions could alter land management trends on the extensive or intensive margins. The next sections show conceptually how biofuel and climate mitigation policies might affect market equilibrium, and additionally how such policies might alter the land use optimization problem. In addition, policy induced shifts in the demand for or price of *f* or *b* will influence land management decisions of the other. Indeed, this result has been shown in the literature for land management decisions with a bioenergy mandate (Feng and Babcock, 2010).

Note that while the joint product supply of *c* is not included in this pre-policy land allocation problem (as it does not affect optimization criteria in the absence of policy), total emissions, or the supply of *c*, can be calculated using optimal land allocation and intensity variables.

4.2.3.1 Adding a Bioenergy Mandate

First, consider the effect of a mandate on a system in market equilibrium. For simplicity, allow food and bioenergy to be derived from the same form of biomass (consistent with corn and ethanol, or soybeans and biodiesel). It has been shown that there is a distinct relationship between these prices, denoted by (Equation 17:

(Equation 17)

$$P_b = \frac{P_f}{\beta} - P_e \phi_b$$

Where:

(Equation 18)

$$\beta = \frac{\alpha\gamma}{(1-\delta_1\delta_2)}$$

The parameter β is formed of several components has been proposed in methodologies presented in Moschini et al., 2009, de Gorter and Just, 2009, and Cui et al. 2010 to show the direct price differential in food and bioenergy prices in market equilibrium. In essence, β is an adjustment factor that relates that price that can be received for a unit of food to the value of energy and food by-products that can be derived from converting a unit of food to bioenergy. Important parameters in this specification include the energy equivalence conversion factor of bioenergy relative to fossil fuel equivalents (γ), the net feedstock required to produce a unit of bioenergy output (α), the proportion of the feedstock that can re-enter the food supply chain as a byproduct (δ_1 -- an example would be Distillers Dry Grain from corn ethanol production), and the price difference of the by-product as a close substitute to the raw commodity (δ_2). Also, to get the price of bioenergy, one must also deduct the energy use and costs of transporting and processing the biomass into fuel, or $P_e\phi_b$. Thus there is a distinct relationship not only between food and bioenergy, but also between fossil energy prices, P_f and P_b.

To illustrate how a biofuel policies affect equilibrium prices for commodities, let aggregate supply functions from the system described above depict the total supply curve, and let the demand for bioenergy be reflected in the aggregate demand curve for food (as this is the primary feedstock driving energy processing). Furthermore, since f

and *b* are derived from the same biomass source, one can combine these supply curves to depict equilibrium conditions in commodity markets (which are influenced exogenously by energy markets).

(Equation 19) $$Q_f^S + Q_b^S = Y^f + Y^b = Q_f^D$$

Consider Figure 7, which depicts the equilibrium supply and demand of food and bioenergy following a format similar to recent welfare analyses of ethanol mandates (Moschini et al., 2009, de Gorter and Just, 2009, and Cui et al. 2010, Feng and Babcock, 2010). The vertical axis on this figure represents the Here, the equilibrium price for food is not met as distortionary policies in the energy sector, such as ethanol blending requirements and production tax credits for biofuels drive the price of food to P_f^0. The initial supply of food and energy are Q_f^{S0} and Q_b^{S0} respectively.

What happens if a stringent mandate requires additional bioenergy from the system? Letting *B* denote the volume of the mandate (hence, $Q_b^1 = B$), this forces a wedge between equilibrium supply and demand, effectively requiring more feedstock production from the system than would have realized under pre-policy conditions. This would boost the equilibrium prices of food to P_f^1, while reducing the supply of food to Q_f^1. With higher food prices, the price of bioenergy climbs as well to a new level of

$$P_b^1 = \frac{P_f^1}{\beta} - P_e\phi_b.$$

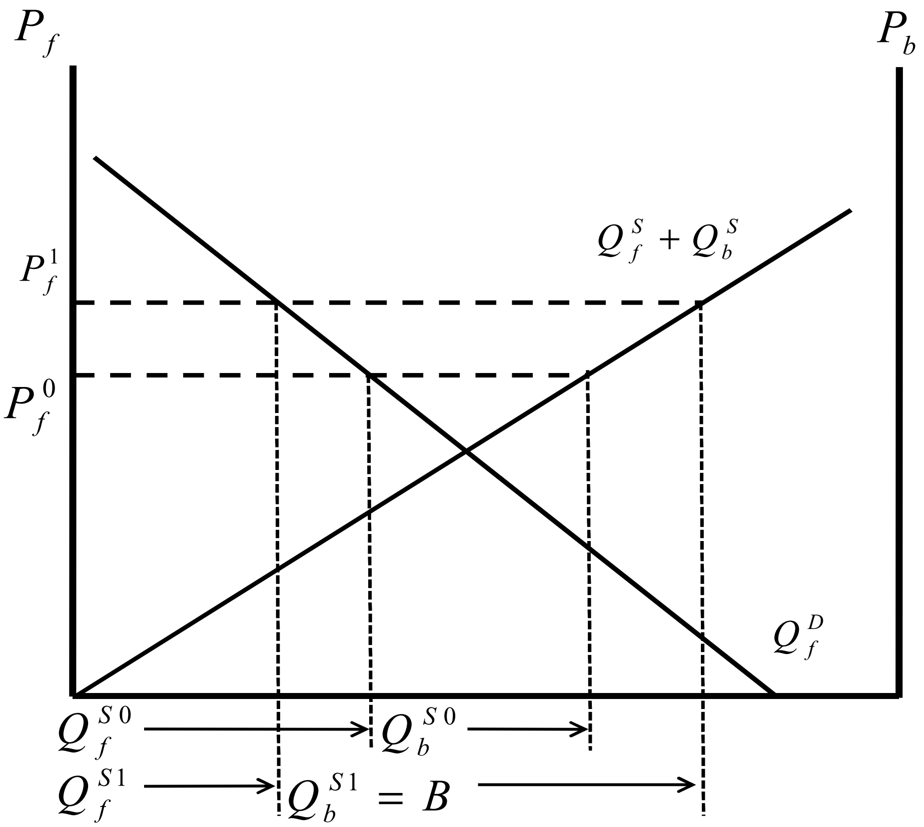


Figure 7: Food and bioenergy market equilibrium with a mandate

Returning to the optimization framework from Equation 9, there are two ways in which the effects of a bioenergy mandate can be incorporated into the model, with similar implications for land management. For a simple producer optimization problem of a single landowner that is a price-taker, one can simply compare optimal land management under baseline and policy-induced price regimes. Alternatively, one could model the land allocation problem as a Social Planner problem in which regional land resources are allocated to produce *f* and *b*. In such a case, one could model the exogenous shift in prices, and a mandatory production threshold for *b* that would not be there under pre-policy conditions. Holding the value function for idle land constant in this new policy regime, the mandatory level of *b* would imply a re-distribution of land resources. Feng and Babcock discuss the influence of an ethanol mandate on land allocation, deriving total expansion and intensification effects across different cropping systems. The Feng and Babcock results are straightforward and applicable to the model presented here—higher prices bring additional land into production, but as this land is of a lower quality, overall intensification occurs to maintain average productivity across the system. That is, if an acre of existing food production is replaced by an acre of energy, a market response would be to demand more food production. If expansion occurs to replace that lost acre, this would be of a lower quality, thus intense management would be required to fully replace the lost acre of production. Thus, by imposing mandatory production levels of b, one can induce expansion of L^f and increase μ_j to make up for the lost productivity.

4.2.3.2 Adding GHG Intensity Thresholds

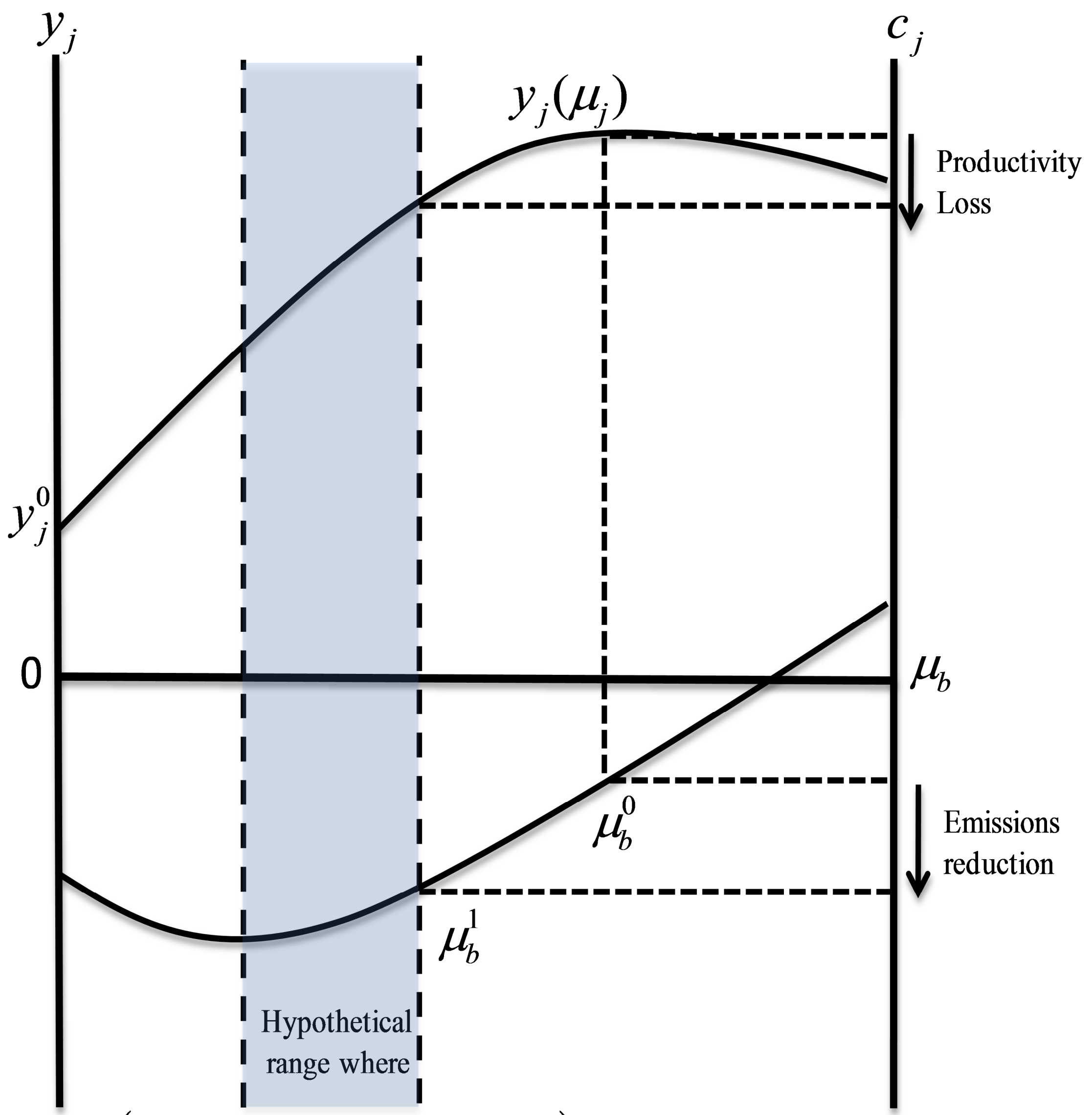
In addition to the binding mandates, the RFS2 and California's LCFS include GHG reduction thresholds for bioenergy. These stipulate that the full life-cycle emissions displacement of renewable fuel must offset fossil fuel emissions by X%. Typically, these metrics involve some correction for indirect LUC emissions internationally, but mostly they are concerned with the well-to-wheel life-cycle emissions from the bioenergy. Assuming that the energy equivalent GHG displacement of bioenergy stays constant (τ), this means that a threshold is imposed on GHG intensity of biofuels in order to maximize the emissions displacement potential from the production system. One idea behind this sort of policy mechanism is to promote sustainable biomass production with limited environmental degradation to reduce emissions from fossil fuel use and promotes alternative forms of energy without sacrificing the productivity of conventional crops. However, such emissions intensity thresholds could reduce overall production and can lead to additional leakage that would not have occurred with just the binding mandate.

Emissions intensity of bioenergy cropping systems can by reduced by lowering cultivation emissions ($c_b(\mu_b)$), or by lowering transport and processing emissions ($\omega\phi_b$). For simplicity, assume that only cultivation emissions can be altered. Thus, emissions intensity for bioenergy must fall below some policy-mandated threshold, ξ. Equation X displays the emissions intensity threshold, where emissions intensity is defined as total emissions per unit area divided by yield:

(Equation 20)

$$\frac{\left(c_b(\mu_b) - (\omega\phi_b - \tau)\, y_b(\mu_b)\right)}{y_b(\mu_b)} \le \xi$$

Following Figure 7 this implies that production and emissions intensity would have to lie somewhere in the range highlighted in blue below (as indicated by Figure 8) such that the per-unit emissions displacement of bioenergy reaches the mandated threshold ξ. Intensity to the right of this area would imply excessively high cultivation emissions, though falling to the left of the shaded area would imply low yields. Assuming that production intensity of bioenergy lies somewhere outside of this range without a GHG reduction threshold, a reduction would be required, thus prohibiting excessive production intensity. For example, if production intensity from the system was initially at μ_b^0 but this violated the emissions threshold, then a decrease in intensity to at least μ_b^1 would be necessary for the system to comply with the intensity threshold. Note that while this de-intensification implies a net reduction in emissions from cultivation, such a shift would lower per-acre productivity as well.



$$\frac{\left(c_b(\mu_b)-(\omega\phi_b-\tau)y_b(\mu_b)\right)}{y_b(\mu_b)}\leq\xi$$

Figure 8: Illustrating the effects of LCFS on production intensity

If a mandate still binds, an overall reduction in bioenergy production intensity would imply a greater allocation of land into bioenergy. As the mandate binds, any reduction in productivity per unit land would require additional land to hit the quota, leading to a re-allocation of land that reduces food production. First, reduced emissions intensity from a bioenergy cropping system could imply decreased transportation emissions from cultivation to processing location, meaning a smaller radius of bioenergy production surrounding the energy facility. This reduced radius implies a greater proportion of energy production within that area, or a trade-off from convention or idle use to bioenergy. The second reason is more intuitive—land is less productive on the margin, and hence requires greater intensity to achieve average productivity levels. Since the point of a GHG threshold is to reduce emissions intensity of production, bioenergy expansion onto marginal cropland would likely not occur. Instead, a producer would substitute productive land currently used for food wherever reductions in management intensity and emissions are possible without sacrificing much in the way of yield. Over the long-term, such a replacement would lead to expansion in conventional commodity production, perhaps onto marginal lands that require intensive cultivation.

If reduced management intensity in *b* requires greater levels of L^b, this would reduce the supply of the conventional commodity, subsequently raising the price, as depicted by Figure 9. This figure builds upon the previous depiction of the effect of the mandate *B* on the supply of *f* and *b*. Now, there is a reduction in total supply due to restrictions on intensity. Supply decreases from $\left(Q_f^{S1}+Q_b^{S1}\right)$ to $\left(Q_f^{S2}+Q_b^{S2}\right)$, and equilibrium prices are increase from P_f^1 to P_f^2.

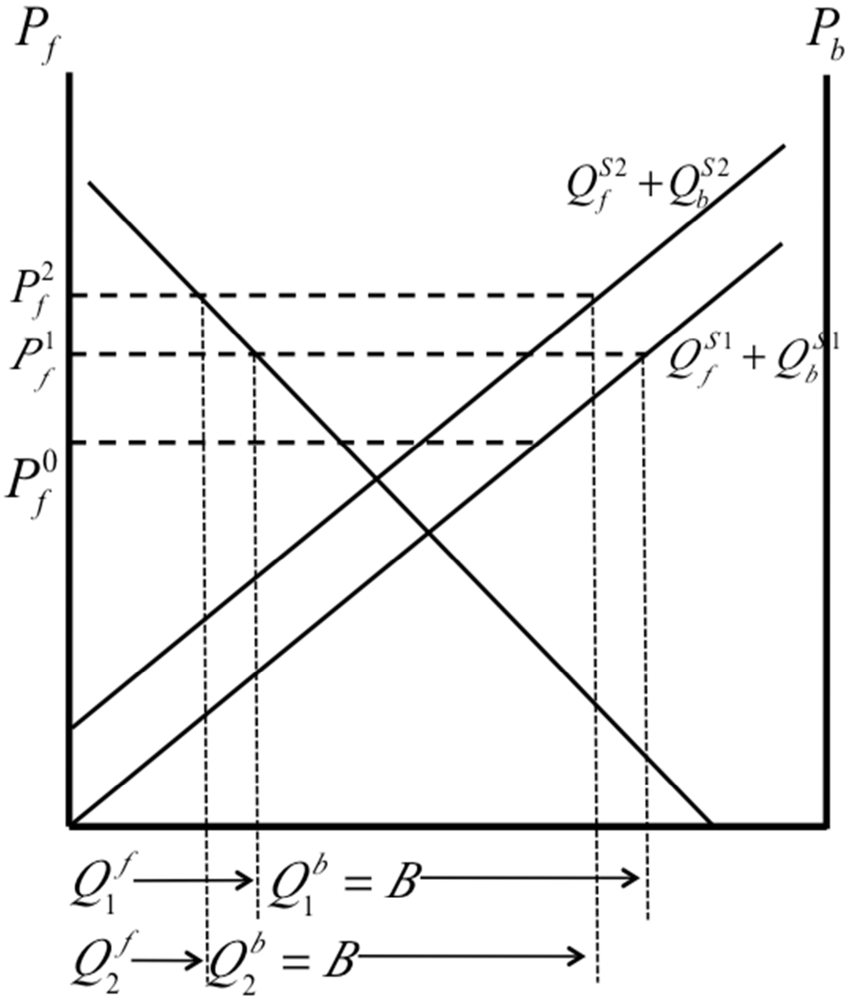


Figure 9: Food and energy market equilibrium with a mandate and GHG intensity thresholds

The following mathematical expression augments the original optimization problem by adding the mandate constraint and the emissions intensity inequality:

(Equation 21)

$$\pi = \max_{L^f, L^e, \mu_f, \mu_e} \sum_{j=1}^{J} \left(P_j^2 Y^j - w_j(\mu_j) L_j - P_e \phi_j Y^j + V_j(L_j) \right) \quad \text{for } j = f, b$$

$$s.t. \qquad \sum_{j=1}^{J} L^j = L$$

$$Y^b = B$$

$$\frac{\left(L^b c_b(\mu_b) - \left(\omega \phi_b - \tau \right) Y^b \right)}{Y^b} \leq \xi$$

Where: $P_j^2, Y^j, w_j(\mu_j) = 0$ for $j = c$

$\phi_j(\mu_j, L^j) = 0$ for j = c, f

$V_j(L_j) = 0$ for $j = f, b$

B = Mandate

$\xi =$ Emissions Intensity Threshold

Optimality conditions from the system would reflect the mandate and GHG intensity threshold for bioenergy. That, in addition to the higher equilibrium prices, P_j^2, could induce additional land expansion and intensification in *f*. Thus, while GHG thresholds can reduce emissions from bioenergy production, such policies can potentially lead to land use shifts and intensification for food production system at a greater rate than a mandate with no GHG reduction thresholds. Once again, the supply function for *c* does not enter the objective function explicitly, but implied land management patterns in optimality can be used to estimate net emissions.

4.2.3.3 Adding GHG Mitigation Incentives

Now, in addition to policies that function similarly to the RFS2, we can explore what happens to the system when GHG mitigation incentives are included into the optimization framework. First, it is important to note that any price-based GHG mitigation incentive mechanism would ideally target emissions reductions that are additional to emissions under baseline practices. For such a policy to be successful, one must first establish baseline emissions for the land us system. Let Y_c^0 represent net emissions under business-as-usual conditions. Using optimal land use shares and intensity proxies, baseline emissions would be given by the following equation:

(Equation 22)

$$Y_C^0 = cs \cdot L^{C\,0*} - L^{f\,0*} c_f(\mu_f^{0*}) - L^{b0*} c_b(\mu_b^{0*}) - \left(\omega\phi_b - \tau\right) Y^{b0*}$$

Now assume that a mitigation policy is enacted that creates a price incentive for emissions reduction within the land use system. The most obvious example would be a carbon offset market that pays farmers for emissions reduction or enhanced sequestration, but other similar programmatic approaches could exist (such as a voluntary program akin to the CRP that pays landowners to adopt mitigation practices and pays them some established mitigation price). For this model, let P_c denote the value of the mitigation price incentive. Also, let Y_c^1 be total emissions from the system after the establishment of the GHG mitigation policy. Thus, the total supply of creditable mitigation from the terrestrial system is given by:[19]

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[19] This specification does not account for leakage of emissions that accompany productivity reductions.

$$Offset\_Supply = \overline{Y^{c0}} - Y^{c1}$$

(Equation 23)

Where $\overline{Y^{c0}}$= baseline emissions

Any reduction in total emissions can come from reductions in μ_b or μ_f, or through a land use shift out of production for carbon sequestration (that is, higher levels of L^c). If a bioenergy mandate binds, then no additional *b* can be produced for mitigation. However, if *B* is not binding (that is, we replace the previous constraint with an inequality), then additional *b* production could contribute to mitigation goals. Note that not all variables need to move uniformly towards mitigation. That is, net emissions reduction might be achievable through greater levels of L^c, accompanied by intensification (increased μ_j). Changes in any of the land use or management variables will imply different levels of production emanating from the system as well.

The new welfare function reflects this new GHG mitigation supply function (relative to baseline emissions). No new constraints are added to the system (depicted by (Equation 24). However, a new term in the objective function that internalizes the value of GHG mitigation through shifting land management patterns, thus incentivizing reductions in intensity or a reallocation of land for increased carbon sequestration:

(Equation 24)

$$\begin{aligned}\max_{L^f, L^e, \mu_f, \mu_e} \pi &= P_f Y^f - w_f(\mu_f) L_f \\ &P_b Y^b - w_b(\mu_b) L_b - P_e \phi_b Y^b \\ &+ V_c(L_c) + P_c(\overline{Y^c} - Y^c)\end{aligned}$$

$$\begin{aligned} s.t. \qquad & \sum_{j=1}^{J} L^j = L \\ & Y^b = B \\ & \frac{\left(L^b c_b(\mu_b) - \left(\omega\phi_b - \tau\right) Y^b\right)}{Y^b} \leq \xi \end{aligned}$$

Where: B = Mandate (optional)

Optimality conditions for the system could fundamentally change in this scenario as the value of idle land is adjusted to account for carbon sequestration potential, or as different levels of intensity are chosen for emissions reduction. Before, bioenergy policies affected the value of productive lands, but now land is reallocated as rents from production compete with the value of carbon sequestration. On the margin, a new unit of land moved to L^c would now include the value of carbon sequestration. This relationship is displayed in the following equation:

(Equation 25)

$$\frac{\partial V_c(L^{c*})}{\partial L^c} + P_c cs = \lambda$$

For a sufficiently high P_c this additional value on idle land assures, at the very least, that production expansion will occur at a slower rate than in the absence of the mitigation policy, implying reduced land use change under a carbon pricing regime.

Now, as the cost of emissions from management intensity is internalized, the marginal value of an additional acre of productive land must be balanced with the costs of that land and the GHG costs of management intensity level μ_j*. Thus, the offset value of changing management intensity must equate with the marginal returns to such a shift.

If commodity prices adjust to supply contraction, the existence of a carbon offset market might not imply a net reduction in intensity. If the commodity price effect of the mandate or shifting land out of production is large enough, or if reductions in intensity only produce small GHG benefits, this could induce an intensification effect that boosts emissions $\left(c_f^0(\mu_f^0) < c_f^1(\mu_f^{1*})\right)$. However, with more moderate shifts in commodity prices and a carbon price that is sufficiently large, one would expect a reduction in management intensity relative to the baseline due to the opportunity costs of forgoing carbon offset credits. The returns to a marginal unit of idle land should be equal to the marginal costs of land conversion, and the opportunity costs of taking land out of production (or $\frac{\partial V_c(L^{c*})}{\partial L^c} + P_c cs$). Note that the opportunity costs of taking land out of production will increase as more land is idled (and as the productivity of land increases with L^c, thus the landowner is surrendering higher quality land with each additional unit of L^c).

4.2.3.4 Combining a Bioenergy Mandate with GHG Mitigation Incentives

To reiterate, the supply of GHG abatement from this representative land use system could come from reductions in management intensification, further production of bioenergy beyond baseline levels, and through land set-asides for carbon sequestration. However, as the previous section argues, bioenergy mandates could increase land use and management intensity. Thus, there are two important interactions of biofuel mandates and GHG mitigation that warrant further attention.

First, a viable market or policy incentive for emissions reduction could reduce the initial land use change and production intensity concerns brought on by the bioenergy expansion policy for any value of P_c. The full extent of this effect he full extent of this effect would depend on the magnitude of P_c, and the magnitude of the bioenergy policy-induced commodity price shifts in P_b^1 and P_f^1. Thus, there is a balancing effect at play, where movement to the intensive and extensive margins is driven in one direction by the bioenergy policy, and in another by the mitigation policy. A high enough value of P_c could introduce a contraction effect, where the total supply under the carbon price regime is lower than under baseline conditions. As the mandate still binds, such a contraction would imply significantly higher prices for food and energy output.

The second important interaction deals with the overall costs of mitigation. If a binding mandate boosts prices and returns productive land, this makes it more expensive to move land into L_c or reduce intensity for mitigation purposes by raising the marginal value of production. This implicitly increases the marginal compensation required to reduce GHG emissions or alter land use for carbon sequestration. Thus, the mere existence of a biofuel mandate shifts the supply of GHG mitigation inward by increasing the marginal costs of GHG abatement. This is depicted by the inward shift in the supply of mitigation from Y_0^C to Y_1^C in Figure 10.

An emissions intensity threshold for bioenergy has a slightly different effect. If the emissions threshold imposes a bound on emissions intensity (and hence, μ_b) that is below baseline production intensity, this arbitrarily lowers potential GHG reductions options for bioenergy cropping systems. Additionally, it decreases flexibility in the system for allocating productive land to carbon sequestration and boosting intensity to make up for lost productivity (as μ_b is potentially constrained). This again will restrict the supply of additional offsets from the system, as illustrated by the second supply shift in Figure 10, or the movement from Y_1^C to Y_2^C).

Thus, resource requirements and price effects of a mandate and the decreased management flexibility of a bioenergy emissions intensity threshold could make GHG mitigation from land-based activities more costly. The net market and environmental effects of combined bioenergy and GHG mitigation policies are more fully assessed in subsequent chapters.

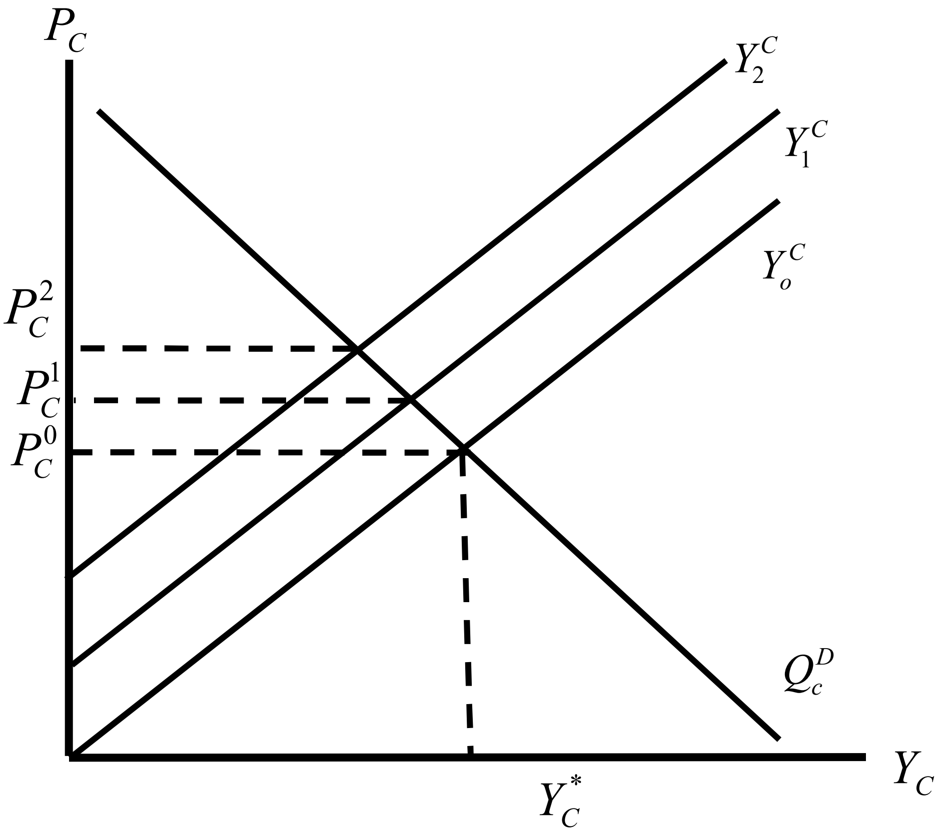

Figure 10: Effects of bioenergy policies on equilibrium GHG mitigation price and supply

4.2.3.5 Expanding the Problem to Multiple Regions

To finish this chapter, consider the problem of managing land resources across multiple regions, each with different biophysical characteristics that affect yield productivity and carbon sequestration potential. For simplicity, consider a two-region case. Aggregate supply of food energy and carbon from this system is found by summing over total production in each region. Region 1 can be described as very productive; both in terms crop yield and carbon sequestration potential. This is shown in Figure 11, which plots yield productivity per-unit area as a function of management intensity on the left-hand side, and the linear relationship between annual carbon sequestration and idle land (L^c) on the right-hand side. Notice that Region 1 is not only more productive in f and b per-unit area, but that idle land in Region 1 sequesters carbon at a much higher rate.

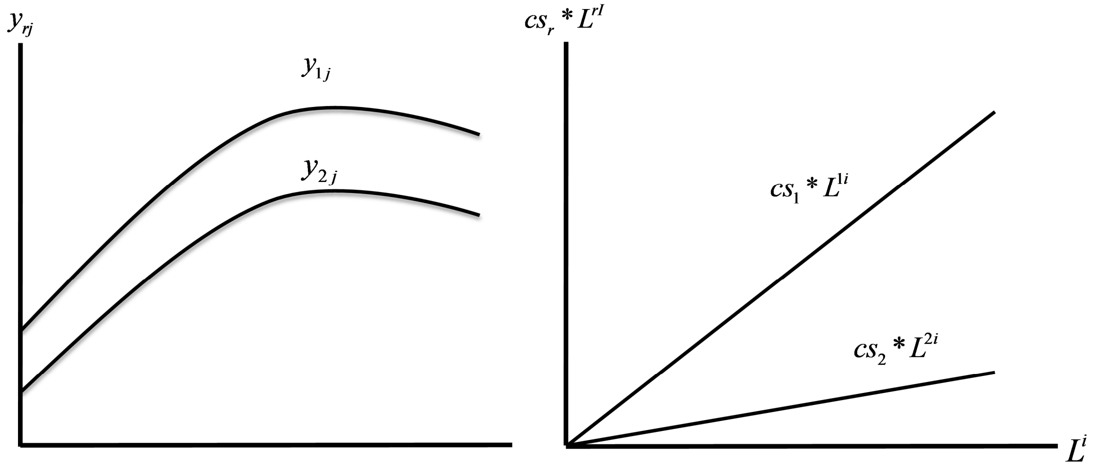

Figure 11: Land characteristics of the two-region model

The following system incorporates production functions and carbon sequestration parameters for both regions directly into the model:

$$\max_{L^f, L^e, \mu_f, \mu_e} \pi = \sum_{r=1}^{R}\sum_{j=1}^{J}\left(P_j Y^{jr} - w_{jr}(\mu_{jr})L_{jr} - P_e\phi_{jr}Y^{jr}\right) \quad \text{for } j = f, b$$

$$+\sum_{r=1}^{R} V_{ir}(L_{ir}) + P_c(Y_0^{cr} - Y_1^{cr})$$

(Equation 26)

$$s.t. \qquad \sum_{j=1}^{J} L^{jr} = L^r \qquad \forall \ r$$

$$Y^b = B$$

$$\frac{\left(L^b c_b(\mu_b) - (\omega\phi_b - \tau)Y^b\right)}{Y^b} \leq \xi$$

Where: $\phi_j(\mu_j, L^j) = 0$ for $j = i, f$

B = Mandate

ξ = Emissions Intensity Threshold

In this new specification, the model will allocate land resources in each region given a policy landscape and market conditions. Each region has its own endowment of land, but aggregate production of food, bioenergy, and carbon is the sum of total supply in each region. The purpose of illustrating this model is to show that in more complex systems composed of multiple regions with different geographic and biophysical characteristics, land use shifts to the extensive and intensive margins will vary. For example, a sufficiently high carbon price could induce cropland contraction and reduced intensity in the more productive region while expanding production in the other, as the productive region has an absolute advantage in both production and carbon sequestration. Incidence of such shifts is tested in the empirical chapters of this dissertation.

4.2.4 Relevance of Intensity to Environmental Quality

Non-GHG environmental impacts of agricultural offsets are perhaps of more concern than pure GHG leakage. An important factor that has been relatively ignored to this point is the importance of the intensity proxy, μ_{jr}, and how spatial production patterns and GHG abatement portfolios might shift resource consumption and agricultural pollution to regions with little advantage in GHG mitigation. Such an impact occurs as an indirect response to higher commodity prices as indicated by the multi-region model above.

A simple conceptual model can illustrate the expansion and intensity effects of various policy drivers, but ultimately a fully integrated model with detailed information on production practices, land quality, spatial crop mix patterns, and biophysical parameters capturing pollution and GHG effects of management activities is needed to understand the net effect of shifting land use patterns. The following chapters seek to more fully understand the unintended consequences of national biofuel expansion and GHG mitigation incentives on non-GHG variables such as water consumption and quality, nutrient use, and energy use by region.

4.2.5 The Importance of Dynamics

Additionally, land management decisions (particularly in forestry) are typically made intertemporally, especially in the forestry sector. This chapter has ignored the land use and terrestrial dynamics. By not modeling the land allocation problem under low-carbon incentives using comparative dynamics, it is likely that I have underestimated

GHG emissions from land clearing, underestimated GHG mitigation potential, and overestimated the full land use consequences of a policy shock. A dynamic model allows for market adjustments to occur more smoothly, instead of assuming a one-tie adjustment to a policy perturbation. The empirical modeling to follow uses an intertemporal model that can assess land use competition, markets

4.3 Conclusions

This chapter has presented a simple model of land allocation and management to illustrate how bioenergy policies and land-based GHG offset incentives interact. The model can be used to show that mandates, GHG intensity metrics for bioenergy, and GHG mitigation will contract the supply of conventional food production. In an equilibrium framework, this implies higher commodity prices. A bioenergy mandate will lead to production expansion and intensification in food and energy cropping systems. Pursuing GHG intensity metrics for bioenergy in addition to a mandate can boost prices further by restricting bioenergy management options (and hence, food supply). GHG mitigation incentives subsidize landowners for GHG reductions from decreased intensity and through reallocation of land for carbon sequestration, though this also constricts supply and boosts prices. Also, bioenergy policies restrict the supply and raise the price of land-based GHG mitigation. The following chapters will expand on this theory and address land use shifts using a detailed economic model.

CHAPTER V

EMPIRICAL MODELING FRAMEWORK

The U.S. Forest and Agricultural Sector Optimization Model with Greenhouses (FASOMGHG) to simulate production responses, land use decisions, and market effects of bioenergy and climate mitigation policies. An introduction to the modeling framework is provided, including recent advances pertinent to this analysis. Then, I discuss the simulation scenarios that form the remainder of this dissertation.

5.1 Modeling Framework: FASOMGHG

This analysis uses the Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG) for this analysis. FASOMGHG has been used in a wide range of studies to evaluate the economic effectiveness of AF-GHG mitigation in the U.S., biofuels, bioenergy, and the subsequent environmental co-effects of such strategies (McCarl and Schneider, 2001, Murray et al., 2004, Murray et al., 2005, Pattanayack et al., 2005, Schneider et al., 2007, Schneider and McCarl, 2005). The FASOMGHG scope and structure allows evaluation of GHG mitigation strategies in the AF sectors and the impact of renewable energy standards on the agricultural supply chain (Murray et al., 2005; Schneider and McCarl, 2003).

FASOMGHG was recently updated (from the version used in Murray et al., 2005) to provide a better portrayal of contemporary forestry and agriculture (Baker et al., 2009). Advances include additional bioenergy activities representing new marketable alternatives for food and timber commodities, as well as residual by-products of harvest and production. The model is particularly unique in its ability to evaluate a full suite of biofuel feedstocks for processing ethanol, cellulosic ethanol, and biodiesel; FASOMGHG now contains more than twenty alternative biofuel feedstocks for processing starch- or sugar- based ethanol, cellulosic ethanol, and biodiesel, and a variety of AF feedstock sources for bioelectricity (with options for 100% or co-fired biomass generation).

Updated technological growth assumptions offer the most up-to-date picture of when advanced biofuel technologies will be economically feasible, drawing from literature and information used by the US-EPA to create RFS2 rules and regulations. Commodity demand, energy market, and input cost growth assumptions have been updated to accurately represent current and future market conditions. The forestry sector has also been updated to 5-year time steps (previously the model was solved in 10 year intervals), recent timberland inventory, distribution of ownership, and harvest schedules with an extensive processing sector and the addition of many manufactured product forms. Additional forest management options were also introduced.

FASOMGHG methodology allows for explicit land use competition between multiple land uses, as a subsequent section will discuss. FASOMGHG is disaggregated into 63 minor production units in the lower 48 states, and 11 main agri-forestry regions. All major FASOMGHG agri-forestry regions include crop and forestry production opportunities except for the Great Plains and Southwest (which includes most of Texas and Oklahoma).

In addition to land use competition, FASOMGHG portrays a full suite of GHG mitigation options, including biological sequestration of carbon in agricultural soils and forest stands, alternative crop and livestock production practices to reduce emissions, and bioenergy feedstock substitutes for fossil fuels. The gasses represented are carbon dioxide, methane and nitrous oxide.

Forest carbon balances are tracked using a methodology consistent with the Forest Carbon accounting system, FORCARB (Birdsey et al., 2000). Forest carbon is tracked in trees, soils, understory, and end products. Forest management offset opportunities are endogenously modeled in FASOMGHG, and include avoided deforestation, rotation extensions, altered species mix, partial thinning, and reforestation. Carbon sequestration rates for forest management opportunities vary significantly by region, topography, and other factors, but typically range 2.1-3.1t CO_2e acre^{-1}year^{-1} (Murray et al., 2005). Bioelectricity production possibilities from forest biomass are possible from a variety of sources. All biofuels and bioelectricity options modeled are listed in Appendix A.

Most of the agricultural mitigation activities discussed in Chapter II are explicitly modeled in FASOMGHG, including:

- sequestering carbon through cropland tillage change,
- reducing nitrous oxide emissions from fertilizer and manure/livestock,
- reducing methane emissions from livestock, manure handling, and rice cultivation,
- sequestering carbon by diverting land to forests and grasslands,

For a more comprehensive list and discussion of mitigation activities in AF there are a variety of sources available (McCarl and Schneider, 2001, Murray et al., 2005). Other recent additions to FASOMGHG have improved our ability to model agricultural soil carbon balances dynamically, and track soil carbon balances when land use changes occur. Changes in overall crop mix strategies or tillage practices (modeled endogenously) can boost carbon sequestration. We model N_2O emissions reductions from changes in nitrogen (N) fertilizer use through overall changes in crop mix and reductions in on-farm N use levels. Emissions factors (and subsequent yield impacts) are based on estimates from the CENTURY model (S.M. Ogle et al., 2009), which is used for the U.S. annual GHG inventory. We also model livestock emissions mitigation in accordance with EPA GHG inventory methods and mitigation cost estimates.

5.2 Price Endogenous Framework

FASOMGHG is price endogenous, and hence solves for price and quantity combinations by maximizing the sum of producer and consumer surplus for all primary and secondary commodities (Bruce A. McCarl and Thomas H. Spreen, 1980). The price endogenous framework is a popular modeling technique for partial equilibrium (PE) as market-clearing price and quantity combinations of produced commodities and factor input usage can be solved for, while evaluating the distributional impacts of market or policy shocks. A general algebraic representation of the price endogenous model with product demand for a number of goods and factor supply from a number inputs, with multiple production processes is provided below:

(Equation 27)

$$
\begin{array}{lllllll}
\text{Max} & \sum_{h}\int_{0}^{Z_h} P_{dh}(Z_h)\, dZ_h - \sum_{i}\int_{0}^{X_i} P_{si}(X_i)\, dX_i & & & & & \\
\text{s.t.} & Z_h & & - \sum_{\beta}\sum_{k} C_{h\beta k} Q_{\beta k} & \leq & 0 & \text{for all h} \\
 & - & X_i & + \sum_{\beta}\sum_{k} a_{i\beta k} Q_{\beta k} & \leq & 0 & \text{for all i} \\
 & & & \sum_{k} b_{j\beta k} Q_{\beta k} & \leq & Y_{j\beta} & \text{for all j and } \beta \\
 & Z_h, & X_i, & Q_{\beta k} & \geq & 0 & \text{for all i, h, k and } \beta
\end{array}
$$

Here, many different types of firms (β) are being modeled, each with a finite set of production processes (k) that combine fixed factors (j) with purchased factors (i) to produce commodities (h). The symbols in the formulation are as follows:

- $P_{dh}(Z_h)$ is the inverse demand function for the h^{th} commodity.
- Z_h is the quantity of commodity h that is consumed.
- $P_{si}(X_i)$ is the inverse supply curve (marginal) for the i^{th} purchased input.
- X_i is the quantity of the i^{th} factor supplied.
- $Q_{\beta k}$ is the level of production process k undertaken by firm β.
- $C_{h\beta k}$ is the productivity (yield) of product h from production process k.
- $b_{j\beta k}$ is the quantity of the j^{th} owned fixed factor used in producing $Q_{\beta k}$.
- $a_{i\beta k}$ is the amount of the i^{th} purchased factor used in producing $Q_{\beta k}$.
- $Y_{j\beta}$ is the endowment of the j^{th} owned factor available to firm β.

Kuhn-Tucker conditions from this system require that the shadow price on the first and second rows are, respectively, the demand and supply prices. First order conditions also maintain that production levels are set so the marginal value of the commodities produced is less than or equal to the marginal costs of the owned and fixed factors for each $Q_{\beta k}$.

The area under the product demand and factor supply functions makes the objective function equal consumer plus producer surplus, which is the net social benefit generated by the market exchange of these goods. The solution of the model generates equilibrium price and quantity for each output, and purchased input, along with the imputed values for the owned factors of production. The competitive behavior simulating properties of this formulation provides a powerful tool for policy simulation. Scenario analysis can be applied to a price endogenous setting to determine the extent to which exogenous policy shocks disrupt optimal demand and supply projections and output prices.

FASOMGHG is fully dynamic in most variables, and thus maximizes inter-temporal economic welfare. The model uses constant elasticity demand functions that are calibrated with elasticity parameters from a variety of public and academic sources. As exogenous policy factors drive production or land use away from the baseline levels in response to bioenergy expansion or GHG mitigation policies, the price endogenous model accounts for these market adjustments over time by depicting changes in equilibrium prices and quantities supplied of all primary and secondary commodities. As commodity markets within AF are highly interdependent, a systematic shock that disrupts the optimal production portfolio of one commodity (e.g., corn) can cycle through other primary or secondary commodity markets (such as ethanol and livestock which use corn as a critical factor input, or corn substitutes such as alternative feed grains).

5.2.1 Factor Input Use and Environmental Variables

To measure overall responses to exogenous policy shocks on the intensive margins, I rely on FASOMGHG crop management options with varying levels of input use, and emissions factors for several important environmental variables. The model has detailed crop budget parameters for each region/crop/management combination, in which a set of factor inputs is used for each sub-regional production activity entering the solution set. The amount of input use in each sub-region depends on chosen management intensity levels and overall crop mix strategies. Production can be irrigated or dryland, with varying levels of tillage intensity (conventional, conservation, and no-till), and nitrogen fertilizer application (full, 85%, and 70%). Input use is consistent with regional estimates provided by USDA-ARMS data. Each management regime has an accompanying crop yield, so changes in management intensity are accompanied by a yield response.

Management intensity has implications for regional water use (depending on the proportion of dryland to irrigated production chosen). Additionally, soil carbon dynamics and overall GHG emissions are influenced by the production intensity decision. FASOMGHG contains detailed biophysical data on GHG emissions, pollution, yield, input use, and carbon sequestration of regional crop production. GHG emissions factors provide the requisite information on the net per-acre emissions associated with a particular crop management option.

Land use changes are accompanied by shifts in carbon balances between land uses. FASOMGHG simulates land competition and transformation between forest, cropland, pasture, and conservation lands (CRP), yielding estimates of domestic indirect land use change emissions. Land competition is critical to this analysis, as land values can be driven in diverging directions from bioenergy and climate mitigation objectives. FASOMGHG weighs all policy forces and allocates land efficiently over time between the different uses to satisfy the demands for conventional commodities, bioenergy, and GHG offsets.

In addition to land use changes, production responses to exogenous policy stimuli are manifested in management intensity changes. Additional environmental variables tied to management intensity are also tracked in the model. Thus, through comprehensive GHG accounting and multiple production possibilities, FASOMGHG is able to estimate a variety of local environmental damages and global GHG emissions (or sequestration), and how these might be altered in alternative policy regimes. These include N percolation and runoff, NO3 runoff and subsurface loss, soil and wind erosion, use of other harmful inputs (herbicide, phosphorous, etc.).

5.3 Model Modifications for this Study

Here I discuss recent FASOMGHG modifications made to accommodate this analysis. These modifications include:

- Updated energy market assumptions consistent with the Annual Energy Outlook (AEO) 2008 and 2009 reports, with options for testing the sensitivity of AF production patterns and land use on energy market assumptions,
- Updated land use categories and methodology for depicting land use competition and land use change,
- Inclusion of a CRP recultivation supply curve,
- Welfare disaggregation in the AF sectors.
- Asymmetric incentives for GHG mitigation activities

5.3.1 Updated Energy Market Assumptions

FASOMGHG incorporates recent projections of energy prices and consumption (AEO 2008, AEO 2009) to depict up-to-date energy market conditions and energy input costs. This is an improved approach over past sectoral modeling efforts that keep the price of these critical inputs constant over time. This allows us to simulate:

- The effects of energy price induced operating cost increases on production decisions over a dynamic time horizon,
- How differences in input costs affect long term investment decisions and land use change,
- The market interactions of bioenergy and fossil fuels, and the relative value of bioenergy when relative GHG emissions reductions are valued across mitigation schemes

- The sensitivity of modeling results to energy market assumptions (AEO 2008 and 2009 projections are quite different)[20]

Before this dissertation was completed, extensive sensitivity analyses were performed on energy market assumptions. Figure 12 displays energy price projections for AEO 2009 (indexed off of 2004 values). AEO projections end in 2030, so we extrapolate beyond that period using an average linear growth rate for projections from 2015-2030, where prices trend upward at a relatively modest rate.

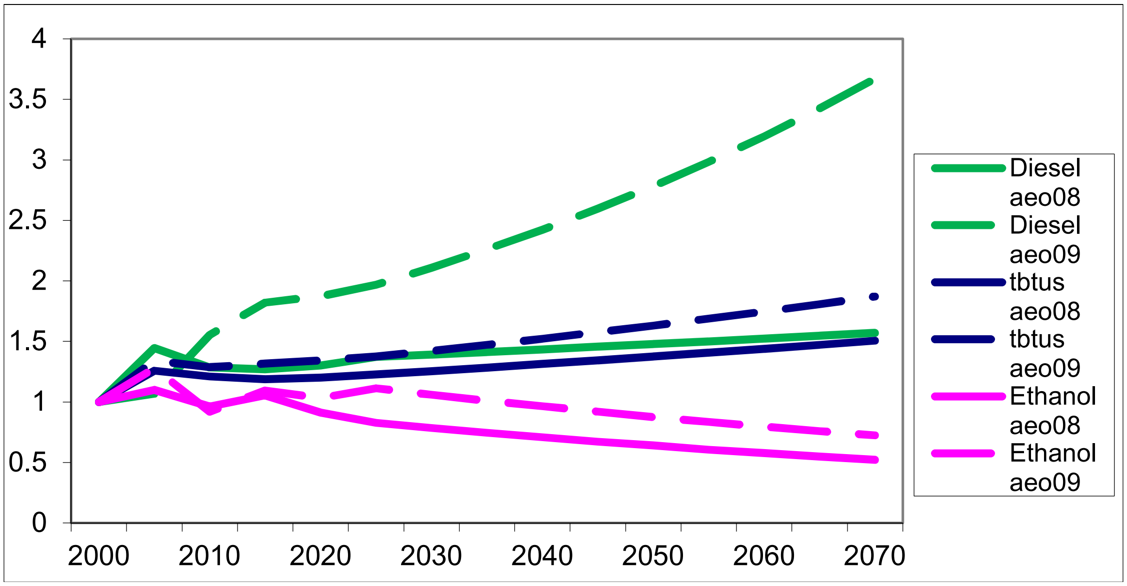

Figure 12: Price trajectories for energy commodities by AEO report date (Source: EIA 2008 and 2009)

Notice that AEO 2008 and 2009 estimates vary considerably. Relying on different sets of price trajectories can have resounding impacts on model results. This

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[20] This is a critical issue. As FASOMGHG uses parameters estimated from other sectoral models (in this case, the National Energy Modeling System, or NEMS), results are often sensitive to byproducts of alternative modeling efforts.

dissertation relies on the latest projections (AEO, 2009), but future work will explore these sensitivities further.

The price of ethanol is equivalent to the ethanol wholesale price, archived in AEO reports beginning in 2006. The price of biodiesel is based off of historic prices of B20. Since the AEO does not explicitly model the price of biodiesel, price changes over time are based off of the price of diesel. This is a valid assumption as diesel and B20 prices have followed similar trajectories over time. Also included in the model are AEO quantity projections for ethanol, cellulosic ethanol, and biodiesel. Constraints are imposed that require baseline levels of biofuel production to meet these projections. Biofuel volumes are held constant after 2030 in the baseline due to uncertainty in transportation sector infrastructure. Table 3 displays prices for important energy inputs following AEO 2009 price trajectories. Notice that all prices are increasing in the baseline, reflecting higher expected costs of production in the future under BAU conditions. The price change for fertilizer was determined to be half the rate of change in the well-head price of natural gas. Carbon pricing will present further deviations from this base as the CO2 equivalent content of each fuel is priced internally.

Table 3: Baseline Energy Price Changes (Index Values Over Time where 2000 Base Price = 100)

	2000	2005	2010	2015	2020	2025	2030
Crop Ethanol	1.00	1.28	0.92	0.96	0.94	0.96	0.99
Biodiesel	1.00	1.07	1.55	2.05	2.09	2.16	2.28
Biodiesel Waste Oil	1.00	1.07	1.55	2.05	2.09	2.16	2.28
Total Ethanol	1.00	1.28	0.92	1.21	1.24	1.28	1.35
TBTUs	1.00	1.34	1.29	1.34	1.32	1.34	1.39
Fertilizer	1.00	1.07	1.55	1.57	1.62	1.66	1.75
Electricity	1.00	1.26	1.24	1.26	1.31	1.38	1.46
Natural Gas Wellhead Price	1.00	2.41	1.37	1.40	1.47	1.53	1.67
Natural Gas Industrial Delivered	1.00	2.41	1.37	1.40	1.47	1.53	1.67
Imported Crude Oil	1.00	1.76	2.89	3.80	3.88	4.01	4.23
Diesel Fuel	1.00	1.45	1.28	1.69	1.73	1.78	1.88
Coal Delivered Price	1.00	1.26	1.21	1.26	1.24	1.26	1.31

5.3.2 Updated Land Use Categories

FASOMGHG accounts for a comprehensive range of land use categories consistent with land classifications from multiple resources. Baseline cropland use comes from the creation of regional crop mixes established from historic agricultural production estimates by crop and region, reported by USDA-NASS. FASOMGHG grazing lands include public and private sources grassland or range, grazed forest, and cropland pasture, following definitions, classification, and estimates from the ERS Major Land Use Database (Lubowski et al., 2002).

While previous versions of FASOMGHG only accounted timberland, cropland, and pasture (McCarl and Schneider, 2001; Murray et al. 2005), the model now has explicit spatial representations of rangeland (public and private), CRP acreage, privately owned-grazed timberland, grazed public forest, cropland pasture, and forest-pasture that is grazed only (this category is freely transferable with timberland). Improved land use dimensions allow for improved simulation of land use change patterns in response to policy. This categorization also allows for improved GHG accounting between different land uses. Figure 13 displays the FASOM land use totals used to form a land base for the remainder of this dissertation (these represent base year totals for the 2000 time period).

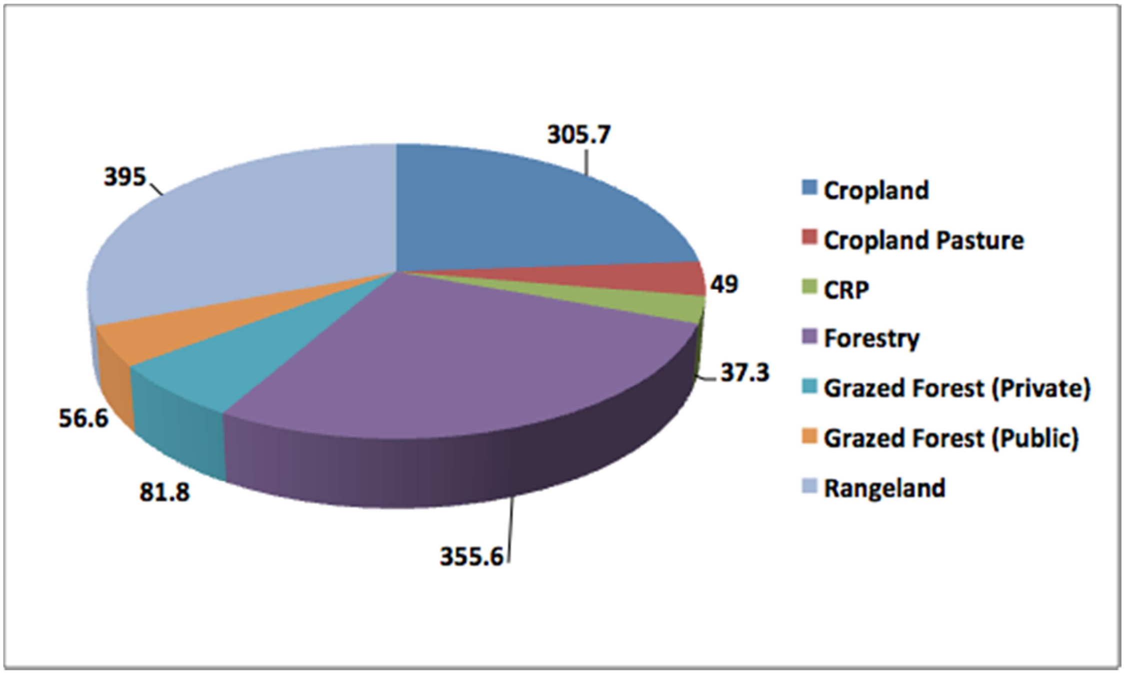

Figure 13: FASOM land base for the U.S. by land use type

Definitions of these land use categories rely on a number of sources, but for the most part are consistent with the ERS-Major Land Use classification system, as follows—

1. **Cropland-** This includes only cropland that is harvested, defined by the ERS and USDA Ag Census as "land from which crops were harvested and hay was cut,

and land used to grow short-rotation woody crops, land in orchards, citrus groves, Christmas trees, vineyards, nurseries, and greenhouses." FASOMGHG does not model all of these activities explicitly, including a number of fruit and vegetable crops that comprise relatively small share of the total land base.

2. **Cropland Pasture-** Primarily used for grazing in the model, cropland pasture are acres *"used only for pasture or grazing that could have been used for crops without additional improvement. Also included were acres of crops hogged or grazed but not harvested prior to grazing."* State totals come directly from AgCensus data:
3. **CRP-** Land enrolled in the Conservation Reserve Program, with state and county level totals available through the USDA-FSA (FSA, 2009)
4. **Public Forest Pasture-** There is a significant portion of publicly owned grazing lands, particularly in the Western U.S. These lands are typically managed by the U.S. Forest Service, Bureau of Land Management (BLM), or a variety of state agencies which allocate grazing permits to producers for a nominal fee. These lands are included in the FASOMGHG base to more accurately map livestock production (per head) to total acres grazed. Beginning with ERS estimates of total forest pasture stocks, regional estimates of public forest pasture are found by using proportions estimated in USFS, 2004.
5. **Private Forest Pasture-** Consists of privately owned grazed forests that fall into two categories. Forest pasture in agriculture is non-timberland grazed forest, defined as *"all woodland used for pasture or grazing during the census year.*

Woodland or forest land pastured under a per-head grazing permit was not counted as land in farms and, therefore, was not included in woodland pastured." (Lubowski, et al. 2002). These lands are in addition to the private timberland areas included in the model, so no forest products are withdrawn. However, endogenous shifts into forestry from this category are possible, indicating a shift in management. The other category of privately held forest grazing land includes land that is actively managed for timber while simultaneously grazed. A management option for these lands is to cease grazing altogether and manage for timber only. Acreage totals for this category were obtained by deducting the US Ag Census estimates of woodland pasture from the private grazed forest totals by region.

6. **Rangeland-** We rely on the ERS-MLU definition for grassland or range, which consists of both public and private sources. *"Grassland pasture and range consists of all open land used primarily for pasture and grazing. It includes shrub and brush land types of pasture and grazing land such as sagebrush and scattered mesquite; all tame and native grasses; legumes; and other forage used for pasture or grazing. Because of the diversity in vegetative composition, grassland pasture and range are not always clearly distinguishable from other types of pasture and range. At one extreme, permanent grassland may merge with cropland pasture; at the other, grassland may intermingle or form transitional areas with forested grazing land. No single agency, other than ERS, accounts for all public and private land used for pasture and range. The*

estimates in this report are composites of data from the Census of Agriculture, Bureau of Land Management, U.S. Forest Service, Natural Resource Conservation Service and several other Federal agencies."

7. **Forests-** Regional timberland stocks, as well as timber demand, inventory, and additional forestry sector information are drawn from the 2005 RPA Timber Assessment (Darius Adams and R.W. Haynes, 2007).

This land use categorization system gives FASOMGHG a comprehensive list of land use types to represent the AF sectors and land use competition. It should be noted that there are discernible differences between the FASOMGHG land base (which categorizes land in a similar manner to the USDA-ERS Major Land Use Database) and non-federal land use totals as classified by the Natural Resource Inventory, (NRI), as indicated in Figure 14. The major difference comes from the ERS-MLU classification of rangeland and Cropland Pasture (which we do model explicitly using ERS regional totals). The ERS Cropland Pasture category overlaps both the Cropland and Pasture estimates in the NRI. That is, NRI likely accounts for a portion of the land classified as "cropland pasture" in both its "cropland" and "pasture estimates". ERS-MLU Rangeland includes federal and non-federal sources, plus non-cropland grassland pasture, or lands that the NRI deems "Pasture". While there is significant overlap across these sources, the FASOMGHG approach offers a well-documented land categorization base with a historic series formed from Agricultural Census (ERS-MLU) data that is not wholly inconsistent with the NRI.

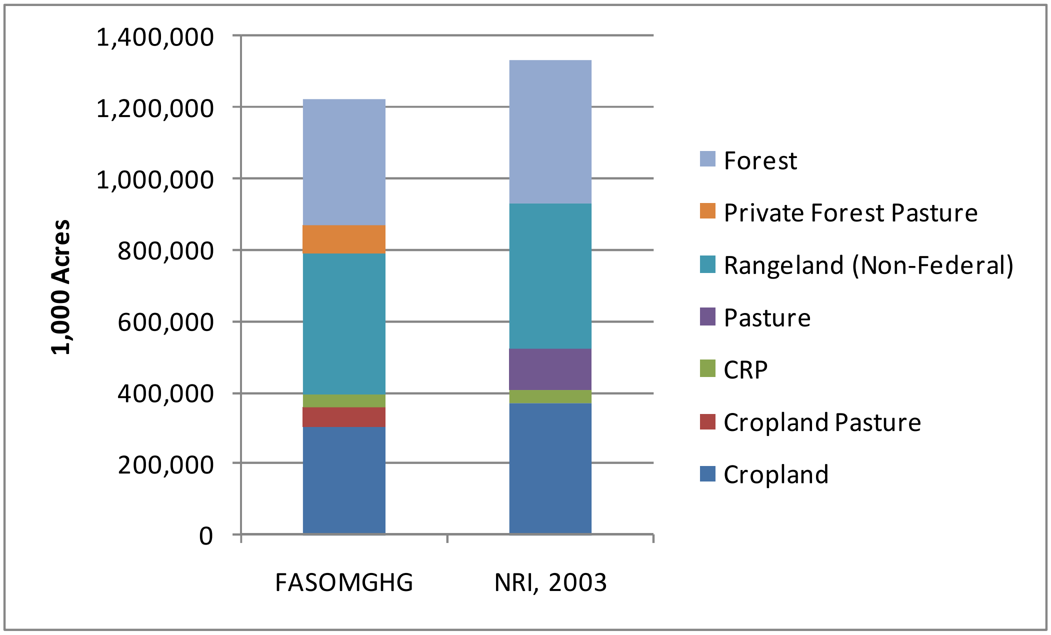

Figure 14: Comparison of NRI and FASOMGHG land use totals

In all, the updated FASOMGHG land base is an improved methodology from past model versions, and one that we continue to improve upon[21]. FASOMGHG methodology allows for explicit land use competition between cropland, pasture, conservation lands (CRP), and forests based on potential profitability between the alternative uses, which allows us to simulate potential LUC impacts of policy drivers that increase the relative value of land holdings in a particular use (Ralph Alig et al., 1998, Ralph Alig et al., 2010). Land can move between freely between cropland and pasture use; transitions into and out of forest are also possible in certain regions. CRP lands are eligible for cropland conversion. GHG accounting methodology tracks changes in overall soil carbon stocks as land shifts between uses. Table 4 displays land

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[21] Later versions will build upon this methodology using a hybrid approach of ERS-MLU and NRI definitions and regional estimates, but this is outside the scope of this dissertation.

transferability between alternative uses in the model. Land can move between freely between cropland and pasture use given certain biophysical constraints the limit total transition potential by region. Transitions into and out of forestry are also possible in certain regions. CRP lands begin with a base are eligible for cropland conversion. GHG accounting methodology tracks changes in overall soil carbon stocks as land shifts between uses.

Table 4: FASOMGHG Domestic Land Use Categories

Base Category	**Possible Land Movement**
Cropland	Cropland-Forest Cropland-Pasture
Cropland Idled	Not Transferrable
Cropland Pasture	Cropland-Pasture Pasture-Forestry
Forest Pasture in Agriculture	Pasture-Forest
Forest Pasture in Timber (Private)	Forest-Pasture
Forest Pasture in Timber (Public)	Not Transferrable
Rangeland (Public and Private)	Not Transferrable
CRP	CRP-Cropland
Land to Development	Not Transferrable

Source: USDA-ERS, 2009; NRI, 2003.

FASOMGHG is disaggregated into 63 minor production units in the lower 48 states, and 11 main agri-forestry regions. All major FASOMGHG regions include crop and forestry production opportunities except for the Northern Great Plains and Southwest Plains (which includes most of Texas and Oklahoma). For more on regional production characteristics, see Adams et al., 2009. For assessing afforestation potential on a regional basis, we draw from USDA-NRCS estimates of environmentally sensitive or lower productivity land. Afforestable cropland is defined as land eroding at levels above a tolerance level (T), and in lower productivity Land Capability Classes (LCC V to VII), or cropland classified as wet soil. Pasture eligible for afforestation was determined using similar criteria except LCC VII and VIII were restricted.

Additionally, transition of cropland, forests, pasture, and rangeland to developed uses are exogenous factors in the model, included to reflect the reality that productive land bases are likely to shrink over time as populations grow and suburban development continues. Land to development transfers are modeled on a regional basis by land type, and are drawn from recent data prepared for the 2010 Resources Planning Act (RPA) Assessment, 2010 (Ralph Alig et al., 2009). These parameters help us depict an AF land base that is decreasing in the baseline due to development pressures. Accounting for land to development pressures in an AF sectoral modeling framework is important, as varying levels of development pressures can affect land use competition between agriculture and forestry, GHG mitigation potential, and commodity prices (Alig et al., 2010). Figure 15 displays regional development trends by region and land use type over time, in million acres per year. There is high variability in the amount of land leaving AF uses for development by region, but these development trends are projected to taper off to an extent over time.

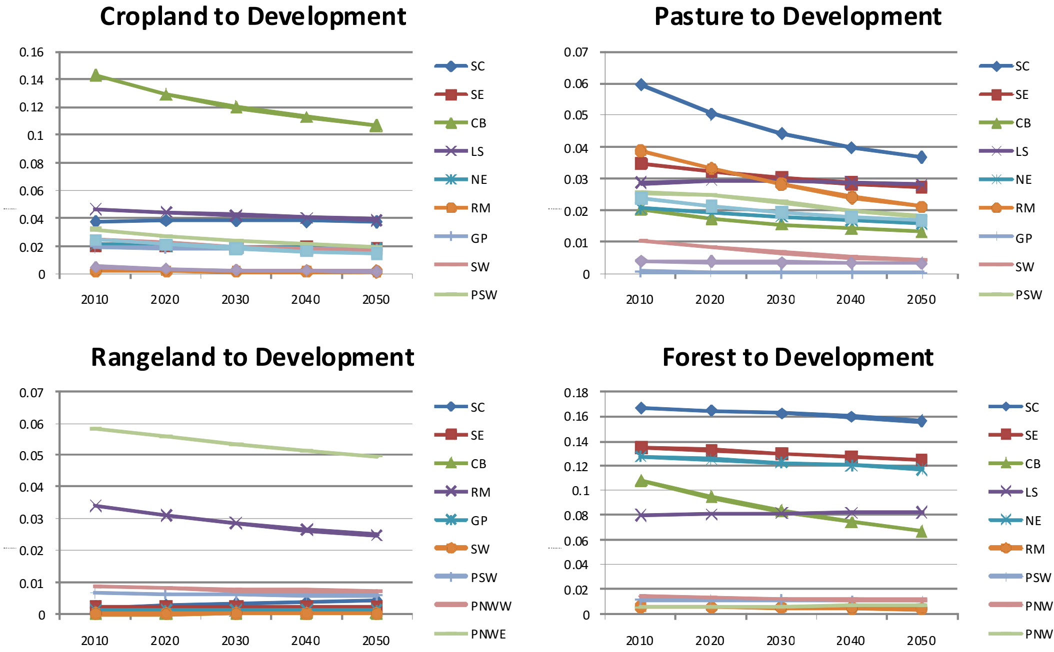

Figure 15: Projected regional development transfers by land use (million acres per year)

5.3.3 CRP Recultivation Supply

FASOMGHG has the option to simulate AF development with and without recultivation of CRP lands. The model defines a total stock of available CRP in each sub-region, using data publically available through the USDA-FSA (USDA Farm Service Agency, 2009). CRP acreage totals are aggregated to each FASOM region. These data include contract termination periods upon which landowners can bid to renew their contract, or revert to crop production. That is, each sub-region has a stock of CRP acreage subject to a termination schedule. The FASOMGHG CRP stock can remain constant over time, meaning the CRP acreage continues to receive a constant rental rate over time, or it can revert to crop production at an economical rate following an upwardsloping supply schedule. Figure 16 illustrates expected national CRP contract termination by acreage totals. The bulk of current CRP contracts are set to expire within the next few years; re-enrollment or additional sign-up will be contingent on expected rental payments and commodity market conditions.

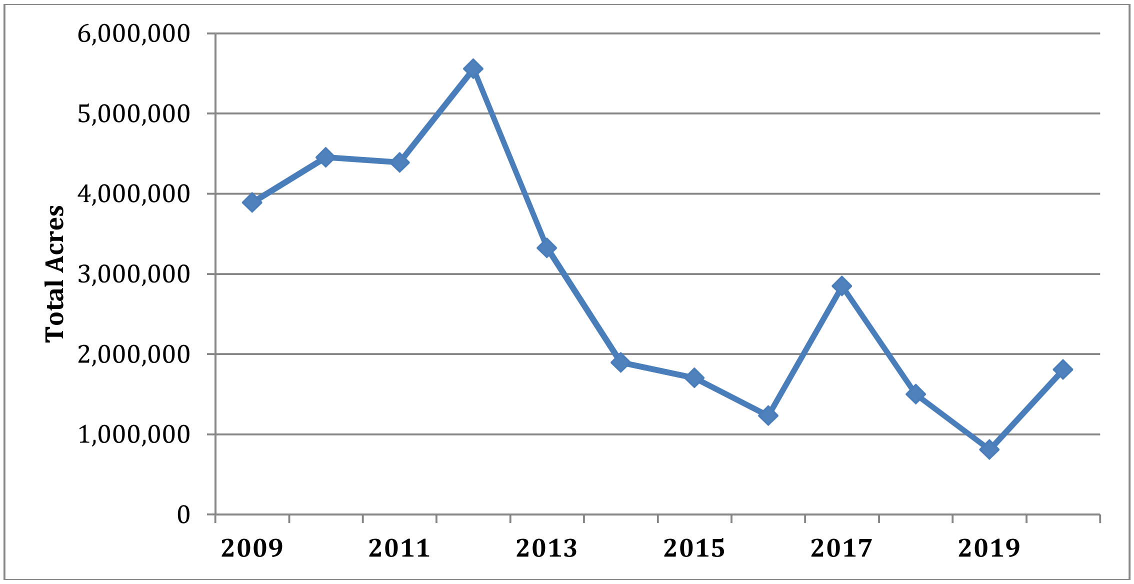

Figure 16: Expiring CRP acreage over time

Existing CRP acreage by state (or FASOMGHG sub-region) is input to the model by current stock, and expected contract termination period. The majority of the CRP stock is concentrated in the Midwestern U.S., in major crop producing regions. These are also the regions that are likely most susceptible to further cropland extensification (or contraction) depending on the policy regime. Table 5 displays expiring CRP acreage by major production regions. Notice that the majority of existing CRP contracts is set to expire from the 2009-2015 period, with a large portion of retiring acreage set in the U.S. Great Plains, an area dominated by cropland. Contemporary drivers of biofuel expansion could significantly affect the amount of land returning to agriculture over the next few years. In fact this trend has already been observed, as CRP stocks declined from a 2007 level of 37.2 million acres to a current (2009) level of 33.6. FSA policy targets of 32 million acres signal that the CRP will continue to see reductions in acreage.

Table 5: Expiring CRP Acreage by Year and Region in 1,000 Acres (Source: USDA-FSA; Aggregated to FASOMGHG Super-Region)

	2009-2012	2013-2015	2016-2020
Corn Belt	1,717	1,291	1,730
Lake States	817	647	919
Western US	5,798	1,948	1,854
Great Plains	8,273	2,092	2,486
Southern US	1,569	857	995
Northeast	107	85	191

Two CRP scenarios are considered in this analysis. The first locks in CRP acreage at 32 million acres, consistent with current Farm Bill acreage aspirations (Farm Bill, 2008). Thus, only a small proportion of CRP can revert to crop production (current CRP stock is approximately 33.6 million acres). The second case allows this land to re-cultivate freely. Like all supplies of land in FASOMGHG, CRP is considered a factor input into the aggregate production process. CRP acreage receives a base rental payment equal to the average CRP rental rate by FASOMGHG sub-region (FSA, 2009). To model a supply function of CRP lands, we rely on parameters estimated my Secchi and Babcock, 2007. This study estimated the effect of higher commodity prices on CRP reversion rates in the state of Iowa. The study finds that re-cultivation maxes out at 72% when corn and soybean prices increase 250% beyond historic levels (a case nearly observed in 2007). These parameters serve as a good proxy for a national CRP reversion estimates as CRP lands range from very low to moderately high qualities in Iowa, as is the case throughout much of the Midwestern U.S. where CRP lands are concentrated[22].

As commodity markets and land rents increase, CRP land can be purchased (recultivated) at a higher proportion consistent with the supply function outlined below. The model weighs the cost of reverting CRP lands against the opportunity costs of keeping the land idle. Figure 17 maps the cost of CRP reversion (compared to the base rental rate) with the proportion of land allowed to revert at that cost. Consistent with other input supply functions in FASOMGHG, the supply curve for CRP reversion is input into the model following a separable programming format. This is a technique for approximating nonlinear functions of endogenous variables that are separable into functions of a single variable (McCarl and Spreen, 1980)[23].

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[22] This methodology can be updated with regionally-specific recultivation parameters as soon as such estimates are available.

[23] Separable programming approximates a separable non-linear function by solving for a convex combination of grid points in the function domain.

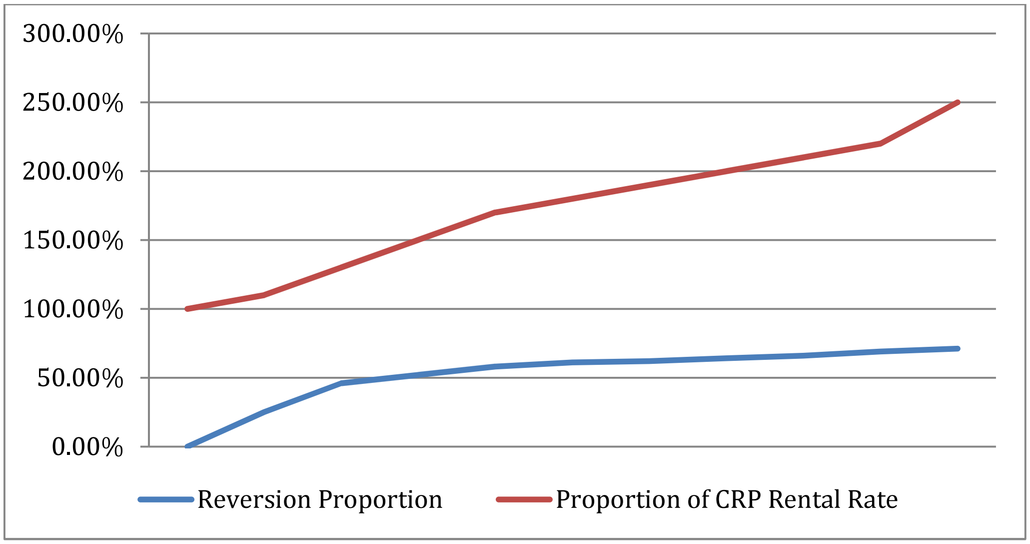

Figure 17: CRP recultivation supply curve

This formulation allows us to measure potential CRP reversion rates under multiple policy drivers. In addition, the CRP could play a variety of roles in a low carbon economy, including landowner participation in a GHG offsets market. In effect, we simulate this option by attaching a CO_2e price to GHG emission/sequestration. Carbon stored in CRP lands above baseline levels would be credited, while CRP reversion results in a debit equal to carbon value of the associated land use change. Essentially, this models the opportunity costs of CRP re-cultivation when contract holders could be subsidized for sequestration potential by participating in a federal GHG offset program.

5.3.4 AF Welfare Disaggregation

Following concerns echoed by the agricultural community of the impacts of climate legislation on net farm income and sectoral economic welfare in general, welfare accounting was disaggregated from an overall producer surplus measure, to individual measures for forestry and agricultural producers and consumers, and between livestock and crop producers, which allows for income distribution effects of exogenous policies to be measured.

First and foremost, returns to production for crop and livestock producers are separated. This welfare measure is the producer’s surplus, or area defined as the space above the marginal cost of production, up to the equilibrium price point. The costs of purchased factor inputs (land, water, labor, and fossil fuels) are also allocated to each respective producer group using explicit FASOMGHG crop budget data.

For mitigation scenarios, payments and GHG credits (debits) were allocated between to each respective producer group. GHG payments for the following accounts are counted as a source of revenue for livestock welfare accounting:

- Improved enteric fermentation
- Manure management (N2O and CH4)
- Reduced N2O emissions from pasture management (including pasture conversion)
- Afforestation on pasture land
- Bioelectricity revenue from manure biomass relative to coal combustion

GHG payments allocated to crop producer welfare include:

- Reduced CO2 emissions from fossil fuel and agricultural input use
- N2O emissions from decreased fertilizer use
- Bioenergy emissions reduction relative to fossil fuel combustion
- Soil carbon sequestration

- Afforestation on cropland

Forestry GHG payments include:

- Carbon sequestration resulting from altered forest management strategies
- GHG payments for improved carbon sequestration in finished forest products
- Revenues from forest biomass sales for bioelectricity

Bioenergy payments were allocated to producer groups based on feedstock type. When land is moved from one account to another, land rents associated with that use are also transferred. For example if cropland pasture is converted to full-time crop production, then returns to production on the new tract of land, and all associate land conversion costs are allocated to livestock producers, reflecting the reality that producers from the original land use will collect all land rents under the new use. This is important for afforestation, as afforestation GHG payments and associated wood product revenues will accrue to crop and livestock producers, not foresters.

This welfare disaggregation allows us to examine distributional effects of energy and climate mitigation incentives on multiple producer groups in the AF sectors,

5.3.5 Asymmetric Incentives for GHG Mitigation Activities

The typical Pigouvian approach for internalizing the social costs of an externality within a market system would be to price that externality equivalently across all sources at the marginal rate of social damages. Past FASOMGHG studies of climate mitigation have done this by pricing all sources of emission and sequestration symmetrically (Murray et al., 2005). However, there is reason to consider asymmetric pricing as some offset activities are not palatable from a policy perspective, or are very difficult to implement in reality. This dissertation employs an asymmetric GHG pricing scheme to consider alternative reduced-carbon policy regimes that might limit the scope of a domestic offset program. Specifically, this dissertation introduces a limited offset eligibility regime that does not incentive reductions in emissions from agricultural non-CO_2 sources, or increased sequestration from altered forest management practices. In another scenario, no offset activities are incentivized, only bioelectricity replacement of coal-fired electricity (where the life-cycle GHG reduction of coal-fired electricity generation replacement is priced). This provides a unique look and land management and production patterns under non-inclusive domestic offset programs.

CHAPTER VI

SIMULATION RESULTS FOR BIOENERGY EXPANSION SCENARIOS

This chapter uses simulation analysis to examine the effects of moving from a business as usual AF trajectory based on historic trends and recent projections to one in which biofuel expansion is included. Specifically, it explores the implications of the RFS2 on land use, GHG emissions, management intensification, water, and commodity markets. Sensitivity of these results is tested with and without Conservation Reserve Program (CRP) recultivation.

6.1 **Description of Scenarios**

6.1.1 Baseline

The FASOMGHG baseline calibrates dynamic trends in important exogenous variables using other existing data sources. Dynamic variables represented in the model include energy price trajectories consistent with the AEO 2009 report, exogenous biofuel production consistent with mandates established prior to the EISA-RFS2 (from the 2005 Energy Bill—some refer to these levels as the RFS1). Agricultural demand and yield productivity growth are consistent with historic and projected trends using USDA-NASS data, U.S. import and export market demand, land use changes (RPA Assessment 2003; NRI, 2003; USDA-ERS, 2009), and technical progress in bioenergy processing. AEO projections of bioenergy production are summarized in Table 6. Note that this includes significant growth in grain-based ethanol over the next few years, even with the absence of the RFS2. The implication is that in the absence of renewable energy mandates, the demand for corn ethanol will continue to rise under baseline conditions, affecting the allocation of lands to food and fiber.

Table 6: Baseline [AEO 2009 (RFS1)] Biofuel Quantity Projections (Billion Gallons per year)

	2010	2015	2020	2025	2030
Crop Ethanol	10.81	11.30	12.29	13.11	13.56
Cellulosic Ethanol	0.25	0.25	0.25	0.25	0.25
Total Biodiesel	0.33	0.36	0.37	0.40	0.43

The baseline scenario is estimated over an 80-year horizon (2000-2080) to fully capture changes in forestry investment decisions and the dynamic interactions of forest and agricultural land use. The following chapters present results on deviations from this baseline as stimulated by renewable fuels mandates and climate mitigation opportunities in AF.

6.1.2 Scenarios Employed to Analyze EISA-RFS2

To simulate the effects of adding the 2007 energy bill RFS mandates to the baseline, the latest version of the EISA-RFS rules (referred to as RFS2) are incorporated into the model by setting minimum biofuel production requirements for ethanol, cellulosic ethanol, and biodiesel at mandated levels, and by feedstock. Requirements are phased in over time until reaching a total of 30 billion gallons of biofuels annually in 2022[24].

The first scenario is henceforth referred to as “RFS2”. CRP is held at 32 million acres. The second “RFS2 with CRP Recultivation,” is a relevant sensitivity case in which CRP lands are allowed to reenter production upon contract completion. This case reveals important information about the potential pressures facing conservation lands under a higher commodity price regime brought on by expanded bioenergy efforts. This study imposes upper bounds on corn ethanol and soybean biodiesel as in RFS2 but allows cellulosic feedstocks to comprise a larger share of the total ethanol portfolio if economically feasible. Table 7 displays upper and lower bounds for important biofuel types.

Table 7: Biofuel Minimum and Maximum Bounds for FASOMGHG Simulations in Billion Gallons

Biofuel Type	Bound	2000	2010	2015	2020	2025	2030
Total Ethanol	Lower	2.131	5.593	13.26	19.71	28.7	28.7
Total Ethanol	Upper	2.131	5.593	12.83	19.377	26.094	30.16
Cellulosic Ethanol	Lower	0	0	0.43	4.71	13.7	13.7
Crop Ethanol	Lower	2.131	5.593	12.83	15	15	15
Forest Ethanol	Lower	0	0	0	0.1	0.1	0.1
Forest Ethanol	Upper	0	0	0	0.1	0.1	0.1
Wet Mill Ethanol	Lower	0.309	0.811	0	0	0	0
Wet Mill Ethanol	upper	0.309	0.811	1.31	1.39	1.39	1.39
Total Biodiesel	lower	0.01	0.918	0.86	1.323	1.466	1.466
Total Biodiesel	upper	0.01	0.918	2.168	3.418	4.668	5.918

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[24] To reach a 36 BGY threshold, there are allowances for imported ethanol, and other “advanced” biofuels from non-AF biomass.

For this scenario ethanol production is locked in at RFS mandated levels beyond 2022 to be consistent with energy demand projections and current transportation sector infrastructure (Figure 18). FASOMGHG solves under EISA-RFS baseline conditions for market clearing levels of production, consumption, feedstock use, and net GHG emissions associated with all commodities modeled within the U.S. agricultural and forestry sectors. Meeting the RFS requires that a significant portion of land resources be allocated to the production of bioenergy, as simulation results will show. Emphasis on cellulosic ethanol creates a new market for agricultural residues (e.g., corn stover, wheat straw), and dedicated energy feedstocks such as switchgrass and hybrid poplar, giving producers more marketable alternatives for managing their land.

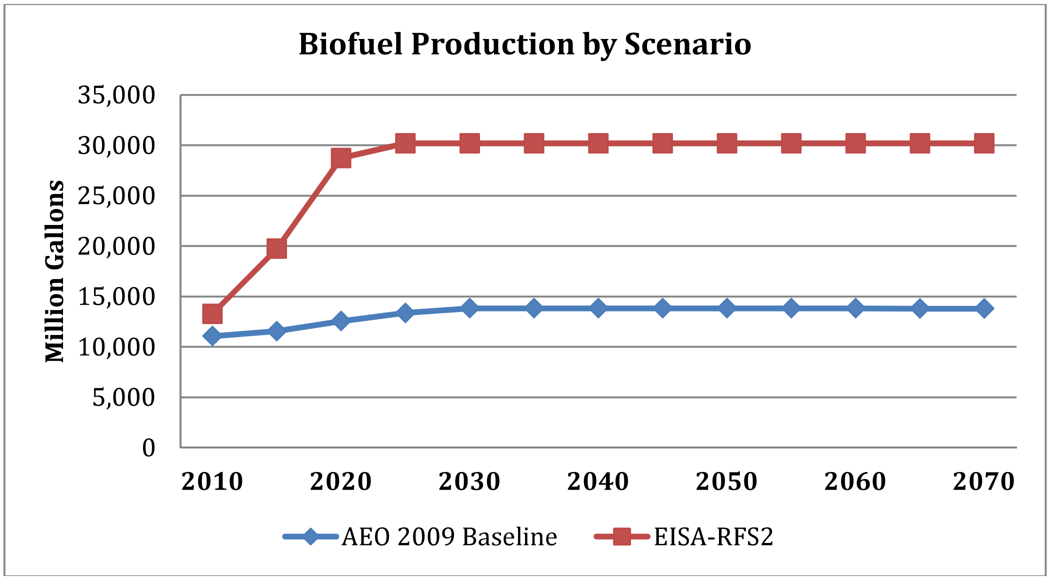

Figure 18: Biofuel production over time and by scenario

6.2 **Results**

The following results tables and discussion are organized such that RFS2 induced energy output is presented first, followed by a discussion of commodity price projections, exports, producer welfare across scenarios, policy implications for natural resource use, and implications for GHG emissions and other environmental variables.

6.2.1 Net Bioenergy Production by Region

National biofuel production rises under RFS2 mandated levels (Table 8). Energy output is summarized in billion gallons for ethanol and biodiesel, and Tbtu for bioelectricity. The mandated production of ethanol under the RFS2 is more than twice AEO 2009 projections. Net ethanol production in 2025 is sustained at the imposed lower bound. Biodiesel energy output increases substantially (more than ten-fold), but this is a relatively small share relative to ethanol. Bioelectricity increases as well under the RFS2 relative to the baseline, due to an increased availability of agricultural residues and dedicated energy crops that compete with cellulosic ethanol feedstock requirements.

6.2.2 Commodity Market Implications

Dramatic shifts in U.S. demand for AF feedstocks and overall land use will impact commodity markets by increasing prices and net returns to crop producers and lowering U.S. exports. First, consider baseline commodity prices as shown in Table 9. Generally these decline over time, consistent with historic trends. Corn prices drop to an average of $3.03 by 2050, a level consistent with corn prices for most of this decade. Other prices display noticeable downward trends as well, especially grain commodities.

This reflects changes in yield productivity and production efficiency over time. The price of cotton actually increases over time, reflecting reduced acreage in the baseline and lower yield growth potential than other crops.

Table 8: Regional Energy Output from RFS2 Expansion (2025)[25]

	Ethanol (Billion Gallons)		Biodiesel (Billion Gallons)		Bioelectricity (TBTU)	
	Baseline	**RFS2**	**Baseline**	**RFS2**	**Baseline**	**RFS2**
Corn Belt	6.41	7.79	0	0.04	21.99	11.13
Great Plains	3.34	7.55	0	0.15	4.16	4.16
Lake States	3.34	7.55	0	0.48	0	8.75
Northeast	0	0	0	0	19.48	19.48
Pac. Northwest	0.23	0.11	0	0	25.03	15.19
Pac. Southwest	0	0	0	0	17.91	15.62
Rocky Mts.	0	0.04	0	0	10.44	10.44
South Central	0	3.47	0.12	0.66	350.38	436.58
Southeast	0	1.36	0	0	406.23	232.88
Southwest	0.03	2.32	0	0	12.88	212.76
U.S. Total	**13.37**	**27.87**	**0.12**	**1.34**	**868.52**	**967.01**

Table 9: Baseline Projected Prices for Important Agricultural Commodities

	2010	**2020**	**2030**	**2040**	**2050**
Wheat ($/Bushel)	6.42	6.31	6.09	5.88	5.61
Corn ($/Bushel)	3.55	3.46	3.37	3.17	3.03
Cotton ($/lb)	256.76	264.80	264.42	266.31	275.80
Soybeans ($/Bushel)	9.27	9.14	9.00	8.93	9.13
Sorghum ($/Bushel)	5.73	5.61	5.53	5.45	5.42
Rice	10.08	9.99	9.84	9.79	9.77
Fed Beef ($/100 lb)	105.13	105.27	103.50	100.93	100.66
Non-fed Beef ($/100 lb)	66.08	68.44	68.10	66.54	67.41
Hogs ($/100 lb)	55.92	55.33	54.69	54.01	54.34
Chicken ($/100 lb)	57.11	56.99	56.43	55.83	55.53

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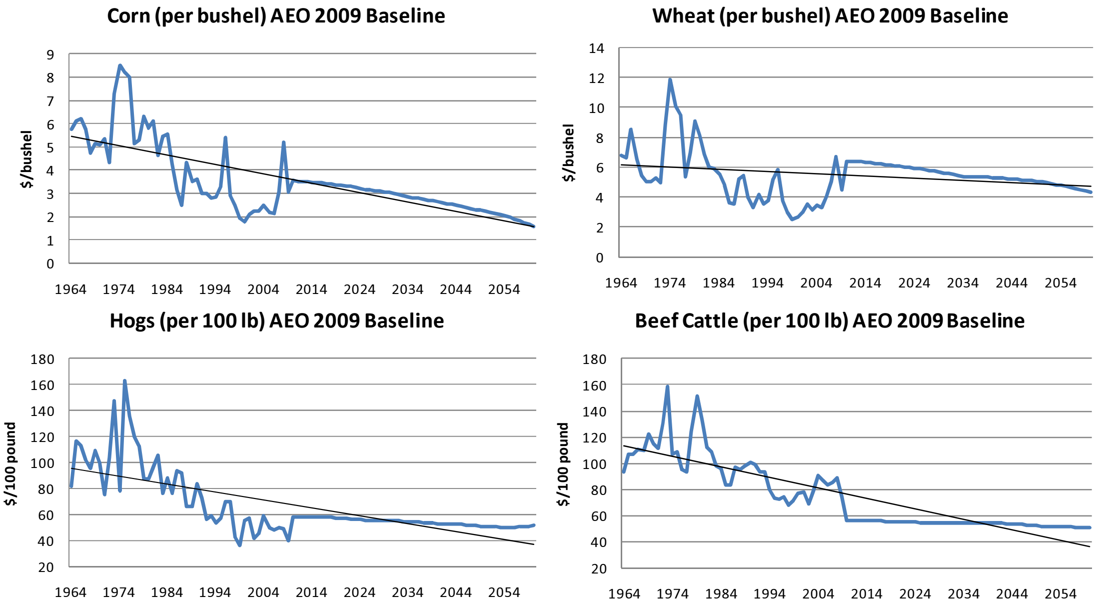
[25] Variable or scenario definitions are found in the Nomenclature section

How do these projections compare to observed trends in commodity prices? Figure 19 displays historic and projected prices for several important agricultural commodities. Historic price data are plotted in real terms from 1964-2009. FASOMGHG baseline commodity price projections are plotted for 2010 and beyond. Notice that there is an ostensible downward trend in all projected commodity prices, though this effect is more pronounced for corn and wheat than for livestock commodities. Other prices exhibit similar trends in these projections, showing that under baseline conditions (i.e., in the absence of biofuel expansion efforts, and following contemporary estimates of demand and productivity growth) the agricultural sector could experience a continuation of historic trends in commodity markets. Declining real commodity prices signal reduced demand for factor inputs over time, including productive land and water resources.


Corn (per bushel) AEO 2009 Baseline

Wheat (per bushel) AEO 2009 Baseline

Hogs (per 100 lb) AEO 2009 Baseline

Beef Cattle (per 100 lb) AEO 2009 Baseline

Figure 19: Historic and future commodity price projections from USDA-NASS and FASOMGHG output

6.2.2.1 Commodity Price Projections across Scenarios

In general, price impacts are modest for most commodities (Table 10). Values are expressed in per-unit prices and percentage changes from baseline. The major grain commodities (corn, soybeans, and wheat) experience relatively small price increases over time. Corn prices deviate less than 7% from baseline levels, though this effect is even smaller in later years. Wheat prices also show little movement (~3% or less). Soybean prices move significantly, rising more than 10% from baseline levels throughout the projection period as a high proportion of soybean production is needed to meet the RFS2 mandates. Livestock prices also rise, with non-fed beef prices rising more sharply than fed beef (as some grazing lands move to other uses).

To put these prices into policy context, consider the Searchinger et al., 2008 study that assessed the international leakage implications of U.S. ethanol expansion. That study considered a case in which ethanol production increases 14.5 billion gallons above baseline levels by 2016 (primarily from corn ethanol). Results indicated that such a shift would result in average price increases of 40%, 20%, and 17% for corn, soybeans, and wheat, respectively. These estimates are much lower, as this study models the RFS2 explicitly, and simulates a much higher proportion of cellulosic ethanol than Searchinger et al. 2008; cellulosic feedstocks rarely compete directly with food and fiber. Also, a greater number of cropping alternatives in FASOMGHG allows for more flexibility in cropland allocation (for instance, corn production can be extended to lands currently used for producing rice, cotton, etc.). Alternative modeling assumptions and the difference in dynamic and static equilibrium modeling also contribute to this difference (further discussion below). Finally, as results project substantial cropland expansion under the RFS2 regime, which alleviates prices impact concerns to an extent.

Thus, results of this study indicate that past analyses might have overstated the price impacts of bioenergy by not fully representing the dynamics of land use and agricultural investment decisions, cropland expansion possibilities, advanced biofuels, or flexible crop mix strategies.

Table 10: Commodity Price Projections and Percentage Change from Baseline under the RFS2[26]

	2010	**2020**	**2030**	**2040**	**2050**
Wheat ($/Bushel)	6.52	6.55	6.29	5.95	5.76
	1.48%	*3.81%*	*3.36%*	*1.08%*	*2.57%*
Corn ($/Bushel)	3.66	3.69	3.46	3.23	3.08
	3.07%	*6.74%*	*2.70%*	*1.86%*	*1.72%*
Cotton ($/lb)	258.73	271.10	276.96	278.53	278.53
	0.77%	*2.38%*	*4.74%*	*4.59%*	*0.99%*
Soybeans ($/Bushel)	9.58	9.73	9.69	9.53	9.35
	3.34%	*6.45%*	*7.70%*	*6.74%*	*2.35%*
Sorghum ($/Bushel)	6.16	6.57	6.42	6.27	6.24
	7.54%	*17.07%*	*16.15%*	*15.04%*	*15.03%*
Rice	10.09	10.02	10.03	9.89	9.85
	0.11%	*0.28%*	*1.94%*	*1.01%*	*0.76%*
Fed Beef ($/100 lb)	106.26	108.31	106.26	103.54	101.87
	1.07%	*2.88%*	*2.67%*	*2.59%*	*1.21%*
Non-fed Beef ($/100 lb)	66.36	70.41	69.48	68.66	68.42
	0.43%	*2.89%*	*2.02%*	*3.18%*	*1.50%*
Hogs ($/100 lb)	56.67	57.01	55.96	55.02	55.06
	1.33%	*3.04%*	*2.32%*	*1.87%*	*1.33%*
Chicken ($/100 lb)	57.63	57.64	57.10	56.30	55.77
	-0.10%	*-1.18%*	*-1.88%*	*-2.04%*	*-3.40%*

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[26] Variable or scenario definitions are found in the Nomenclature section

Table 11 displays indexed deviations from baseline commodity prices. Here, prices of agricultural commodities are bundled into crop and livestock categories using an index number (AEO 2009 = 100). I focus on non-poultry livestock prices, which are most sensitive to changes in land use (particularly pasture), and the price of feed grains. Crop commodity prices are impacted more heavily by the implementation of the RFS2 than livestock as land is re-allocated to the production of biofuel feedstocks. Price differentials are greatest in later years of the simulation period, due primarily to the significant decline in prices prevalent in the baseline. Livestock prices remain higher than baseline projections due to reductions in cropland pasture acreage, and higher costs of feed and an accompanying reduction in production. When CRP lands are allowed to re-enter production, crop and livestock price effects are smaller, dropping an average of 1.67% and 0.70%, respectively, below the constrained CRP case.

Table 11: Commodity Price Indices across Biofuel Expansion Scenarios (Baseline Price = 100)[27]

		2010	**2020**	**2030**	**2040**	**2050**
RFS2 Base	**All Crops**	102.70	105.25	102.91	111.44	119.71
RFS2 with CRP	**All Crops**	102.41	103.58	100.82	108.99	117.88
RFS2 Base	**Grain Crops**	102.91	105.42	103.19	111.21	118.55
RFS2 with CRP	**Grain Crops**	102.56	103.60	100.85	108.71	116.66
RFS2 Base	**Livestock no Poultry**	101.06	102.29	101.19	102.20	105.51
RFS2 with CRP	**Livestock no Poultry**	100.80	101.16	100.61	101.93	104.26
RFS2 Base	**Processed Commodities**	101.78	104.63	100.41	110.68	120.54
RFS2 with CRP	**Processed Commodities**	101.63	103.68	99.33	109.78	120.21

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[27] Variable or scenario definitions are found in the Nomenclature section

6.2.2.2 Net Producer Welfare Implications of the RFS2

Higher prices and production levels induced by the RFS2 lead to economic welfare gains for crop producers. Figure 20 displays regional producer surplus shifts across the RFS2 scenarios. Crop producer welfare gains are positive across all major agri-forestry regions, though vary significantly. The Corn Belt, Great Plains, and Lake States see the highest net gains under the RFS2, with the Corn Belt realizing gains ranging $4.6-$5.3 billion annually. Other regions see only marginal changes in producer welfare.

Notice that for all regions, crop producer welfare declines when CRP reversion is included. While this might seem counter-intuitive as more acres are in production and a constraint on land is being relaxed, higher rents bring additional land into production, which relaxes equilibrium commodity prices and lowers the rents. FAOSMGHG maximizes the sum of all welfare accounts, including domestic and foreign producer and consumer welfare. Additional cropland under the CRP reversion case reduces output prices and producer welfare, but consumer gains (reduced consumer losses relative to the no reversion case) lead to a net increase in total welfare.

Figure 21 displays deviations from baseline livestock producer welfare. Notice that for most regions, livestock producers experience a net loss in welfare, though the scale of these losses is much less than the gains received by crop producers. Welfare losses are due to higher feed costs and losses in pasture acreage (discussed in the next section). The implication is that livestock producers may not be able to pass through the higher costs of production onto consumers, and could experience sustained losses in net income relative to business as usual conditions. CRP reversion lowers commodity prices and welfare losses to livestock producers.

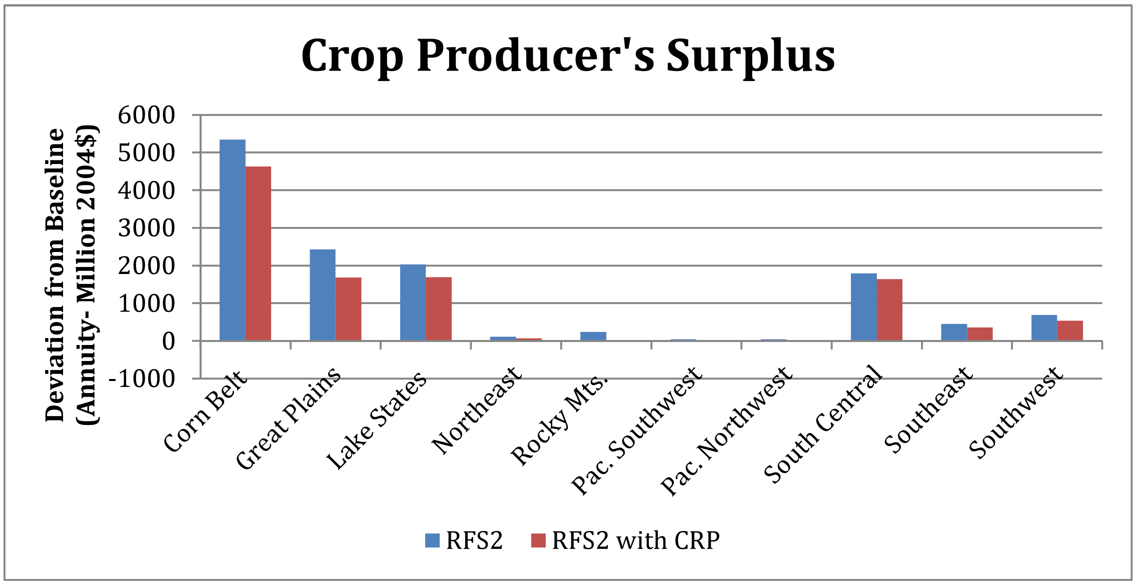

Figure 20: Crop producers' surplus changes from base across the RFS2 scenarios

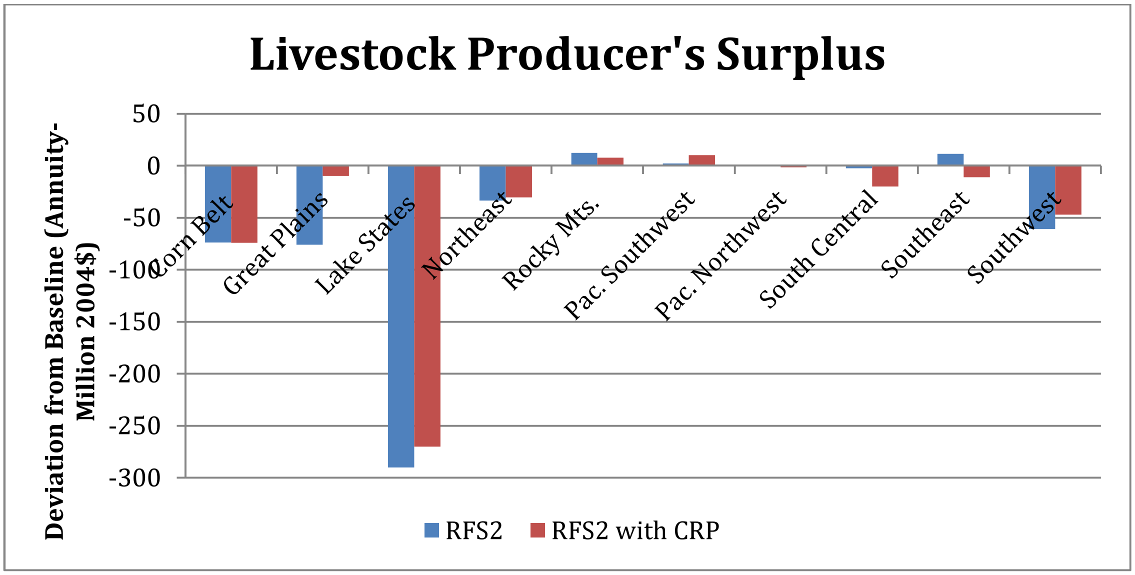

Figure 21: Livestock producers' surplus changes from base across the RFS2 scenarios[28]

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[28] Variable or scenario definitions are found in the Nomenclature section

As the previous section has shown, a projection of agricultural production characteristics under the RFS2 and recent market conditions can sustain higher commodity prices (undoubtedly affecting export markets in the long run), and raise U.S. cropland rents over time. The following sections relate these market factors to natural resource use, GHG emissions, and implications for environmental quality.

6.2.2.3 Total Welfare Implications of the RFS2

Total U.S. producer welfare is measured as the sum of crop producer gains, livestock producer losses, and welfare gains to processors of secondary agricultural products (Figure 22). While not previously displayed, processors see substantial gains under the RFS2 (approximately $10.5 billion) from the sale of liquid biofuels[29]. Total producer welfare gains are found to be in excess of $20 billion per year. However, welfare gains to producers are accompanied by losses to consumers due to higher commodity prices (ranging $3.3-5 billion). Total U.S. welfare gains of approximately $18 billion. While substantial, more than 50% of these welfare gains are directly attributed to biofuels revenue, the rest is due to higher commodity prices received by producers.

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[29] Note that while processors consume primary agricultural commodities, FASOMGHG models processor welfare on the producer surplus side of the objective function.

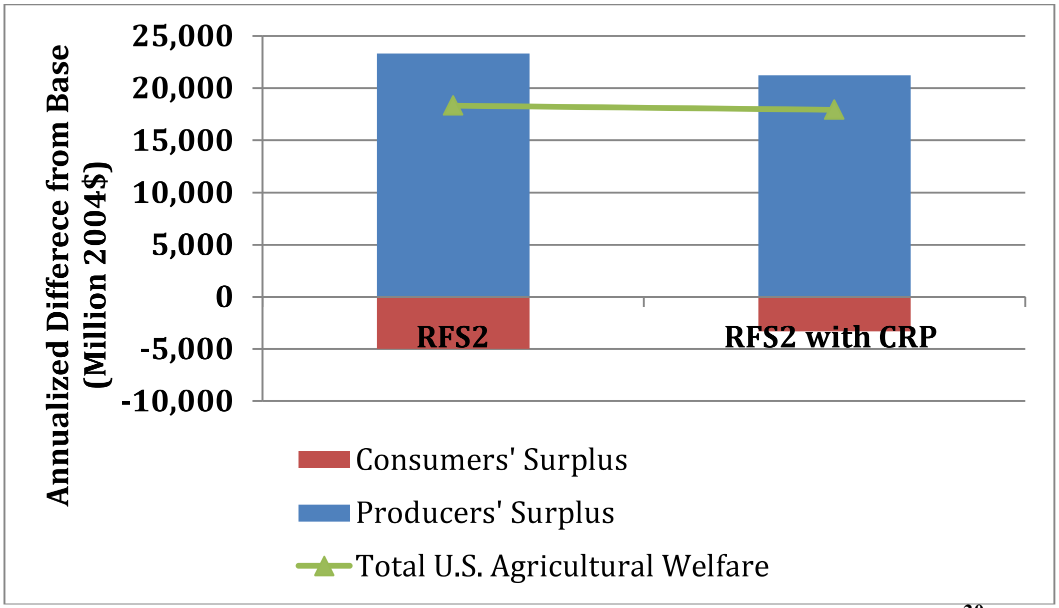

Figure 22: Total U.S. agricultural welfare changes from base (annuity)[30]

6.2.2.4 Implications for Exports

The RFS2 will reach beyond U.S. markets, affecting international agricultural trade and production in the rest of the world. Consider U.S. agricultural exports, and estimated percentage change from base for several important agricultural commodities (Table 12). Most exports displayed here decrease, some substantially. For instance, soybean exports decrease 28-30% from base levels, as U.S. soybeans are needed to satisfy RFS2 biodiesel mandates. Corn and wheat do not increase significantly, due in part to U.S. cropland expansion. Other crops not used for bioenergy processing experience significant indirect export changes as crop mixes adjust to the RFS2 (including cotton, sorghum, and rice).

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[30] Variable or scenario definitions are found in the Nomenclature section

Table 12: U.S. Export Changes across RFS2 Scenarios (Percent Difference from Baseline Annuity)[31]

	RFS2	RFS2 with CRP
Corn	-3.75%	-2.00%
Soybeans	-30.10%	-28.23%
Wheat	-1.15%	0.69%
Cotton	-9.39%	-8.81%
Sorghum	-28.38%	-24.82%
Rice	-9.46%	-9.58%
Non Fed Beef	-1.27%	-0.32%
Pork	-0.62%	0.01%
Chicken	-0.14%	-0.05%

Higher commodity prices and lower U.S. export levels stimulate export activities in other regions internationally, which can induce land use change. Figure 23 displays export index values from the base period (2000), presented in annuity terms. These values express expected changes in export levels, by country of origin, from a historic base. Notice that in the baseline, most regions are expected to increase their exports over time, implying higher production levels and potentially cropland use (China and India are the two exceptions). However, forecasted exports increase across the RFS2 scenarios in regions presented here relative to the baseline. While some of these deviations are small, other regions see significantly increased exports, including large shifts in Argentina and Brazil (6-11%), where indirect land use change in response to U.S. policies is a concern.

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[31] Variable or scenario definitions are found in the Nomenclature section

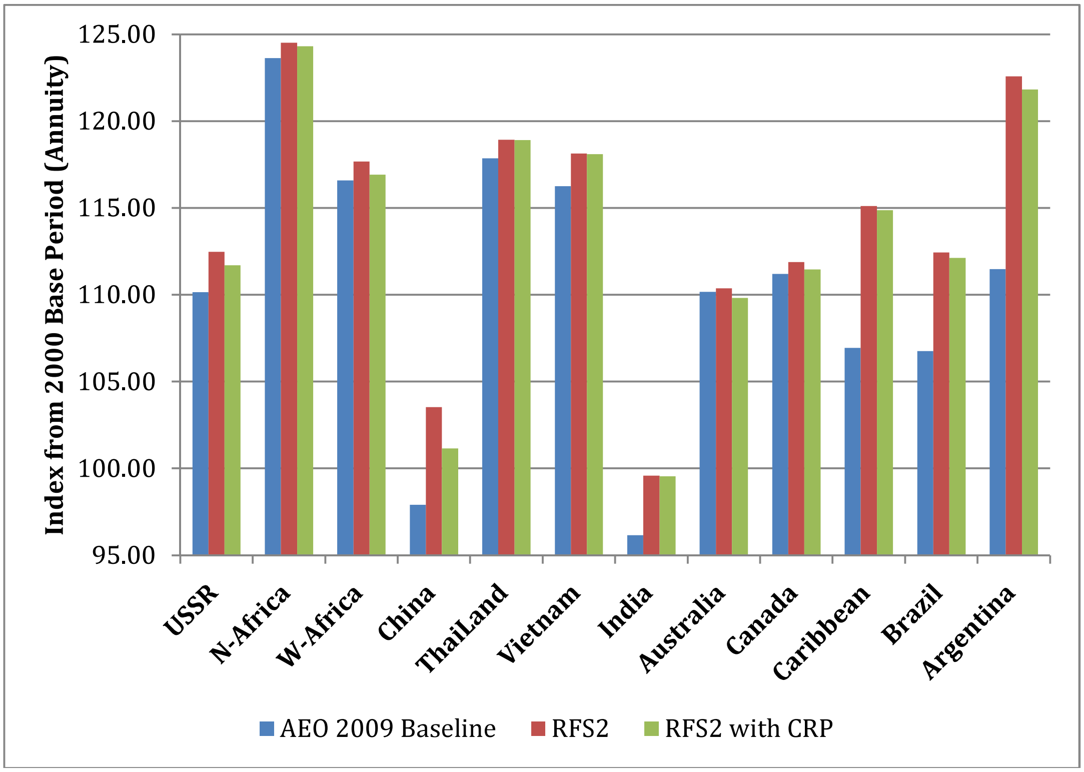

Figure 23: Export increase by international region and scenario (2000 level = 100)

6.2.3 Land Use Implications

The RFS2 driven biofuel expansion requires a shift in crop production patterns and mixes as well as the entry of additional land into production as detailed here.

6.2.3.1 Baseline Land Use Trajectories

In the baseline, with no RFS2 mandates, and no CRP reversion, results show a net decrease in total cropland and forested acres over time. Simply put, yield productivity growth outpaces demand growth in this scenario, causing reduced demand for cropland.. In addition, exogenous urban development takes cropland, grazing lands, and timberland out of production. As Figure 24 displays, both cropland and forested land area declines significantly in the baseline. In 2050, cropland declines approximately

33 million acres from the base (2000) period, or roughly 10-12% of the current cropland base. More than 19 million acres is transferred to development (cumulative), with the rest being set aside or transferred to pasture or forest. Private timberland decreases approximately 30.5 million acres mostly due to development losses (34 million acres), though some land transfers into forest from other uses.

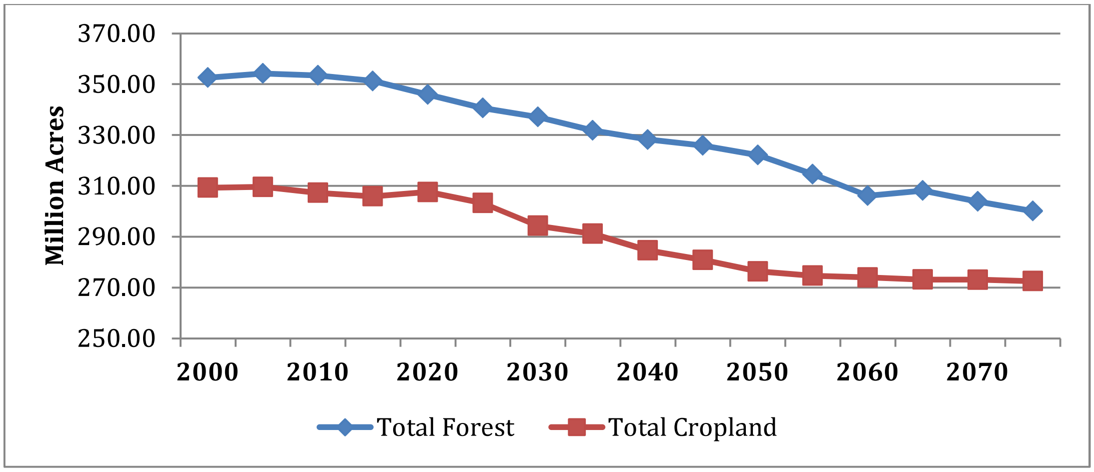

Figure 24: Crop and forest land use trajectories under AEO 2009 baseline conditions[32]

6.2.3.2 Land Use across the RFS2 Scenarios

Figure 25 expresses cropland and forest stocks on an annuity basis for the AEO 2009 Baseline, RFS2 and RFS2 with CRP reversion scenarios, respectively[33]. Compared to baseline levels, forest use increases only marginally between the AEO 2009 baseline

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[32] Variable or scenario definitions are found in the Nomenclature section

[33] Many of the results presented in the remainder of this dissertation will be presented in annuities over the simulation time horizon (2010-2080). Since the amount of output data analyzed is so expansive, I collapse the time element where appropriate and present dynamic data in annuity form. Annuities are formed using the net present of output variables, be they monetary or physical, calculated using a 4% real discount rate.

and RFS2 scenarios (approximately 2 million acres), attributed to cellulosic ethanol and bioelectricity feedstock demand. There is no discernible change in forest use between the CRP 32 million acres and reversion allowed scenarios (though land use change trajectories are affected). However, total cropland use increases considerably under the elevated bioenergy mandates (approximately 14.5 million acres). The RFS2 stimulates commodity demand and pushes agricultural land to the extensive margin, while also retaining cropland that would otherwise be idled or transferred out of crop production. Allowing CRP reversion adds an additional 3.9 million acres to the cropland stock on an annuity basis.

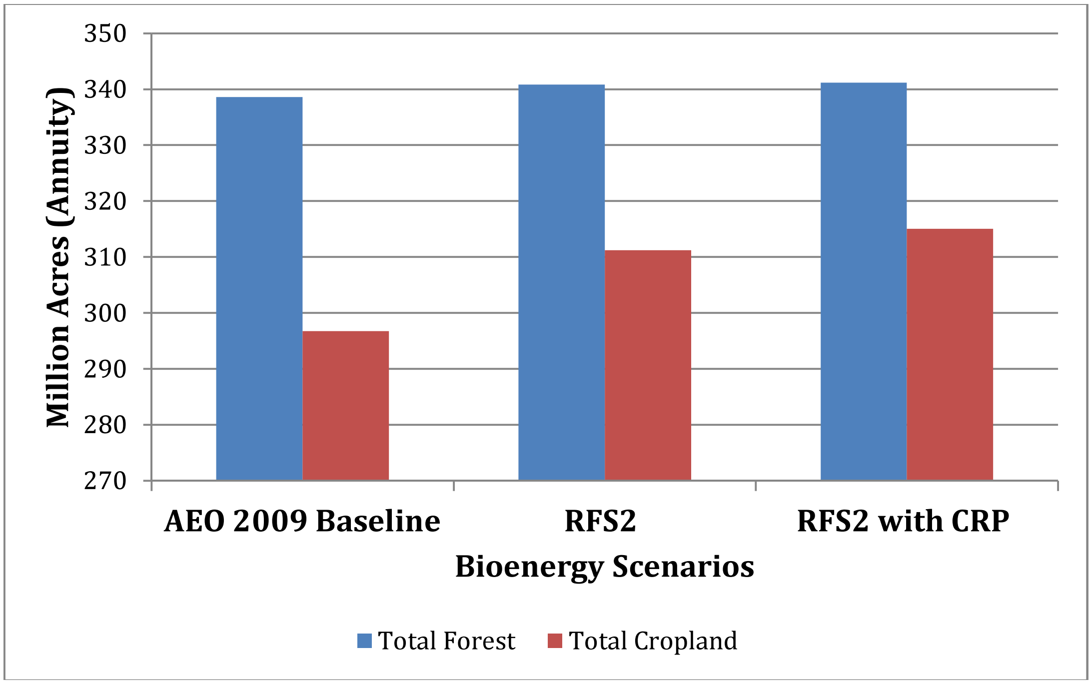

Figure 25: Cropland and forest stocks across bioenergy scenarios (million acre annuity)[34]

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[34] Variable or scenario definitions are found in the Nomenclature section

Land use trends change temporally as well. The difference in cropland and forest stocks over time is plotted in Figure 26. Total cropland use is substantially higher under the RFS2 scenarios than in the baseline. Beyond 2050, we see a difference of approximately 40 million acres in cropland above baseline levels. Forest use stays relatively the same across all three scenarios, but the transition of lands into and out of forestry is altered by the influence of the RFS2 mandates (discussed below). Total cropland use grows at an increasing rate when CRP reversion is allowed, and stays consistently higher for the length of the simulation.

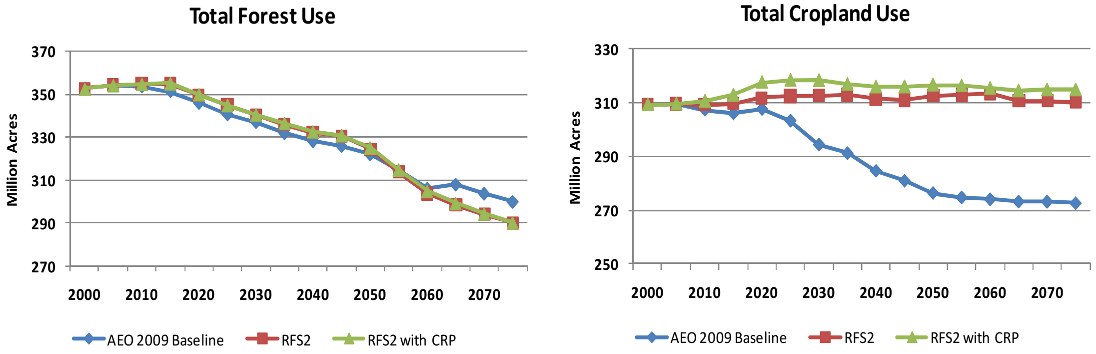

Figure 26: Crop and forest land use trajectories across biofuel expansion scenarios[35]

6.2.3.3 Land Use Change across Scenarios

In general, land-use allocation between alternative uses (cropland, forest, pasture, and conservation) is significantly affected by the RFS2 mandates (Table 13). Several observations arise from these data:

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[35] Variable or scenario definitions are found in the Nomenclature section

- Deforestation to cropland (which exist in the baseline) increases with the RFS2, reflecting greater potential returns to crop production than in timber in some regions, consistent with LUC concerns echoed in the literature. By 2020, Cumulative simulated cropland deforestation increases 4.77 million acres under the influence of the RFS2.
- There is little difference in deforestation for cropland rates by 2020 between the "with" and "without" CRP reversion cases. This is contrary to the hypothesis that greater use of marginal or idled cropland will reduce cropland expansion, and is indeed contrary to past simulations using the FASOMGHG model (Baker et al., 2008). The main difference between these simulations and those in past settings is the influence of cropland pasture transitions on CRP reversion rates (as moving land from cropland pasture to cropland is a lower cost land use shift in some FASOMGHG regions than CRP to cropland), a feature of the model that has been enhanced since the earlier simulations.
- The major differences in cropland deforestation occur in early periods of the simulation, which is consistent with the time frame in which the RFS2 drives the demand for agricultural feedstocks (2010-2020).
- Transition of lands from crop to forests (afforestation), which also exists in the baseline, decreases across the RFS2 scenarios.
- The largest shifts into dedicated crop production come from pastureland conversion and CRP re-cultivation. Pasture conversion is quite large in early years under the RFS2 scenario, exceeding baseline levels by 6.7 and 9.1 million

acres for 2020 and 2050, respectively. When CRP is included, this conversion decreases only slightly (0.7 and 0.9 million acres).

- There is a negligible amount of CRP reversion in the baseline where we allow CRP reversion up to the point of the Farm Bill 2008 target of 32 million acres constant in the RFS2 scenario, though the baseline begins with 37.2 million acres of CRP (leaving more than 5 million for recultivation purposes). This supply is exhausted in the RFS2 case (based on 2004 levels of CRP acreage). This movement is very consistent with the rates of change we've observed in CRP enrollment over the last three years, as enrollment has declined substantially (FSA, 2009).
- When we allow optimal CRP reversion under the RFS2, we see approximately 11.5 million acres reverting, or 34.2% of the current CRP stock, a significant shift away from conservation priorities. Loss in soil carbon and other environmental benefits (biodiversity and wildlife habitat protection, soil erosion protection, etc.) are likely accompanied by such a shift. This result shows that holding CRP rental payments at historic levels will not maintain conservation lands under higher commodity price regimes stimulated by the RFS2 (data show that rental payments for general CRP sign-up have remained steady since 2001, while comparable cropland rents have increased steadily.
- The largest land-use shift in the baseline runs is pasture afforestation, or 1) pure afforestation from cropland pasture, and 2) a management shift out of grazed forest pasture into permanent timber management. As timberland decreases

under the RFS2, a large portion of pasture shifts over to fill this void. This effect is enhanced by the RFS2 in later years of the simulation, as pasture moves to forest to replace timberland lost to crop production in earlier periods.

Table 13: Land Use Change by Category (Million Acres)[36]

	AEO 2009 Baseline		RFS2		RFS2 with CRP	
	2020	**2050**	**2020**	**2050**	**2020**	**2050**
Forest to Cropland	15.42	22.46	16.29	25.42	15.88	24.69
			5.61%	*13.16%*	*2.99%*	*9.93%*
Cropland to Forest	1.90	2.99	1.84	1.84	1.82	2.04
			-2.77%	*-38.29%*	*-3.92%*	*-31.60%*
Forest to Pasture	0.80	2.97	0.78	3.26	0.78	3.26
			-3.07%	*9.68%*	*-3.07%*	*9.65%*
Pasture to Forest	24.54	29.14	29.79	35.84	29.45	35.63
			21.38%	*22.98%*	*20.02%*	*22.26%*
Pasture to Cropland	9.76	9.76	9.76	10.95	9.76	10.57
			0.00%	*12.16%*	*0.00%*	*8.33%*
CRP to Cropland	3.65	3.65	5.32	5.32	11.62	11.62
			45.84%	*45.84%*	*218.63%*	*218.63%*

6.2.3.3.1 Comparison with Other Studies

In general, most studies of LUC and bioenergy have been performed using global economic models to simulate LUC in international regions (Dumortier et al., 2009; Hertel et al., 2009; Searchinger et al., 2008). The idea is that cropland expansion is

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[36] Variable or scenario definitions are found in the Nomenclature section

expected to occur at higher rates in developing nations where land is essentially more "mobile". The bulk of this expansion is expected in tropical regions such as those found in Brazil, or in productive grasslands such as the Argentine Pampas. FASOMGHG results indicate that there is significant cropland expansion potential within the U.S. Different modeling approaches and baseline assumptions and input data all factor into final estimates of LU/LUC over time.

As a relevant comparison study, consider Keeney and Hertel, 2009, which measures land use responses globally to increased biofuel production in the U.S. (specifically ethanol) using a computable general equilibrium model of global trade. For every billion gallon increase in ethanol production, they find a 0.1 percent increase in the demand for U.S. cropland. This is accompanied by reductions in forests and pasture at 0.35% and 0.53%, respectively. Their approach uses a static computable general equilibrium model that relies on Allen-Uzawa elasticities of substitution between factor inputs (i.e., land use types) to simulate land use competition and LUC responses to increased U.S. biofuel production. This is different from the dynamic FASOMGHG approach that weighs the expected returns to alternative land uses over time, contingent on biophysical parameters that constrain total land use transferability by region.

Comparing land use totals and total ethanol output from FASOMGHG results similar land use responses are found for pasture, very little response in total forest use, but a much greater affect in the demand for cropland. Total cropland differences in 2025 are 9.3 and 15.1 million acres, respectively for the RFS2 and RFS2 with CRP cases (Table 14). For every one billion gallon increase in ethanol demand in 2025, results show a 0.20% and 0.32% increase in total cropland (three times the expansion rate of Keeney and Hertel, 2009). Contrary to Keeney and Hertel et al., forest use increases, but only marginally so (0.08% per billion gallons ethanol). I find a much stronger reduction in the demand for pasture resulting from a one billion gallon increase in ethanol. Thus, FASOMGHG shows stronger cropland expansion and pasture contraction effects in the U.S. than Hertel et al. 2009, though one might argue that a lack of significant land use movement in the U.S. in a global modeling effort is specifically due to the global land use coverage. This has implications for commodity markets and international leakage, as subsequent sections will discuss.

Table 14: Land Use Responses to U.S. Ethanol Expansion (FASOMGHG Estimates)

	Ethanol (bgy)	**Cropland (million acres)**	**Forest (million acres)**	**Pasture (million acres)**
Absolute Difference by 2025 (RFS2 Base)	15.59	9.27	4.35	-11.95
Absolute Difference by 2025 (RFS2 with CRP)	15.59	15.10	4.40	-55.41
Percent change per 1 billion gallon (RFS2 Base)	n/a	0.20%	0.08%	-1.15%
Percent change per 1 billion gallon (RFS2 with CRP)	n/a	0.32%	0.08%	-1.10%

6.2.3.3.2 Commodity Production Implications of Land Use Responses

Land use affects total cropland stocks by major U.S. crop (Table 15), and livestock production practices. Results here are presented in annuities, by million acres (for simplicity, land use totals are converted to annuity to collapse the time element and allow for a simple comparable measure of land use stocks).

- The RFS2 scenarios cause U.S. corn acreage to increase by more than 3 million acres.
- Wheat acreage actually declines by 0.5-1.5 million acres as crop mix strategies adjust to the biofuel expansion policy. In addition there is crop residue harvesting for cellulosic ethanol production.
- Across the RFS2 scenarios, approximately 13-14 million acres of corn and 15-16 million acres of wheat include residue harvesting for energy production. One should note that residue harvesting could undermine other environmental objectives such as boosting soil carbon sequestration through changing tillage practices. Removing residues from a field reduces the rate at which soil carbon accumulates over time. Research has shown that intense residue harvesting can also degrade water quality by enhancing erosion and nutrient leaching (Mann et al., 2002). As the next chapter will discuss, the existence of the RFS2, can augment AF GHG mitigation potential by limiting certain practices that conflict with RFS2 demands.
- The greatest net change in cropped acres is seen in soybeans, which increases 7.5-8.6 million acres from baseline to RFS2 conditions due to the large land requirements needed to produce soybean biodiesel. Again, while soybean biodiesel is a relatively minor portion of the RFS2 total, the

- Cotton acreage decreases slightly, and rice acreage decreases appreciably. While this reduction in rice acreage is small in absolute terms, global rice markets have shown to be very sensitive to acreage totals and short-term reductions in supply (Trostle, 2008).
- Switchgrass, a dedicated energy crop, is grown on approximately 5 million acres of cropland under the RFS2, a ten-fold increase above baseline levels. All dedicated energy crop acreage occurs in the Southern U.S.

Table 15: U.S. Land Use by Crop and Scenario (Million Acres Annuity)[37]

	AEO 2009 Baseline	**RFS2**	**RFS2 with CRP**
Corn	**69.39**	**72.46** *4.42%*	**72.92** *5.08%*
Soybeans	**66.34**	**73.83** *11.30%*	**74.95** *12.97%*
Wheat	**64.32**	**62.94** *-2.15%*	**63.80** *-0.81%*
Cotton	**11.58**	**11.22** *-3.10%*	**11.21** *-3.18%*
Sorghum	**9.93**	**11.33** *14.04%*	**11.54** *16.14%*
Rice	**3.13**	**2.88** *-7.98%*	**2.88** *-8.06%*
Switchgrass	**0.59**	**5.13** *773.45%*	**5.21** *786.72%*

Shifts in land use and crop production driven by the RFS2 affect the U.S. livestock industry as well. As conventional feed grains are used for biofuel processing, the price of feed rises accordingly, inducing distinct management shifts in livestock, and

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[37] Variable or scenario definitions are found in the Nomenclature section

lowering herd size. Table 16 displays changes in livestock production. Results indicate that poultry, eggs, and dairy production will decrease only marginally due to higher feed costs. However, cattle production is significantly affected. Total herd size (denoted by the Cow/Calf row entry) drops approximately 10% below baseline levels, with stocker cattle decreasing the most, indicating a shift away from pasture grazing.

Table 16: Livestock Changes from Base in Absolute (Thousand Head) and Percentage Terms[38]

	RFS2	**RFS2 (% Diff)**	**RFS2 with CRP**	**RFS2 with CRP (% Diff)**
Sheep	104	*2.16%*	127	*2.63%*
Total Cow/Calf	-1,108	*-2.77%*	-821	*-2.05%*
Feedlot Yearlings	-2,690	*-18.49%*	-3,322	*-22.84%*
Feedlot Calves	1,879	*7.25%*	2,621	*10.11%*
Dairy	-56	*-0.88%*	-31	*-0.48%*
Farrow Hog	3,127	*24.94%*	3,097	*24.71%*
Feeder Pig	-217	*-3.60%*	-156	*-2.58%*
Pig Finishing	-4,490	*-3.86%*	-3,284	*-2.82%*
Horses and Mules	-62	*-1.02%*	-35	*-0.58%*
Steer Calf (Stocker)	-1,286	*-10.12%*	-1,803	*-14.19%*
Heifer Calf (Stocker)	-1,565	*-56.72%*	-1,560	*-56.55%*
Steer Yearling (Stocker)	-1,329	*-9.70%*	-1,866	*-13.62%*
Heifer Yearling (Stocker)	-1,630	*-55.79%*	-1,625	*-55.63%*
Turkey	2,936	*1.44%*	2,855	*1.40%*
Broiler	-21,961	*-0.29%*	-10,438	*-0.14%*
Egg	-1,561	*-0.48%*	-418	*-0.13%*

Optimal feed portfolios also change under the RFS2 (Figure 27) as corn is allocated for ethanol production. In total, corn fed to beef cattle, dairy cattle, and hogs

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[38] Variable or scenario definitions are found in the Nomenclature section

decreases by approximately 350 million bushels, helping to explain the dramatic reduction in total herd size and livestock producer welfare across the RFS2 scenarios. However, some of this loss is supplemented by increased barley, silage, and hay feeds. Additionally, DDG from corn fractionation and use of gluten meal are stimulated by the RFS2.

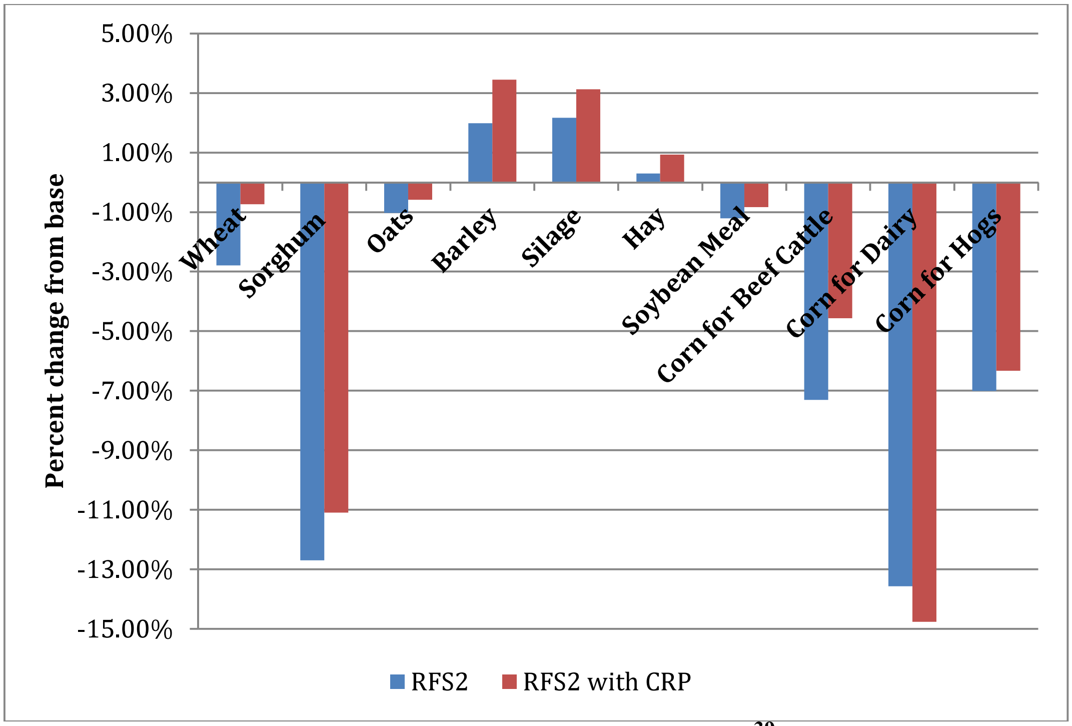

Figure 27: Change in feed use from base by commodity[39]

6.2.3.3.3 Regional Land Use: Indirect Policy Consequences

Cropland expansion responses to the RFS2 scenarios vary widely by region.

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[39] Variable or scenario definitions are found in the Nomenclature section

Table 17 expresses regional cropland use projections across scenarios on an annuity basis. Most regions see an increase in cropland use. The greatest acreage increase occurs in the Lake States and Southwest regions, where annual cropland use is projected to increase 4-5 million acres, representing approximately 17.5% and 11.5% shifts in cropland, respectively. This includes an increase in switchgrass acreage in the Southwest (~3.5 million acres), and use of additional cropland for grain production to satisfy the void left in conventional commodity markets as food products are used for fuel processing in the Corn Belt and Great Plains regions. Also, I find reductions in crop acreage in the baseline (especially in the Southwest region), as this is less productive land than the Corn Belt and Lake States; while higher energy prices and low crop prices drive some of this out of production in the baseline, but the RFS2 brings it back in.

Other large deviations from the baseline in the RFS2 case occur in the Corn Belt, Lake States, Southeast, and South Central. When CRP reversion is allowed, an additional 2-3 million acres re-enter production in the Great Plains. Additionally, as more productive CRP lands revert in the Corn Belt, Great Plains, and Lake States, there is a smaller amount of cropland used in less productive regions like the Southwest.

All regions experience shifts in overall cropland use and net gains in biofuel output. Given that the RFS2 is a national based policy, one cannot call regional cropland expansion effects leakage. However, as the majority of energy production is concentrated in a few regions, and cropland expansion effect is prevalent in most, there are indirect market responses (i.e., land use changes) occurring in regions with little energy production potential. This can cause increased GHG net emissions from agricultural practices in those regions.

Table 17: Regional Cropland Use and Percent Difference from Base across Biofuel Scenarios (Million Acres, 2025)[40]

	AEO 2009 Baseline	**RFS2**	**RFS2 with CRP**
Corn Belt	**79.37**	**81.26** *2.38%*	**81.72** *2.96%*
Great Plains	**76.02**	**75.29** *-0.96%*	**78.84** *3.72%*
Lake States	**29.41**	**34.45** *17.15%*	**34.60** *17.67%*
Northeast	**4.85**	**6.40** *31.92%*	**5.76** *18.72%*
Rocky Mts.	**25.26**	**24.88** *-1.49%*	**25.32** *0.24%*
Pac. Southwest	**3.79**	**3.79** *0.00%*	**3.79** *0.00%*
Pac. Northwest	**5.85**	**5.85** *0.02%*	**5.84** *-0.04%*
South Central	**35.80**	**36.94** *3.17%*	**37.20** *3.89%*
Southeast	**12.84**	**14.30** *11.35%*	**14.34** *11.65%*
Southwest	**22.99**	**27.65** *20.28%*	**27.21** *18.36%*

6.2.3.4 Baseline Emissions across AF Sectors

Baseline emissions across all AF activities, expressed in decadal averages out to 2050 are in Figure 28. Here, positive values indicate a net source of emissions and negative values a net sink. The results show:

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[40] Variable or scenario definitions are found in the Nomenclature section

- Forest management decisions account for a large source of emissions throughout the time horizon (206 million tCO_2e per year), but are significantly higher in early periods of the simulation as land moves out of forest into crop production. This includes carbon uptake from existing/reforested stands, emissions from deforestation, forest fuel use, harvesting timber, and transporting/processing final products.
- Carbon stored in final wood products over the long term completely offsets the emissions from land management activities (-259 million tCO_2e in the baseline).
- Carbon stored in afforested stands converting from cropland or pasture is also counted, and provides a significant sink in the baseline (-72 million tCO_2e). Taken together, forest product and afforestation sequestration, plus emissions from forest management produce a net annual sink of 125 million tCO_2e.
- Agricultural methane (CH_4) accounts for an average of 194.3 million tCO_2e per year. This includes emissions from rice cultivation, livestock manure management, and enteric fermentation. Crop soil C sequestration is variable, reflecting soil carbon dynamics, differences in tillage practices, land use changes into and out of crop production, and changes in overall crop mix strategies over time.
- Nitrous oxide (N_2O) emissions amount to ~150 million tCO_2e per year across the projected period, which is less than EPA GHG Inventory estimates of ~200 million tCO_2e per year (EPA, 2009).
  - N_2O emissions include those from fertilizer use (122 million tCO_2e), indirect N2O emissions from soil volatilization or N leaching, N_2O emissions from

pasture use (~29 million tCO_2e), and N_2O fluxes from bioenergy and manure management activities.

- CO_2 emissions from agricultural energy input use, which account for an average of 68.4 million tCO_2e[41].
- Carbon is sequestered in cropped soils at a rate of 47.2 million tCO_2e
- In all the model projects a total annualized source of emissions from AF activities of ~176 million tCO_2e (in annuity terms).

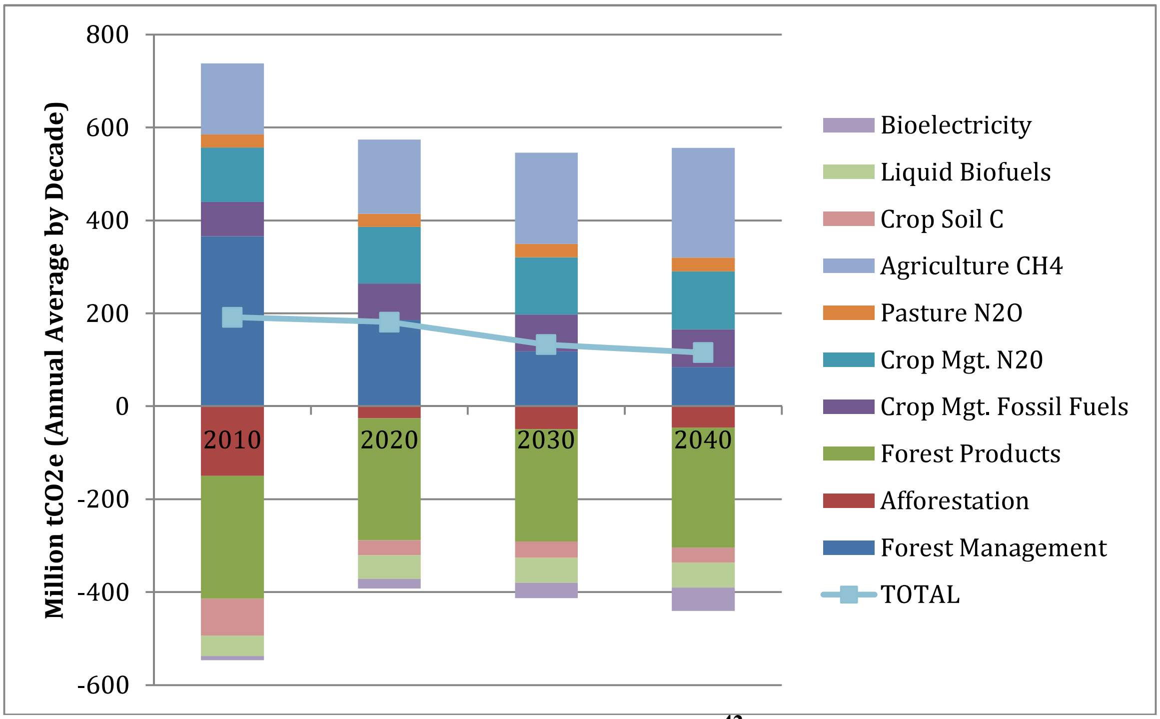

Figure 28: Baseline emissions flux (decadal averages)[42]

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[41] It is worth noting that in other accounting systems, fossil fuel use emissions in AF would be accounted for in "upstream" capped entities such as energy and industry. I include these here for purposes of illustration, and later to show how policy induced shifts in input use can alter net AF emissions.

[42] Variable or scenario definitions are found in the Nomenclature section

6.2.3.5 GHG Implications of Biofuel Expansion

To examine the impact of the RFS2 on net GHG emissions, Figure 29 includes a side-by-side comparison of the total annualized emissions flux. The bottom portion of the figure takes an annualized difference from baseline for each of the major GHG accounts. The annualized emissions flux is quite similar across these scenarios, with the major difference coming in the liquid biofuel offset category[43]. The RFS2, which produces a high volume of low-carbon cellulosic ethanol, produces a much larger offset of fossil fuel equivalent GHGs than the baseline (we find a 75.5 million tCO2e difference in this account alone). Net emissions from U.S. AF decrease across the RFS2 scenarios at a rate consistent with biofuel emissions reduction from fossil fuel replacement (80.9 million tCO_2e per year without CRP, and 81.2 million tCO2e with CRP).

This is an important result, indicating that increased emissions from land use change, increased fossil fuel use and N application use resulting from the RFS2 do not produce a source of emissions large enough to discount the GHG benefits of biofuel production (ignoring emissions from land use changes and production in international regions).

Specifically, we find increases in:

- N2O emissions from N application (6.8-7.8 million tCO_2e per year),

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[43] The liquid biofuels account includes emissions offsets from biofuel replacement of fossil fuels after life-cycle emissions of biofuels from cultivation, harvest, transportation, processing, and combustion are accounted for.

- CO2 emissions from fossil fuel use (2.7-3.4 million tCO_2e per year), and
- A reduction in soil carbon sequestration, due to land use changes that reduce soil organic carbon stocks (16.7-18.1 million tCO_2e per year).

However, these emissions are completely offset by biofuels (~75 million tCO_2e per year), and other sources emissions reduction, including:

- Increased carbon sequestration through afforestation and forest management activities (21-25.6 million tCO_2e per year).
- Reduction in methane emissions caused by a shift in livestock management practices and reduced herd size (~9.5 million tCO_2e)

If only agricultural GHG accounts are considered, increased emissions from agricultural activities discount the GHG benefits of biofuels by 20-25% (with higher leakage when CRP reversion is allowed). However, when forestry accounts are included, there is no net GHG leakage. This contradicts recent evidence that net N2O emissions from increased nitrogen application under an RFS2 regime alone would outweigh the net gains from biofuel expansion (Crutzen et al., 2009). Obviously, these estimates do not include emissions from international LUC, or other environmental impacts of significant cropland expansion and agricultural input use.

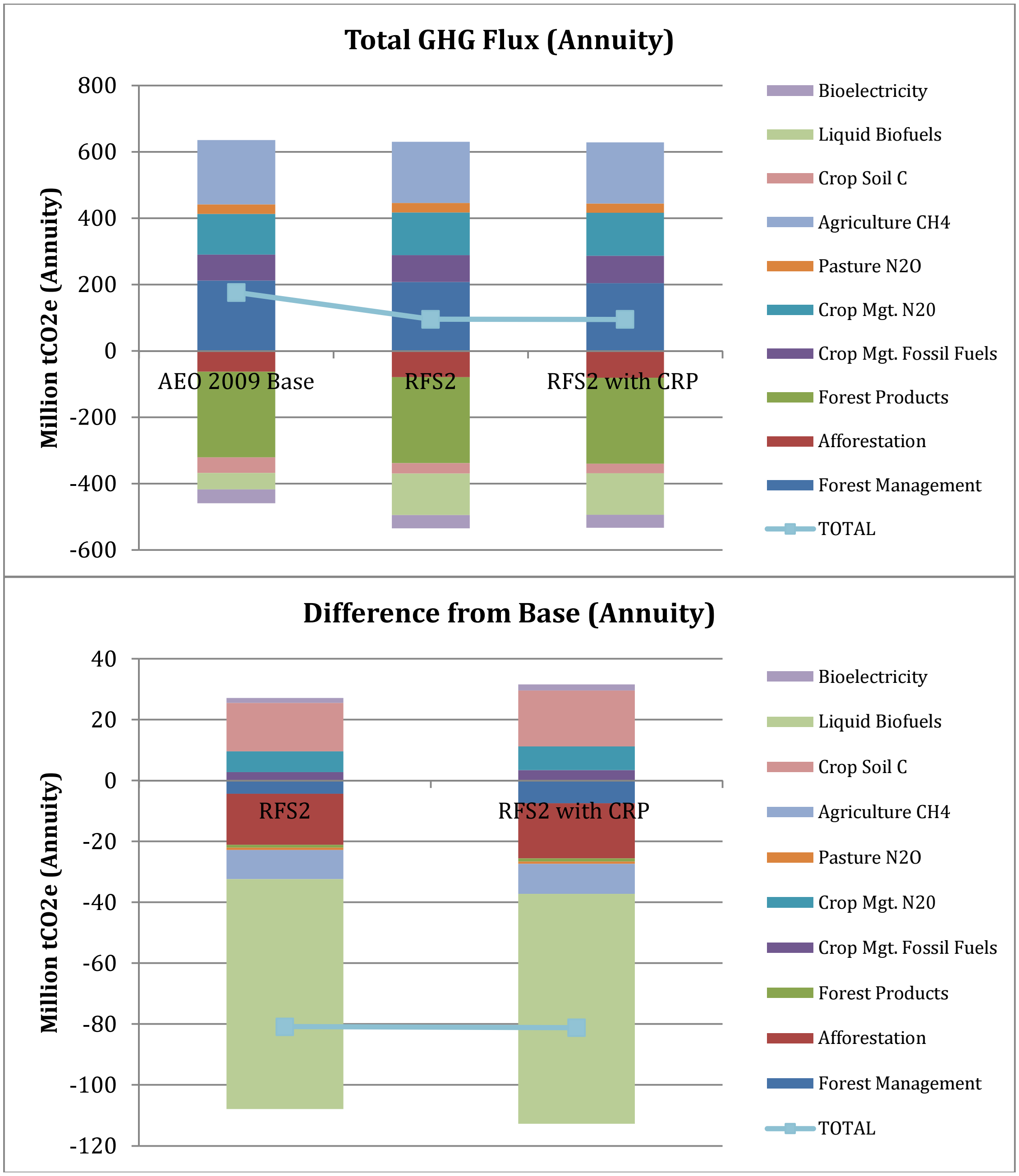

Figure 29: Annualized GHG emissions and difference from base across RFS2 scenarios[44]

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[44] Variable or scenario definitions are found in the Nomenclature section

6.2.4 Management Intensity and Water Resource Implications

RFS2 implications for water use and management intensity are also important. Here I show national and regional deviations from baseline in the use of important energy intensive inputs, both on an annualized aggregate basis, and per-acre.

6.2.4.1 National Water Use

As previous chapters have discussed, use of freshwater for irrigated agricultural is expected to increase significantly under expanded biofuel production. Results of this analysis show the following response in water use:

- Total water use, displayed by Figure 30, increases marginally across the RFS2 scenarios by approximately 0.6 million acre-feet on an annuity basis- roughly a 1% increase[45].
- While total cropland increases ~14 million acres annually, projected irrigated acreage only expands 0.31-0.34 million acres, a 0.7% increase in irrigated production.
- However, this is not an insignificant amount of water in terms of alternative uses. This amounts to an additional 0.54 billion gallons per day withdrawn for irrigation purposes. The American Water Works Association reports that average

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[45] Keep in mind that FASOMGHG water use totals do not completely depict water withdrawals from U.S. agriculture. USGS reports much higher water use totals out of the sector. This difference is prevalent for two main reasons. First, FASOMGHG does not model a number of crops that rely heavily on irrigation, including peanuts, some vegetables and fruits, orchards, and vineyard crops that comprise a small share of the land base but a very large share of water use in the West Coast, Southwest, and Southeastern U.S. Also, our per-acre water use factors are based on Agricultural Resource Management Survey data, in which farmers possibly under-report water application rates. Further development is under way to reconcile these differences.

water use per household per year amounts to approximately 127,400 gallons. Thus, putting the RFS2-driven increased irrigation burden of 0.54 billion gallons per day into the context of municipal use, this amounts to enough water to satisfy the municipal demands of 1.5 million households annually (roughly 6 million people). A secondary implication of this result is that the RFS2 will increase competition for scarce water supplies, raise the opportunity costs of agriculture-to-urban water transfers, and could alter long-term water planning strategies. Thus, while the extent of this flux is small relative to the entire share of irrigation water consumed by the agricultural sector, volumetrically, this represents a very high share of water consumed for other purposes.

- When CRP reversion is allowed, there is no discernible change in total water use.

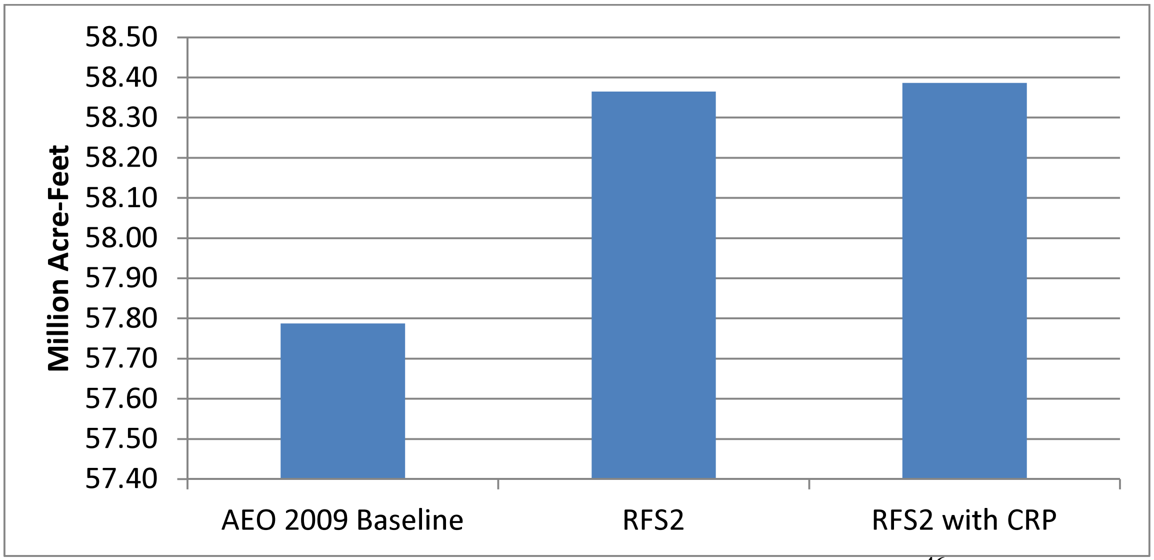

Figure 30: Projected agricultural water use (million acre-feet, 2025)[46]

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[46] Variable or scenario definitions are found in the Nomenclature section

6.2.4.2 Regional Water Use: More Indirect Consequences

The spatial distribution of additional water use also merits attention. Table 18 displays regional deviations in water use in annualized million acre-feet. Net water use increases in all regions, though the extent varies widely by region.

- The largest percentage changes in water use occur in the Southwest, Northeast, and Corn Belt, though the latter two represents a very small change in absolute terms. The Great Plains and Southwest regions, which is notable because land there is either water scarce or predominately irrigated by groundwater. This adds to concerns of over-exploitation of the aquifer moving forward. This is consistent with recent concerns that the sustainable management of the Ogallala could be undermined long-term by biofuel expansions incentives (Environmental Defense, 2008).
- Some regions experience a net decrease in total water use under the RFS2, including the South Central, which consumes approximately 1 million acre-feet of water less under the RFS2 due to shifting crop mixes.
    - If this reduction were not counted, the total water response would be more significant (~1.6 million additional acre-feet consumed),
    - Additionally, cropland shifts in the South Central indirectly stimulate irrigation intensity in other regions. Some irrigated cotton and rice in the South Central is replaced with dryland grain and dedicated bioenergy feedstock production, indirectly stimulating production of rice and cotton in the Southwest.

- Deviations in water use are smaller in some regions when CRP reversion is allowed since land and water can be substitutable in increasing production, reflecting a tradeoff on the intensive and extensive margins. As additional cropland comes into production, this relaxes management intensity and the demand for irrigation water. That is, additional cropland production can adjust the demand for irrigated production, and reduce water use in some regions.

Table 18: Difference in Regional Water Use (Million Acre-feet Annuity and Percent Difference from Base)[47]

	RFS2		**RFS2 with CRP**	
	Absolute Diff.	***% Diff***	**Absolute Diff.**	***% Diff***
Corn Belt	**0.03**	*9.14%*	**0.03**	*9.25%*
Great Plains	**0.66**	*5.39%*	**0.72**	*5.88%*
Lake States	**0.00**	*-0.76%*	**0.01**	*1.90%*
Northeast	**0.02**	*33.58%*	**0.01**	*20.94%*
Pac. Northwest	**0.03**	*1.71%*	**-0.01**	*-0.74%*
Pac. Southwest	**0.07**	*0.99%*	**0.08**	*1.13%*
Rocky Mts.	**0.11**	*0.49%*	**0.12**	*0.56%*
South Central	**-0.97**	*-14.02%*	**-0.98**	*-14.12%*
Southeast	**0.03**	*2.74%*	**0.04**	*2.96%*
Southwest	**0.62**	*9.54%*	**0.59**	*9.15%*

There are important social trade-offs to consider when renewable energy mandates significantly boost overall water consumption for irrigation purposes. The full magnitude of this effect may not be alarming at a national level, but the regional distribution of increased irrigation relative to the baseline is perhaps more troubling, consistent with those in Berndes, 2002. Social gains in increased renewable energy

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[47] Variable or scenario definitions are found in the Nomenclature section

supplies should be carefully weighed with local water resource management goals to ensure long-term viability of valuable freshwater supplies.

6.2.4.3 Other Management Intensification Responses

Table 19 displays percentage changes in important input use by major production region for the RFS2 and RFS2 with CRP recultivation cases, respectively. This value serves as a rough estimate of the aggregate intensification effect of production by major AF region. In general, results show that management intensification effects vary by input and are not consistent across regions. Changes in crop mix compositions driven by biofuel expansion can significantly alter nutrient use and agricultural energy use portfolios. Important observations include:

- Total input use increases for every input considered (except natural gas—a common input used to fuel irrigation systems) at a national level, driven by aggregate cropland expansion.
- Nutrient use expands significantly (especially for Nitrogen fertilizer applied). Phosphorous and potassium application also increase substantially under the altered crop mix portfolio (potassium use expands more than 14% from base).
- The largest volumetric gains in N use occur in the Southwest regions, which is also the highest percentage increase at more than 50%.
- Nutrient use in the Corn Belt and Great Plains can affect water quality downstream or groundwater systems through runoff and nitrate leaching. Here, I find that N use increases by approximately 4% under the RFS2.
- Fossil fuel use does not increase consistently across regions.

Table 19: Percent Change from Baseline in Total Input Use by Region and RFS2 Scenario[48]

Percent change in total input use across the RFS2

	Nitrogen	Phosphorous	Potassium	Diesel	Electric	Gasoline	Nat. Gas	Water
Corn Belt	2.65%	7.68%	14.99%	2.70%	-4.37%	2.86%	12.14%	9.14%
Great Plains	0.68%	-0.09%	1.67%	-0.81%	4.65%	-2.14%	1.02%	5.39%
Lake States	4.25%	14.86%	30.05%	19.85%	-13.72%	-5.35%	14.65%	-0.76%
Northeast	33.71%	33.26%	35.89%	34.72%	34.16%	29.11%	0.00%	33.58%
Pac. Northwest	0.14%	-0.45%	-0.79%	-0.07%	1.84%	0.17%	0.00%	1.71%
Pac. Southwest	0.17%	0.40%	-4.05%	1.10%	-0.57%	0.68%	0.00%	0.99%
Rocky Mts.	-2.23%	-1.99%	-0.14%	-0.57%	0.00%	-3.88%	-13.94%	0.49%
South Central	-4.42%	4.91%	0.34%	-0.70%	-14.04%	-11.03%	-13.55%	-14.02%
Southeast	10.91%	14.07%	9.42%	9.54%	3.23%	8.52%	0.00%	2.74%
Southwest	22.45%	32.64%	123.36%	16.39%	9.87%	-10.54%	0.00%	9.54%
U.S. Total	**3.47%**	**7.73%**	**14.71%**	**4.61%**	**2.27%**	**0.05%**	**-9.71%**	**1.00%**

Percent change in total input use across the RFS2 with CRP

	Nitrogen	Phosphorous	Potassium	Diesel	Electric	Gasoline	Nat. Gas	Water
Corn Belt	3.11%	7.91%	14.89%	3.29%	-3.93%	3.47%	12.17%	9.25%
Great Plains	5.07%	4.34%	5.27%	4.01%	4.63%	2.57%	5.71%	5.88%
Lake States	3.80%	14.38%	30.13%	20.27%	-10.74%	-4.19%	16.99%	1.90%
Northeast	20.61%	19.99%	22.55%	20.47%	20.96%	17.46%	0.00%	20.94%
Pac. Northwest	-0.15%	-0.51%	-0.46%	-0.16%	-0.83%	-0.12%	0.00%	-0.74%
Pac. Southwest	0.19%	0.61%	-5.68%	1.75%	-1.87%	0.89%	0.00%	1.13%
Rocky Mts.	-0.91%	-1.03%	0.54%	0.94%	0.05%	-2.58%	-13.64%	0.56%
South Central	-4.41%	5.57%	0.84%	-0.25%	-14.21%	-11.76%	-13.56%	-14.12%
Southeast	11.73%	15.19%	9.99%	9.63%	2.77%	6.86%	0.00%	2.96%
Southwest	20.08%	30.51%	116.82%	14.55%	9.61%	-14.09%	0.00%	9.15%
U.S. Total	**4.33%**	**8.73%**	**14.40%**	**5.97%**	**2.15%**	**0.87%**	**-9.34%**	**1.04%**

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[48] Variable or scenario definitions are found in the Nomenclature section

An appropriate proxy for regional management intensification responses is the deviation in per-acre use of agricultural inputs, which eliminates the effect of cropland expansion on total input use (Table 20). This is a more valuable metric for understanding the influence of policies on farm-level production behavior and input use.

- For the U.S., aggregate management intensity decreases for all energy inputs and N fertilizer, but increases for water use and phosphorous/potassium application. This result indicates that although cropland use increases, total input use and per-acre intensity decline, indicating a trade-off along the extensive and intensive margins. The cropland expansion effect of the RFS2 appears to dominate the management intensity effect.
- However, management intensity increases for fertilizer and chemical application rates in all regions but the Lake States, Rocky Mountains, Pac. Northwest, and South Central. Thus, the RFS2 can lead to cropland expansion and a shift along the intensive margin, which is consistent with initial expectations and theoretical framework. Furthermore, national reductions in management intensity are driven by large reductions in the Lake States and South Central.
- In the Rocky Mountains and South Central, per-acre use of most inputs declines. These regions bring additional cropland into production under the RFS2 and shift crop mix strategies, but manage to reduce on-farm input use in the process (reflecting the intensity/expansion effect observed at the national level).
- In general, CRP reversion relaxes management intensification increases as additional land comes into production.

Table 20: Percentage Change from Baseline in Per-acre Input Use by Region and RFS2 Scenario[49]

Percent change in per-acre input use across the RFS2								
	Nitrogen	Phosphorous	Potassium	Diesel	Electric	Gasoline	Nat. Gas	Water
Corn Belt	0.27%	5.18%	12.32%	0.31%	-6.59%	0.46%	11.59%	-0.17%
G. Plains	1.65%	0.88%	2.65%	0.15%	5.66%	-1.20%	17.49%	0.45%
Lake States	-11.01%	-1.96%	11.01%	2.30%	-26.35%	-19.21%	11.59%	2.84%
Northeast	1.36%	1.02%	3.02%	2.13%	1.71%	-2.12%	0.00%	-0.16%
Pac. Northwest	0.13%	-0.47%	-0.80%	-0.08%	1.83%	0.15%	0.00%	-0.28%
Pac. Southwest	0.17%	0.40%	-4.05%	1.10%	-0.57%	0.68%	0.00%	0.04%
Rocky Mts.	-0.75%	-0.52%	1.37%	0.93%	1.51%	-2.43%	-13.11%	0.30%
South Central	-7.35%	1.69%	-2.74%	-3.75%	-16.68%	-13.76%	-26.21%	0.06%
Southeast	-0.39%	2.45%	-1.73%	-1.62%	-7.29%	-2.54%	0.00%	0.30%
Southwest	1.80%	10.28%	85.71%	-3.23%	-8.65%	-25.63%	0.00%	0.13%
Total	**-1.40%**	**2.66%**	**9.31%**	**-0.31%**	**-2.55%**	**-4.66%**	**-13.96%**	**0.26%**
Percent change in per-acre input use across the RFS2 with CRP								
	Nitrogen	Phosphorous	Potassium	Diesel	Electric	Gasoline	Nat. Gas	Water
Corn Belt	0.15%	4.81%	11.59%	0.32%	-6.69%	0.50%	11.55%	-0.17%
G. Plains	1.30%	0.60%	1.50%	0.28%	0.88%	-1.11%	23.09%	0.74%
Lake States	-11.78%	-2.79%	10.60%	2.21%	-24.14%	-18.57%	13.62%	2.78%
Northeast	1.60%	1.07%	3.23%	1.48%	1.89%	-1.06%	0.00%	-0.07%
Pac. Northwest	-0.11%	-0.47%	-0.42%	-0.12%	-0.80%	-0.08%	0.00%	0.04%
Pac. Southwest	0.17%	0.60%	-5.69%	1.74%	-1.88%	0.88%	0.00%	0.17%
Rocky Mts.	-1.14%	-1.27%	0.30%	0.70%	-0.18%	-2.81%	-16.73%	0.43%
South Central	-7.99%	1.62%	-2.94%	-3.99%	-17.42%	-15.06%	-26.54%	0.08%
Southeast	0.07%	3.17%	-1.49%	-1.81%	-7.95%	-4.29%	0.00%	0.22%
Southwest	1.45%	10.27%	83.19%	-3.21%	-7.39%	-27.41%	0.00%	0.11%
U.S. Total	**-1.79%**	**2.36%**	**7.69%**	**-0.25%**	**-3.84%**	**-5.05%**	**-14.65%**	**0.38%**

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[49] Variable or scenario definitions are found in the Nomenclature section

6.2.4.3.1 Other Environmental Effects

Management responses along the intensive and extensive margins imply non-GHG environmental co-effects of the RFS2. FASOMGHG contains technical coefficients that relate per-acre use of agricultural practices to environmental impact measures. Figure 31 summarizes various nitrogen and phosphorous pollution measures in percentage differences from the baseline. These are emissions factors associated with regional production practices and per-acre use of agricultural inputs. In general, sources of N percolation, subsurface loss, and NO_3 runoff increase 3-6% across the RFS2, while P runoff and sediment loss increase 4-10%.

In general these results indicate that the non-GHG environmental consequences of the RFS2 are non-trivial, and merely measuring responses in input use relative to a baseline forecast might not reveal appropriate estimates of N and P pollution, nutrient loading, runoff, or sedimentation given geographic and biophysical factors that influence pollution.

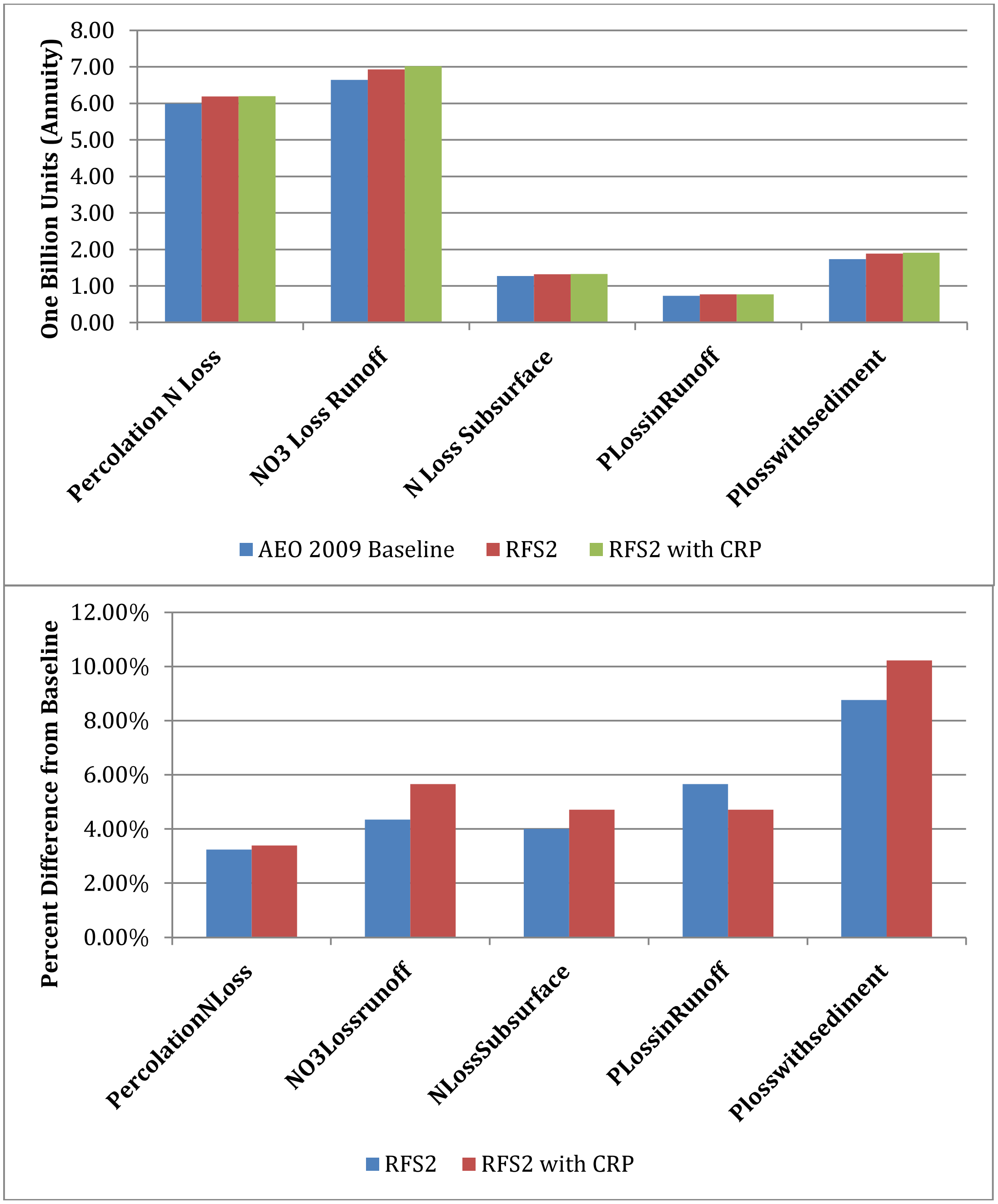

Figure 31: Absolute and percent differences in aggregate environmental indicators[50]

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[50] Variable or scenario definitions are found in the Nomenclature section

6.3 **Conclusions**

This chapter has developed simulation-based evidence that RFS2 driven biofuel expansion can:

- Alter land use through higher resource demands
    - This is includes significant cropland expansion, and pasture contraction, increased forest to cropland transitions (though this is offset by pasture to forest transitions), and lead to significant CRP recultivation
- Shift production patterns
    - In particular, lower total livestock production is a possible consequence of higher feed costs and reduced pastureland. In addition, the RFS2 can alter crop mix and management strategies as land is used for dedicated energy feedstock production or agricultural residue harvesting,
- Boost management intensity
    - Results indicate that the RFS2 can stimulate the use of water resources, with significant regional variations in water use responses. In addition, the RFS2 could stimulate substantial increases in fertilizers and other agricultural input usage, eliciting regional water quality concerns through higher simulated levels of N and P pollution.
- Significantly boost net energy output directly related to the policy mandates.
- Marginally reduce GHG emissions from the U.S. AF sectors (however, this does not account for potential leakage affects of the RFS2 in international production regions).

- Alter commodity markets and trade flows
  - While results show significant commodity price response to the RFS2 mandates, note that these effects are smaller than previous studies have shown. This is a potential silver lining of extensive U.S. cropland expansion, be it on pasture or conservation lands; greater use of land resources domestically can reduce concerns of land use change in more sensitive ecosystems elsewhere (such as Brazilian rainforest or Argentine Pampas). This is a result that warrants further attention; even though FASOMGHG does not represent international production possibilities and land use, international trade results indicate that the RFS2 can alter export projections in the U.S. and internationally.
- Increase net lead to net welfare gains for U.S. crop producers, losses for livestock producers, but a net gain in U.S. agricultural welfare overall

CHAPTER VII

RESULTS FROM MITIGATION SCENARIOS

Here, results from the previous chapter are expanded to consider the combined effects of the RFS2 mandates and climate mitigation incentives. Whereas biofuel mandates can result in significant cropland expansion, GHG mitigation can have the opposite directional effect, transferring land out of conventional food and fiber production for dedicated bioenergy production and terrestrial sequestration.

7.1 Scenarios Employed

Several GHG mitigation scenarios are considered using alternative carbon dioxide equivalent (CO_2e) pricing schemes (using the 100 year global warming potential for methane and nitrous oxide). There are two main parts to these scenarios that are discussed separately:

- Assumed carbon price
- Payment eligibility assumptions

Each will be discussed separately. Biofuel production constrained to levels modeled in the previous chapter**.** Thus, a carbon price signal does not manifest itself in the volume of biofuels produced, only on the composition of the biofuel portfolio. The spatial distribution and feedstock portfolio will switch to one that provides the greatest life-cycle GHG gains given the magnitude of the CO_2e price. Combining biofuel mandates with GHG mitigation serves two purposes. First, as EISA-RFS has already been established and comprehensive climate policy could become a reality, this scenario can serve as an enhanced baseline that factor in all current policy drivers to discuss the resulting implications of a GHG mitigation policy for sectoral economic performance, land use decisions, and management intensity. Then, this case can be compared to the RFS scenario with no carbon price signals to determine the extent to which GHG offset incentives can alleviate environmental damages brought on by the RFS (including deforestation or pasture conversion rates, water use/quality, and net GHG emissions). In addition the mitigation scenarios below will also be run with and without CRP re-cultivation. Potential roles of the CRP in a low carbon economy include use of CRP soils for dedicated bioenergy production, direct government payments for CRP carbon sequestration benefits, and landowner participation in an offsets market.

7.1.1 Carbon Price Alternatives

FASOMGHG methodology assigns price on all eligible GHG flows within the sector (spanning carbon sequestration, bioenergy offsets, or changes in GHG emissions from altered management practices and land use but controlled by eligibility scenarios below). This does not explicitly evaluate a specific U.S. GHG cap-and-trade proposal. Instead, this chapter considers low to high GHG incentives for changing AF practices that might arise under different proposals. Real constant prices of \$15, \$30, and \$50/tCO_2e are evaluated. In all, these prices give this analysis a wide range of CO_2e prices in line spanning those projected by the EPA under the two most comprehensive climate bills (like HR 2454 Waxman Markey in 2009).

7.1.2 Alternative Offset Eligibility Scenarios

To reflect the reality that alternative forms of climate legislation will contain differences in offset provisions (including which activities will be eligible to receive payments), three alternative offset cases are considered: (1) Full offset eligibility, (2) Limited Offset Eligibility, and (3) No Offsets.

7.1.2.1 Full Offset Eligibility

In the full offset eligibility case all sources of emissions and sequestration in AF are priced, accounting for a full suite of offset AF offset activities and mitigation strategies. All activities are included once the policy is enacted, and no activities are discounted for potential transaction costs resulting from carbon market participation. Only emissions changes relative to a baseline are credited (and any increased flux is taxed), thus all simulated mitigation is additional by definition, and FASOMGHG implicitly discounts for permanence and leakage.

7.1.2.2 Limited Offset Eligibility

The second offset scenario considered models only a limited set of mitigation "offset" activities by introducing payment restrictions that vary by activity. Here, certain offsets that are considered difficult to implement in practice or which conflict with food security goals are not incentivized. Only those activities that are expected to be included in offset protocols initially are credited[51]. The greatest change here is limiting forest management offset eligibility with payment incentives excluded for carbon sequestration from existing forest management practices (including avoided deforestation). Also excluded are forest product carbon storage, pasture carbon sequestration, reduced emissions from rice cultivation, and improved enteric fermentation. In effect, this limits the offset portfolio to changing N application rates, tillage practices, afforestation, and lagoon treatment of hog and dairy operations. By not incentivizing these practices, net mitigation potential in AF is lowered, and the mitigation portfolio shifts to other activities (including bioenergy).

7.1.2.3 No Offsets—Bioenergy Only

In the no offsets case, CO_2 payments only accrue to energy use, and bioenergy emissions reductions. This simulates a case in which a carbon pricing policy is in effect directed toward fossil fuels only, with no offset provision. Here, AF sectors can respond to a carbon price signal through changing production practices and crop mixes as a result of higher energy costs, or by producing biomass and harvesting residuals that can be used for co-fired electricity generation. Here, additional bioenergy production would represent a direct mitigation response, though indirect mitigation (or emissions) is possible through shifting land use and production patterns.

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[51] This is consistent with S 2191 legislation, which included provisions of certain offsets, but makes no mention of other potential activities.

7.2 **Results**

Here I analyze the implications that carbon pricing has on land use, land use change, GHG mitigation potential, provision of renewable energy, management intensification, commodity markets, economic welfare, and other important items.

7.2.1 GHG Mitigation

Net GHG emission mitigation was calculated by taking the annuity of emissions flux throughout the simulation horizon (by source) across all mitigation scenarios, then calculating the difference from baseline-annualized emissions (discussed in the previous chapters).

7.2.1.1 Mitigation Potential under Full Offset Eligibility

Figure 32 shows net mitigation potential under the all offsets are eligible scenarios under 3 different carbon prices. Notice that a relatively small carbon price incentive (\$15/tCO_2e) can influence AF practices such that the sectors become a net GHG sink. The following observations can be drawn from these results:

- Mitigation potential ranges 678-1144 million tCO_2e per year. Put into context, this ranges approximately 11-20% of total U.S. emissions per year from all sources (EPA 2009 GHG Inventory), The greatest mitigation potential comes from altered forest management practices, afforestation, and bioenergy, with agricultural activities providing a modest share of the portfolio.
    - In fact, some emissions sources increase across the mitigation scenarios, pasture soil carbon (reduced sequestration), and N2O emissions from

crop management (a by-product of increased management intensity stimulated by the RFS2, as outlined in the previous chapter).

- Mitigation from altered forest management practices ranges 155-292 million tCO_2e per year, driven primarily by lengthened rotations and avoided deforestation.
- Afforestation of dedicated cropland or pasture is an economically competitive abatement strategy even at $15/$tCO_2e$, and provides a significant offset source at higher price (ranging 158-354 million tCO_2e).
- Emissions offsets from biofuels do not change significantly across scenarios.
- Agricultural methane and emissions decrease significantly (33-55 million tCO2e per year) across the mitigation scenarios due to shifting livestock production patterns, improved enteric fermentation, and manure management practices that offset methane emissions.
- Other mitigation strategies that play a less predominant role in the overall AF mitigation portfolio include reduced N2O emissions (which increase at $15 and $30/$CO_2e$, but decrease marginally at $50/$tCO_2e$).
- Agricultural soil carbon sequestration changes from baseline actually represent a net source of emissions when compared to the baseline, but this is strictly a by-product of land shifting out of pasture use. The aggregate soil carbon account includes crop and pasture soil carbon stocks. As pastureland is afforested or converts to crop production, pasture carbon is reduced relative to the baseline. Thus, carbon is essentially shifted from one account to another. Since

afforestation increases soil carbon sequestration relative to grazing lands, this represents a net gain in total terrestrial carbon, but a small decrease in agricultural soil C (as the loss in pasture C outweighs the soil C gained form adoption of conservation or no-till practices).

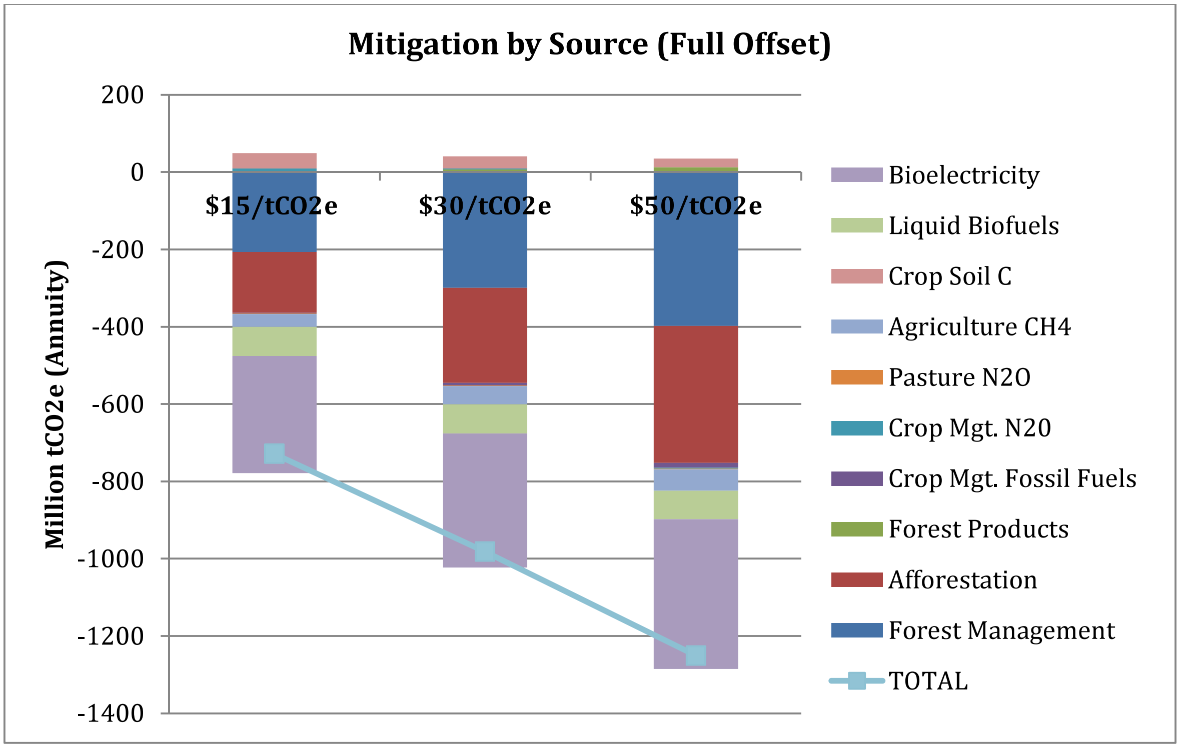

Figure 32: Net GHG mitigation (annualized emissions flux from base) for the full offset eligibility scenarios[52]

Allowing land use shifts from conservation (CRP) priorities to cropland can increase net AF mitigation potential, but only marginally so (Table 21). Some studies have maintained that the CRP can contribute to GHG mitigation goals if kept intact

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[52] Variable or scenario definitions are found in the Nomenclature section

(Baker and Galik, 2009 and Pineiro et al. 2009). Results here show that continued participation in the CRP could be significantly reduced under a low carbon policy regime, even when further subsidized by the value of maintaining *in situ* carbon stocks. Here, allowing a portion of CRP to re-enter production can contribute to GHG mitigation goals at rates that outweigh the soil carbon losses from re-cultivation. Results suggest allowing CRP re-cultivation increases net mitigation potential by 9-23 million tCO2e per year. A larger productive land use base allows for additional mitigation options through bioenergy feedstock cultivation, and it enhances conventional commodity production in some regions, freeing up productive land for carbon sequestration elsewhere. Total CRP reversion above baseline levels ranges 10.1-16.3 million acres (cumulative), so the per-acre carbon benefits to CRP recultivation under a full offset scenario range 0.9-1.8 tCO2e per acre per year (above the soil carbon loss as recultivated). The U.S. average C sequestration for lands set aside for the CRP is approximately 0.85 tCO_2e per acre per year[53], suggesting that alternative uses of this land might contribute more greatly to the AF system's mitigation potential.

Table 21: Difference in Mitigation Potential with CRP Reversion Relative to Mitigation without CRP Reversion

	\$15/tCO2e with CRP	**\$30/tCO2e with CRP**	**\$50/tCO2e with CRP**
Total Mitigation Difference (million tCO2e)	9	23	21
% Difference in Mitigation Potential	*1.3%*	*2.5%*	*1.8%*

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[53] For a summary of C sequestration potential from the CRP, see Piñeiro et al., 2009.

7.2.1.1.1 Mitigation Potential for the Limited Offset Eligibility Case

Now, consider mitigation for the limited offset scenarios. When we eliminate offset payments for forest management, enteric fermentation, and N_2O emissions, this incentivizes alternative abatement strategies and land use patterns in the AF sector. Mitigation potential changes in the following manner:

- Total mitigation potential now ranges 506-920 million tCO_2e per year, which is 20%-26% less abatement than under the full offset scenarios (Figure 33), with afforestation and bioenergy as the dominant abatement options
- Afforestation offset potential ranges 178-414 million tCO_2e per year, which is 13-17% higher than afforestation mitigation under the full offset case.
- Mitigation from bioenergy ranges 313-401 million tCO_2e per year, and increases only marginally (1-2%) from the full offset case
- Notice that GHG accounts associated with forest management practices now create a net source at lower GHG prices ($15-$30) as there are not avoided deforestation incentives to keep forestland from converting to agriculture,
- Methane emissions reductions do not register in this new mitigation portfolio
- Agricultural soil carbon and N_2O produce a net source of emissions relative to baseline levels, driven by land use shifts and the RFS2 mandates.

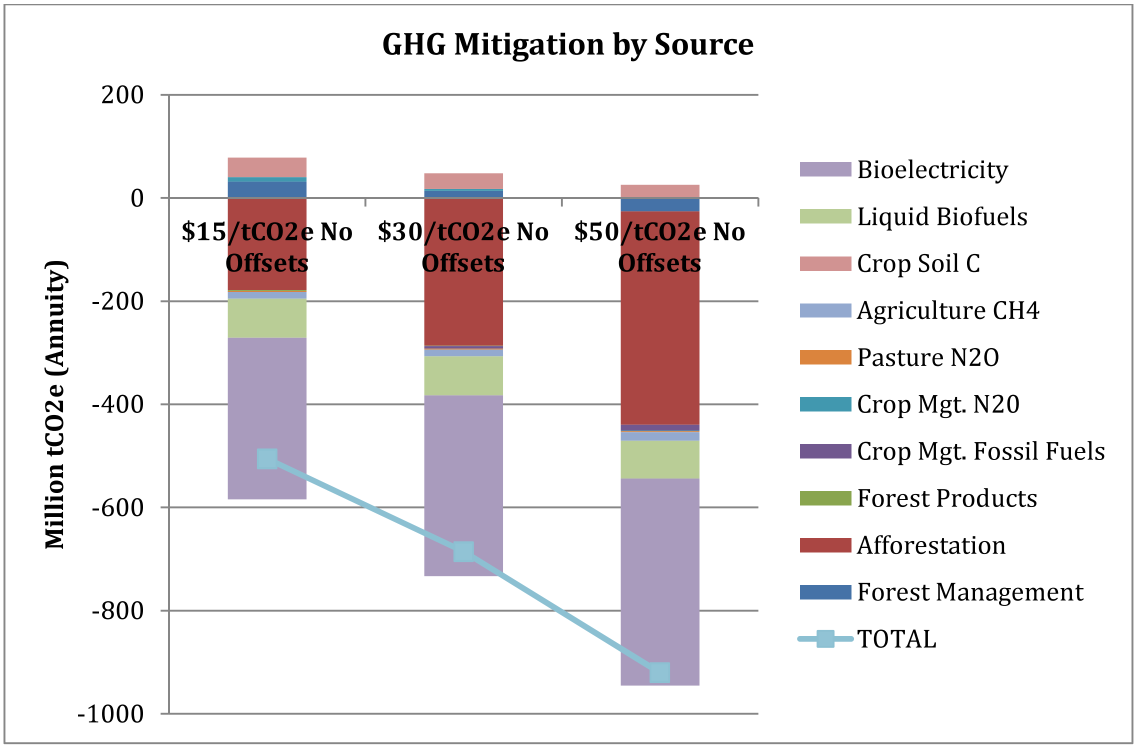

Figure 33: Net emissions and mitigation (annualized emissions flux from base) for the limited offset eligibility scenarios[54]

7.2.1.1.2 Mitigation Potential for the No Offset Case

For the no offset scenarios, some sources of abatement respond directly to the carbon price incentive that affects input costs and stimulates bioenergy production (Figure 34). Other sources of abatement occur indirectly as management practices respond to the new set of economic stimuli (including higher costs of production)

- Full abatement potential ranges 424-730 million tCO_2e per year, a 37-43% reduction from full offset abatement levels,

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[54] Variable or scenario definitions are found in the Nomenclature section

- Abatement potential from bioelectricity ranges 346-560 million tCO_2e per year, which is substantially more than under a GHG policy where bioenergy must compete with AF offset practices such as afforestation.
- Notice that afforestation and forest management contribute to the estimated mitigation potential under this scenario for the $30 and $50 scenarios. While not subsidized directly through a carbon payment mechanism, the demand for bioenergy from AF feedstocks boosts land transitions from agriculture to forestry, and indirectly contributes to the overall mitigation portfolio

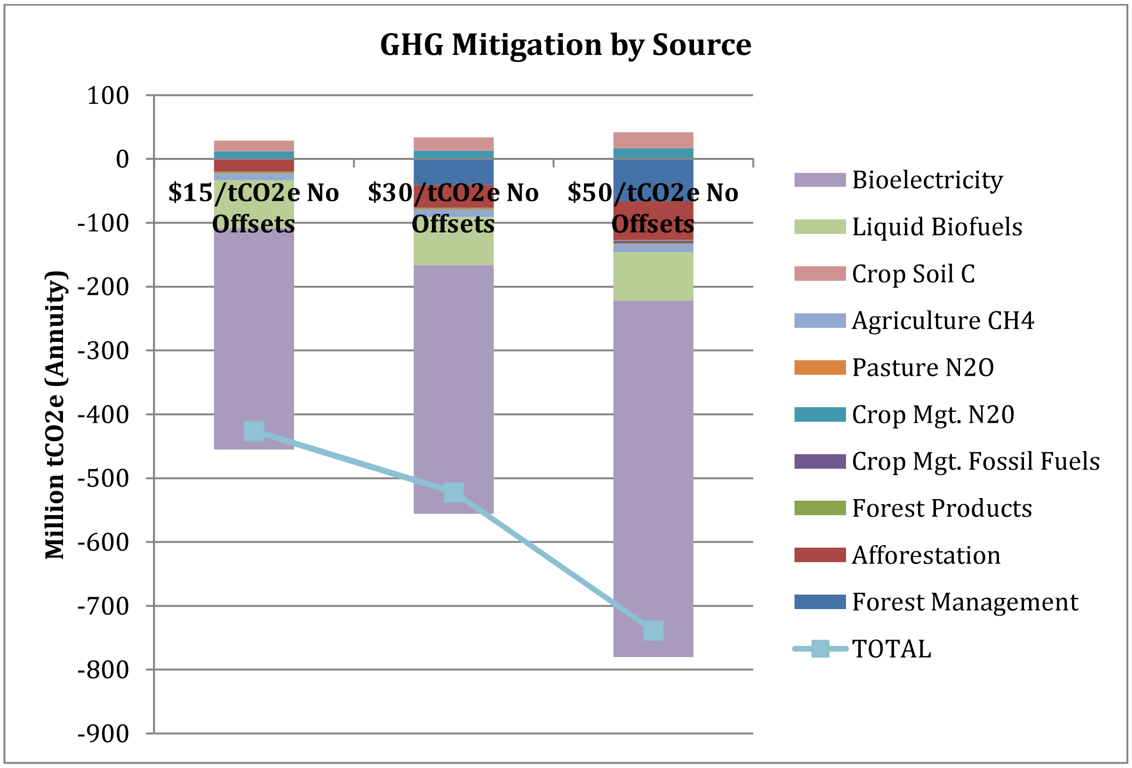

Figure 34: Net emissions and mitigation (annualized emissions flux from base) for the no offset eligibility scenarios[55]

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[55] Variable or scenario definitions are found in the Nomenclature section

7.2.1.1.3 Importance of Offset Eligibility Restrictions

To reiterate, restricting offset payments for a number of AF activities can significantly reduce the AF's role as a low-cost abatement source (Figure 35). A comprehensive abatement approach that considers a full suite of direct emissions reductions, offsets, and bioenergy will produce the greatest mitigation gains. Annualized mitigation potential at $30/tCO$_2$e under full offset eligibility is 24.3% higher than for limited offsets case, and 43% higher when only bioenergy is incentivized. However, GHG abatement is not the sole variable of interest, and as the rest of this chapter illustrates, pursuit of full mitigation potential could bring legitimate concerns regarding international leakage, commodity prices, and the regional distribution of agricultural input use.

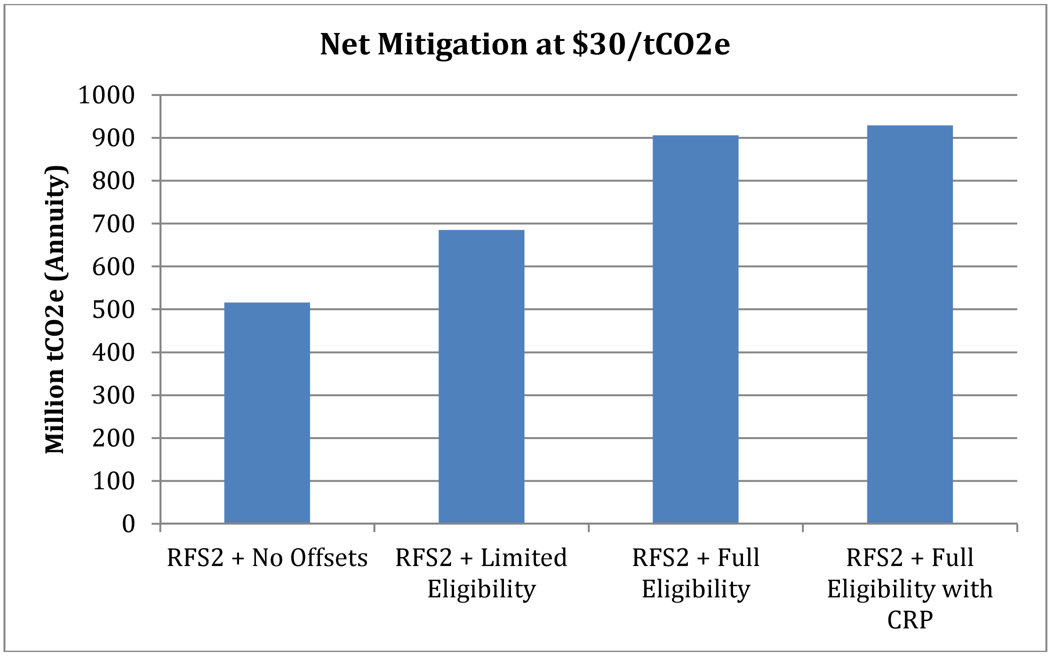

Figure 35: Net mitigation potential by scenarios at $30/tCO2e

7.2.2 Commodity Price and Welfare Projections

Climate mitigation incentives in addition to biofuel mandates alter the demand for land resources, placing further upward mobility on commodity prices. Results below show that land shifts stimulated by combined RFS2 and mitigation incentives can lead to price impacts that that are much larger than those stimulated by the RFS2 alone. Also, commodity price fluctuations stimulated by low-carbon policies depend not only on the magnitude of the carbon price considered, but the scope of the mitigation policy enacted.

7.2.2.1 Commodity Prices across Mitigation Scenarios

First, consider how commodity prices might vary with the magnitude of the carbon price imposed on the system. Figure 36 displays price indices for important grain and livestock commodities to illustrate the impact of GHG mitigation incentives on commodity markets over time. Grain and soybean prices rise sharply once the policy is implemented (2010), and this continues into later years of the simulation period. Prices are consistently higher for greater carbon prices, an artifact of increased incentives to alter production and management activities for GHG abatement and higher production costs as the GHG content of fossil fuel use and other agricultural inputs are explicitly priced. In all, short term (2010-2015) commodity price movements range 5-25% across the CO2 prices, stabilize in the medium term (2020-2030), then start to rise again beyond 2030. It is important to note that a portion of these price fluctuations occur as a direct result of the RFS2 mandates, and not in response to the mitigation efforts. It is the combined effect that of the RFS2 and mitigation that leads to excessively high price impacts. CRP recultivation serves as a buffer against significant commodity price movements, especially at higher CO_2 prices. So in addition to improving GHG mitigation potential, reverting CRP acreage adds to total AF production and relaxes commodity price concerns of managing land for carbon.

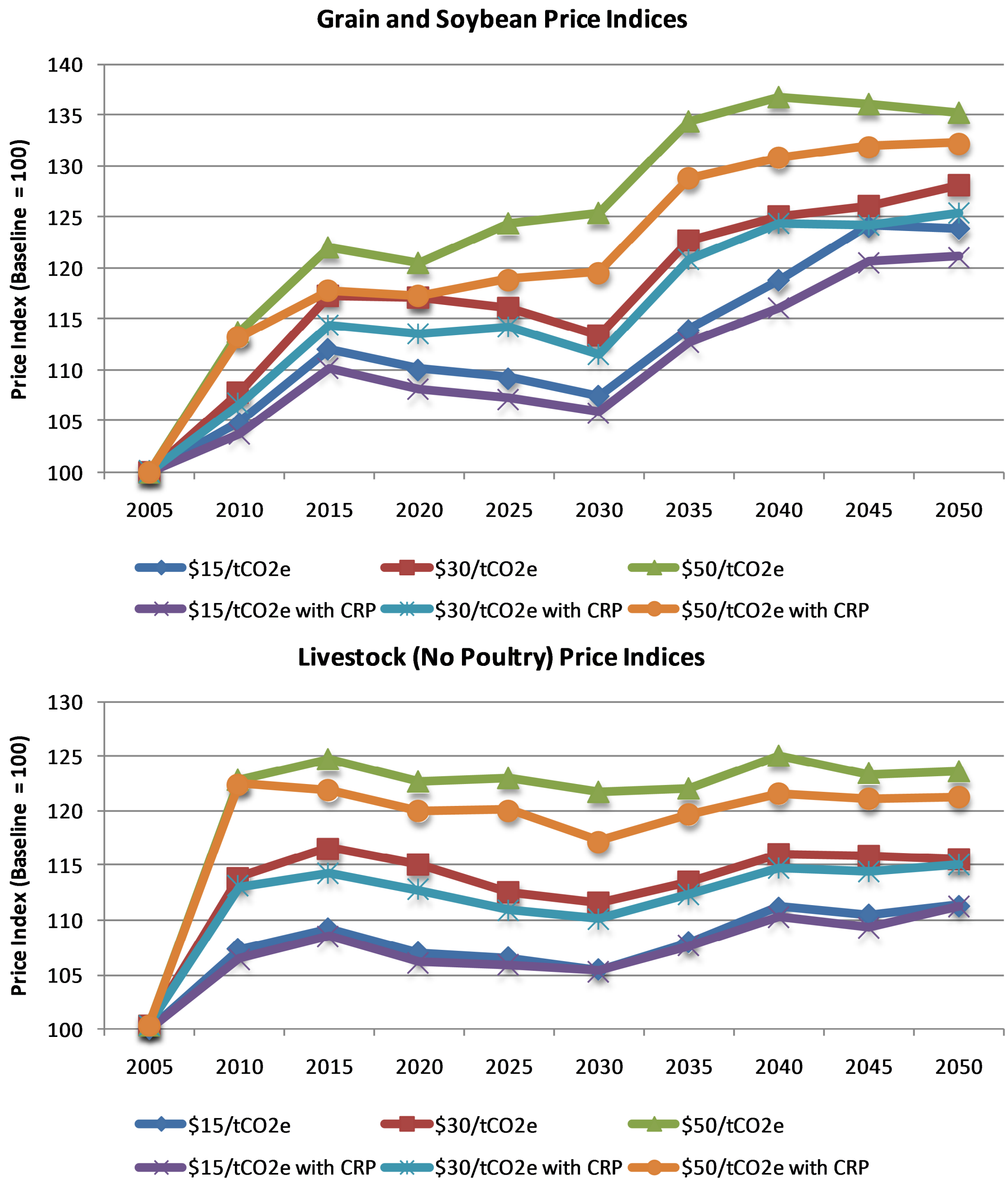

Figure 36: Commodity price index values across full offset mitigation scenarios[56]

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[56] Variable or scenario definitions are found in the Nomenclature section

Tables 22-25 display important commodity price trajectories over time in absolute terms and in percentage change from base. The following important observations can be made:

- Full Offset Eligibility
    - All prices displayed see significant increases, especially in the long term.
    - Corn and soybean prices vary the greatest amount, due to decreased crop acreage
    - Fed beef prices rise due to reduced herd size and higher costs of feed, non-fed beef prices rise as land moves out of pasture
    - Rice and chicken see little movement throughout the horizon
    - Wheat fluctuates greatly initially, but this effect tapers off
- Restricted Offset Eligibility
    - Under the limited offset case, commodity price trajectories show similar movement as in the full offset case.
    - For the no offset case, however, most commodity prices fall relative to the Baseline and RFS2 scenario presented in the previous chapters. Without incentives for carbon sequestration and livestock herd reductions, agricultural acreage expands significantly (contributing to reduced prices). This is consistent with other recent papers and reports that find little change in commodity prices (with slight downward pressure) when significant emphasis is put on bioelectricity from AF residues (de la Torre Ugarte et al. 2010).

Table 22: Commodity Prices and Deviations from Base at $30/tCO2e (Full Offset Eligibility)

	2010	**2020**	**2030**	**2040**	**2050**
Wheat ($/Bushel)	**6.61**	**6.63**	**6.08**	**5.85**	**5.01**
	2.97%	*9.02%*	*8.25%*	*10.00%*	*-0.65%*
Corn ($/Bushel)	**3.94**	**3.85**	**3.32**	**3.12**	**3.01**
	11.00%	*14.26%*	*9.47%*	*18.34%*	*34.99%*
Cotton ($/lb)	**262.15**	**305.33**	**308.68**	**367.49**	**410.57**
	2.10%	*15.46%*	*11.92%*	*30.81%*	*42.11%*
Soybeans ($/Bushel)	**9.96**	**11.03**	**10.73**	**14.11**	**15.30**
	7.36%	*22.58%*	*17.49%*	*56.25%*	*65.84%*
Sorghum ($/Bushel)	**6.53**	**6.88**	**6.70**	**6.55**	**5.94**
	14.09%	*24.43%*	*23.39%*	*21.48%*	*13.61%*
Rice	**10.23**	**10.28**	**10.17**	**10.00**	**9.97**
	1.51%	*4.48%*	*4.11%*	*3.71%*	*3.04%*
Fed Beef ($/100 lb)	**106.26**	**109.16**	**113.08**	**110.02**	**105.13**
	1.07%	*5.48%*	*12.34%*	*14.12%*	*12.60%*
Non-fed Beef ($/100 lb)	**73.56**	**76.75**	**82.91**	**80.72**	**79.89**
	11.33%	*12.71%*	*22.99%*	*23.26%*	*20.85%*
Hogs ($/100 lb)	**60.99**	**61.08**	**57.84**	**57.09**	**56.73**
	9.06%	*11.69%*	*6.42%*	*7.12%*	*10.29%*
Chicken ($/100 lb)	**58.69**	**59.29**	**57.62**	**56.25**	**56.25**
	2.77%	*5.07%*	*3.77%*	*2.97%*	*4.36%*

Table 23: Commodity Prices and Deviations from Base at $30/tCO2e (Full Offset Eligibility with CRP)

	2010	2020	2030	2040	2050
Wheat ($/Bushel)	**6.60**	**6.30**	**5.79**	**5.64**	**4.72**
	2.76%	*3.54%*	*3.12%*	*6.09%*	*-6.43%*
Corn ($/Bushel)	**3.87**	**3.75**	**3.31**	**3.13**	**2.99**
	9.02%	*11.32%*	*9.34%*	*18.98%*	*33.96%*
Cotton ($/bale)	**260.84**	**303.56**	**305.96**	**369.17**	**410.57**
	1.59%	*14.79%*	*10.94%*	*31.41%*	*42.11%*
Soybeans ($/Bushel)	**9.85**	**10.68**	**10.64**	**14.09**	**15.30**
	6.25%	*18.67%*	*16.54%*	*56.05%*	*65.79%*
Sorghum ($/Bushel)	**6.45**	**6.83**	**6.60**	**6.45**	**5.88**
	12.57%	*23.49%*	*21.65%*	*19.63%*	*12.48%*
Rice	**10.23**	**10.27**	**10.18**	**10.00**	**9.97**
	1.51%	*4.31%*	*4.22%*	*3.71%*	*3.04%*
Fed Beef ($/100 lb)	**106.26**	**108.44**	**111.16**	**108.52**	**104.15**
	1.07%	*4.79%*	*10.44%*	*12.57%*	*11.55%*
Non-fed Beef ($/100 lb)	**73.92**	**77.24**	**82.01**	**80.40**	**79.89**
	11.87%	*13.43%*	*21.65%*	*22.77%*	*20.85%*
Hogs ($/100 lb)	**60.55**	**60.19**	**57.49**	**56.88**	**56.67**
	8.27%	*10.06%*	*5.78%*	*6.72%*	*10.17%*
Chicken ($/100 lb)	**58.58**	**58.87**	**57.58**	**56.25**	**55.98**
	2.58%	*4.32%*	*3.69%*	*2.97%*	*3.85%*

Table 24: Commodity Prices and Deviations from Base at $30/tCO2e (Limited Offset Eligibility)

	2010	2020	2030	2040	2050
Wheat ($/Bushel)	**6.53**	**6.46**	**5.96**	**5.85**	**5.07**
	1.67%	*6.21%*	*6.21%*	*10.11%*	*0.64%*
Cotton ($/bale)	**257.60**	**288.89**	**301.28**	**369.79**	**410.52**
	0.33%	*9.25%*	*9.24%*	*31.62%*	*42.14%*
Corn ($/Bushel)	**3.74**	**3.68**	**3.24**	**3.10**	**3.01**
	5.50%	*9.30%*	*6.96%*	*17.50%*	*34.87%*
Soybeans ($/Bushel)	**9.64**	**10.38**	**10.49**	**14.31**	**15.39**
	3.95%	*15.26%*	*14.81%*	*58.48%*	*67.02%*
Sorghum ($/Bushel)	**6.27**	**6.71**	**6.58**	**6.53**	**5.98**
	9.48%	*21.41%*	*21.22%*	*21.02%*	*14.47%*
Rice	**10.17**	**10.21**	**10.15**	**10.00**	**9.97**
	0.91%	*3.76%*	*3.89%*	*3.71%*	*3.12%*
Fed Beef ($/100 lb)	**105.27**	**108.44**	**104.91**	**103.69**	**98.13**
	0.14%	*4.78%*	*4.23%*	*7.55%*	*5.08%*
Non-fed Beef ($/100 lb)	**66.11**	**71.01**	**70.61**	**72.52**	**72.54**
	0.05%	*4.28%*	*4.76%*	*10.74%*	*9.72%*
Hogs ($/100 lb)	**59.46**	**59.28**	**57.18**	**57.43**	**57.22**
	6.32%	*8.38%*	*5.21%*	*7.73%*	*11.28%*
Chicken ($/100 lb)	**58.10**	**58.60**	**57.33**	**56.29**	**56.04**
	1.73%	*3.84%*	*3.25%*	*3.03%*	*4.00%*

Table 25: Commodity Prices and Deviations from Base at $30/tCO2e (No Offset Eligibility)

	2010	2020	2030	2040	2050
Wheat ($/Bushel)	**6.54**	**6.14**	**5.68**	**5.13**	**4.33**
	0.13%	*-5.00%*	*-4.66%*	*-12.37%*	*-14.57%*
Cotton ($/bale)	**261.86**	**271.98**	**280.65**	**365.89**	**422.07**
	1.65%	*-5.85%*	*-6.84%*	*-1.06%*	*2.81%*
Corn ($/Bushel)	**3.72**	**3.55**	**3.13**	**2.79**	**2.75**
	-0.69%	*-3.62%*	*-3.45%*	*-9.88%*	*-8.42%*
Soybeans ($/Bushel)	**9.85**	**9.81**	**9.47**	**13.20**	**15.28**
	2.18%	*-5.41%*	*-9.69%*	*-7.79%*	*-0.75%*
Sorghum ($/Bushel)	**6.35**	**6.53**	**6.36**	**6.35**	**5.66**
	1.32%	*-2.68%*	*-3.30%*	*-2.68%*	*-5.38%*
Rice	**10.20**	**10.13**	**9.98**	**9.92**	**9.92**
	0.25%	*-0.78%*	*-1.72%*	*-0.77%*	*-0.54%*
Fed Beef ($/100 lb)	**106.26**	**105.76**	**101.20**	**96.01**	**92.96**
	0.94%	*-2.48%*	*-3.54%*	*-7.41%*	*-5.27%*
Non-fed Beef ($/100 lb)	**66.51**	**70.14**	**68.42**	**67.55**	**70.41**
	0.60%	*-1.22%*	*-3.11%*	*-6.86%*	*-2.93%*
Hogs ($/100 lb)	**57.17**	**56.33**	**54.91**	**53.62**	**53.98**
	-3.85%	*-4.97%*	*-3.97%*	*-6.64%*	*-5.66%*
Chicken ($/100 lb)	**57.79**	**57.31**	**55.89**	**53.87**	**54.01**
	-0.53%	*-2.19%*	*-2.52%*	*-4.29%*	*-3.63%*

7.2.2.2 Producer Welfare Effects of Combined Biofuel and GHG Policies

The previous chapter showed that higher commodity prices, in addition to increased revenue for processed biofuels can boost agricultural producers’ net income (as measured by producer surplus. Here, RFS2 mandates contribute to producer welfare, as do GHG offset payments, revenue from bioelectricity feedstock sales, higher input costs, and indirect commodity market revenue stimulated by production decisions

Figures 37-39 display regional changes in crop and livestock producer welfare, across the mitigation prices modeled. This provides a measure of net U.S. economic welfare flowing to the agricultural sector across the suite of low-carbon policies simulated. Again, welfare measures are reported as annualized deviations from baseline levels.

Under the full offset mitigation scenarios, crop producers' surplus increases for all FASOMGHG agro-forestry regions, at all prices. Livestock producers are hurt by higher commodity prices in a few select regions under the $15 case (Corn Belt, Great Plains, and Northeast), but benefit under both of the higher price scenarios in all regions. The regional distribution of potential welfare gains is an important consideration for mitigation policy development, as this indicates where the greatest offset potential resides spatially, and how contemporary agricultural land rents in a particular region might compare in the long term with high carbon offset incentives. Regions with the greatest afforestation potential see significant welfare gains (Corn Belt, Lake States South Central, and Southeast), but even regions without forestry options see significant producer welfare gains through the production of bioenergy feedstock production or indirect commodity market revenue.

Total welfare gains (the sum of offset payments, bioenergy revenue, processed biofuel revenue, and indirect commodity market revenue across all regions), as shown in

Figure 40, are substantial across the full offsets scenario (ranging $37-$90 billion per year). In general, crop producers receive the majority of these surplus flows (92%-96%). Livestock producers balance the benefits of offset payments and higher output prices with increased feed and operating costs. The limited offsets scenario produces even higher producer gains ($37-$104 billion annualized) when the carbon value of land use transitions is not explicitly priced. Under no offsets, producer gains are limited to bioenergy processing revenue and indirect commodity market impacts, and range $29-$56 billion). Additionally, producers are faced with higher input prices, but no incentives for emissions reduction.

Higher commodity prices will ultimately be realized by households, and are an important factor in total economic welfare accounting of national climate legislation. Annualized consumer welfare losses range $11.6-$28 billion under full offset eligibility, $9-$23 billion under limited offset eligibility, and $6-$11 billon under no offsets. However, these losses are more than outweighed by producer gains, signaling net economic gains to U.S. AF under a variety of low carbon policy futures.

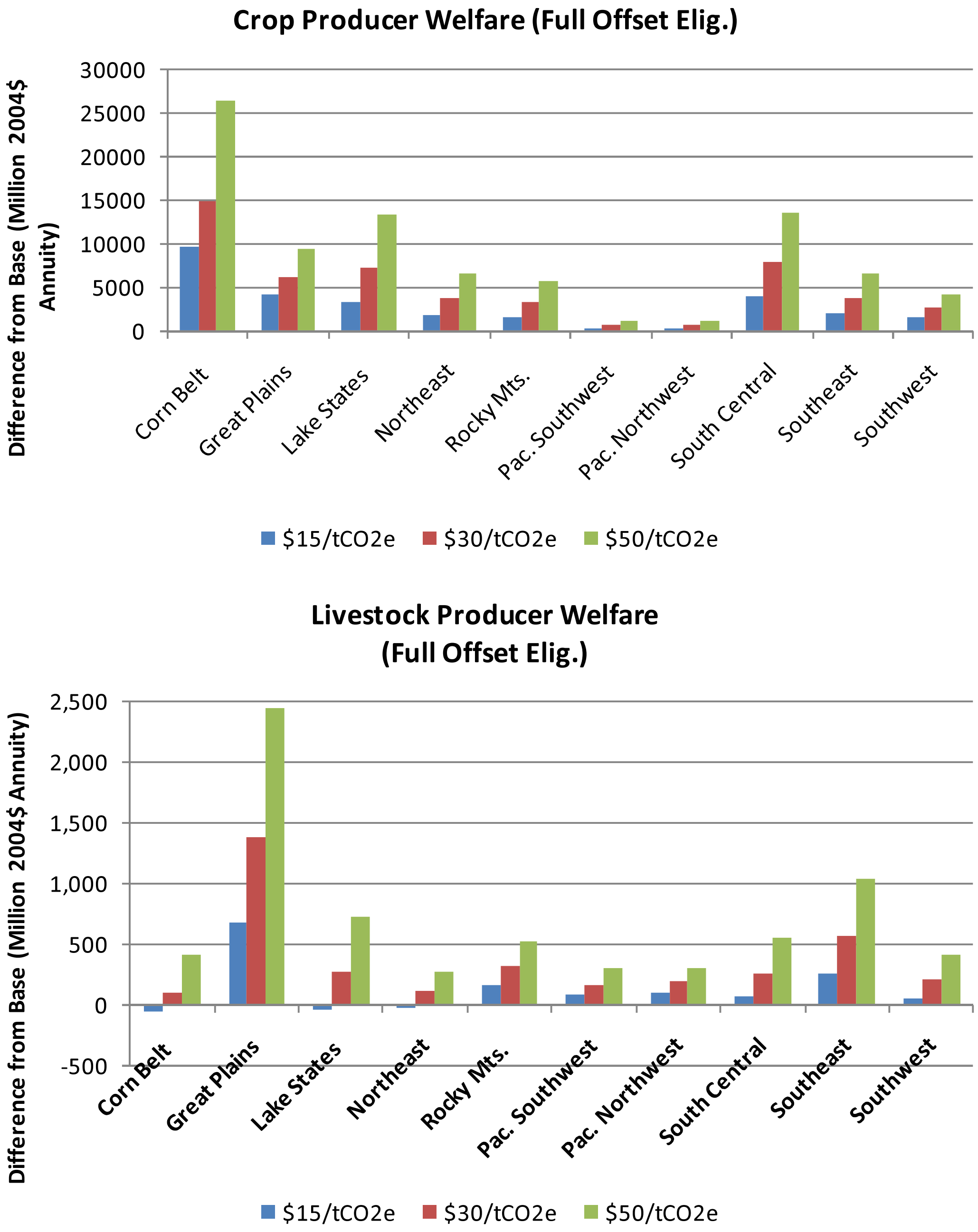

Figure 37: Annualized change in producer welfare under the full offset eligibility[57]

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[57] Variable or scenario definitions are found in the Nomenclature section

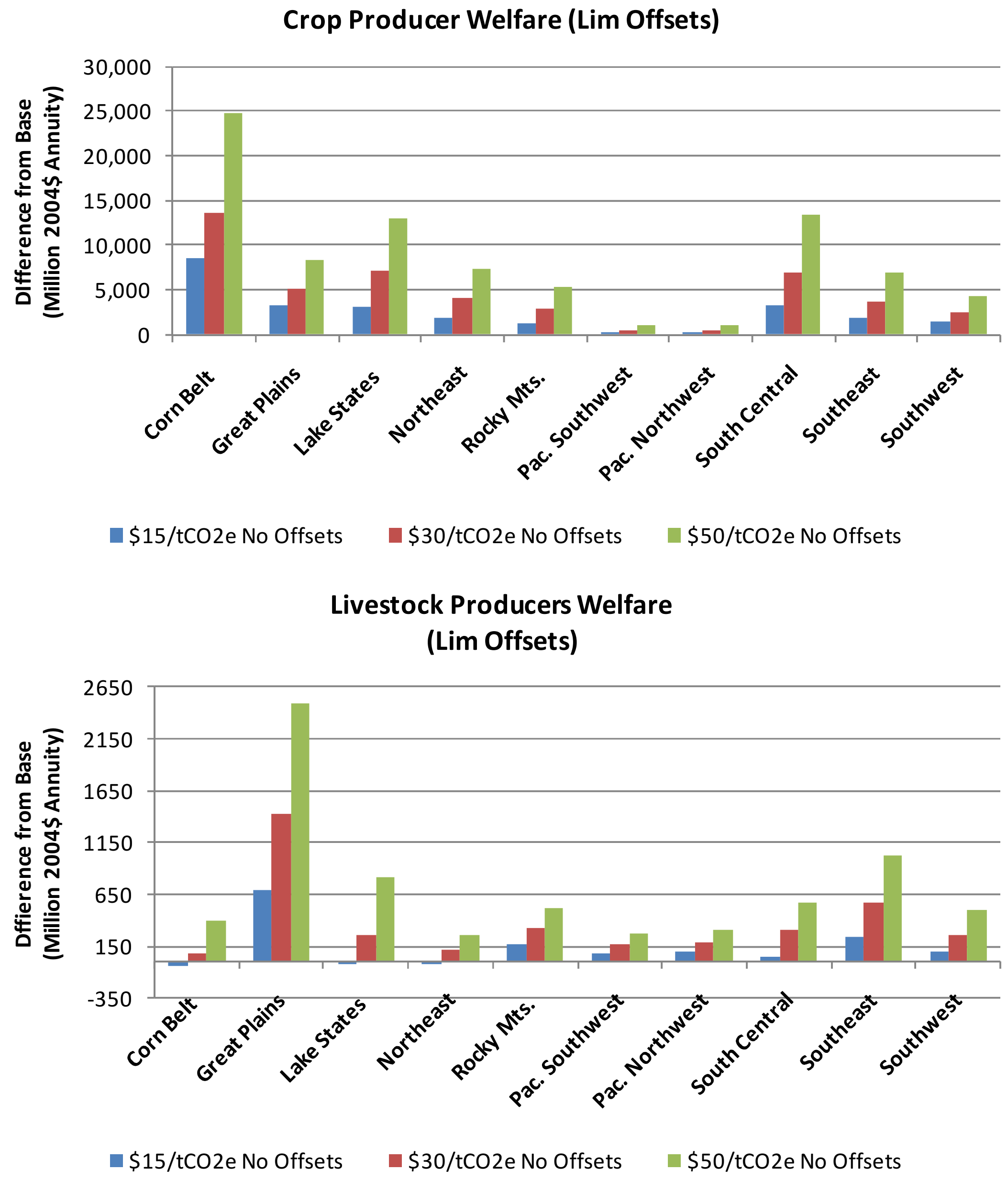

Figure 38: Annualized change in producer welfare under limited offset eligibility[58]

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[58] Variable or scenario definitions are found in the Nomenclature section

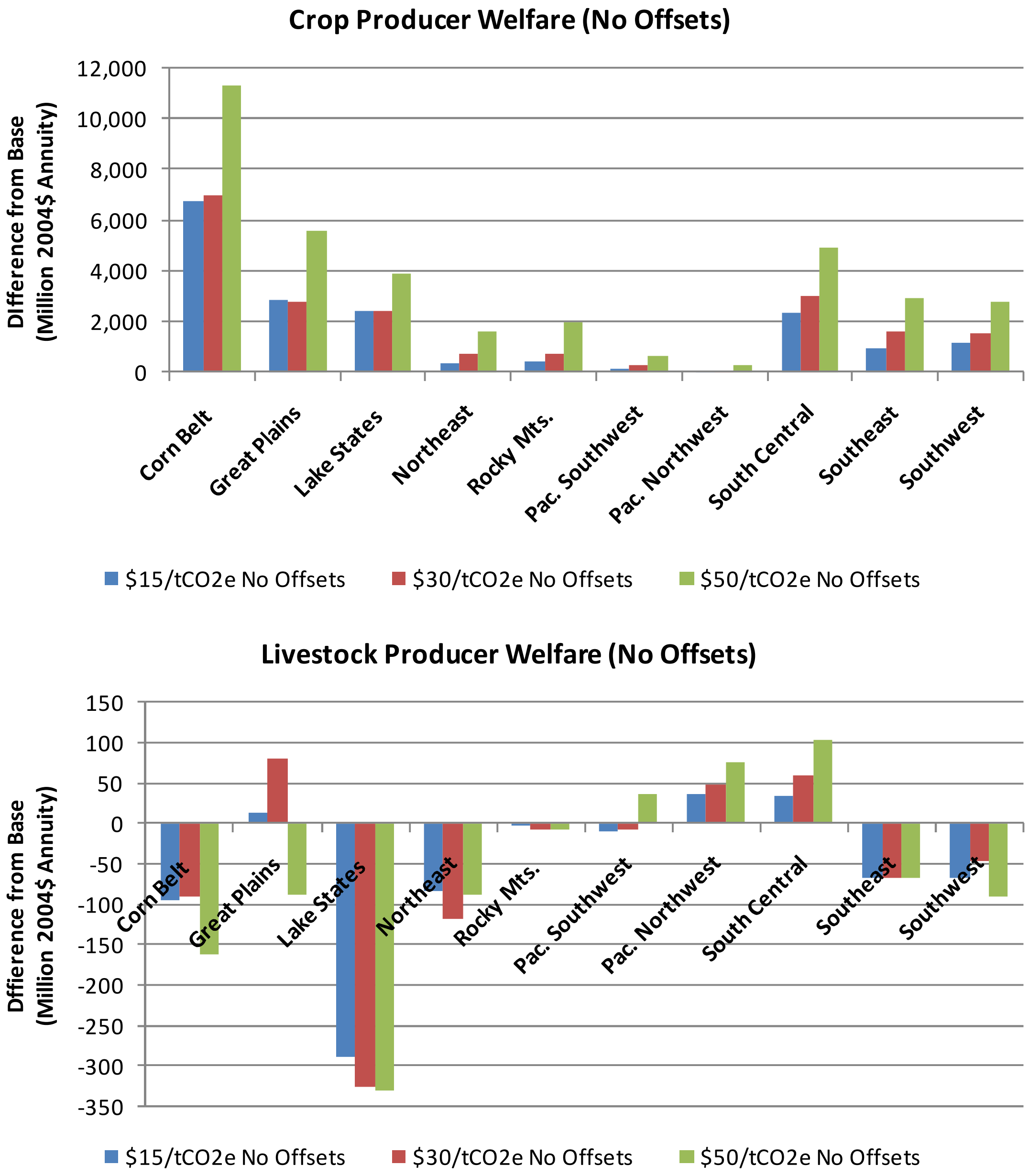

Figure 39: Annualized change in producer welfare under no offset eligibility[59]

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[59] Variable or scenario definitions are found in the Nomenclature section

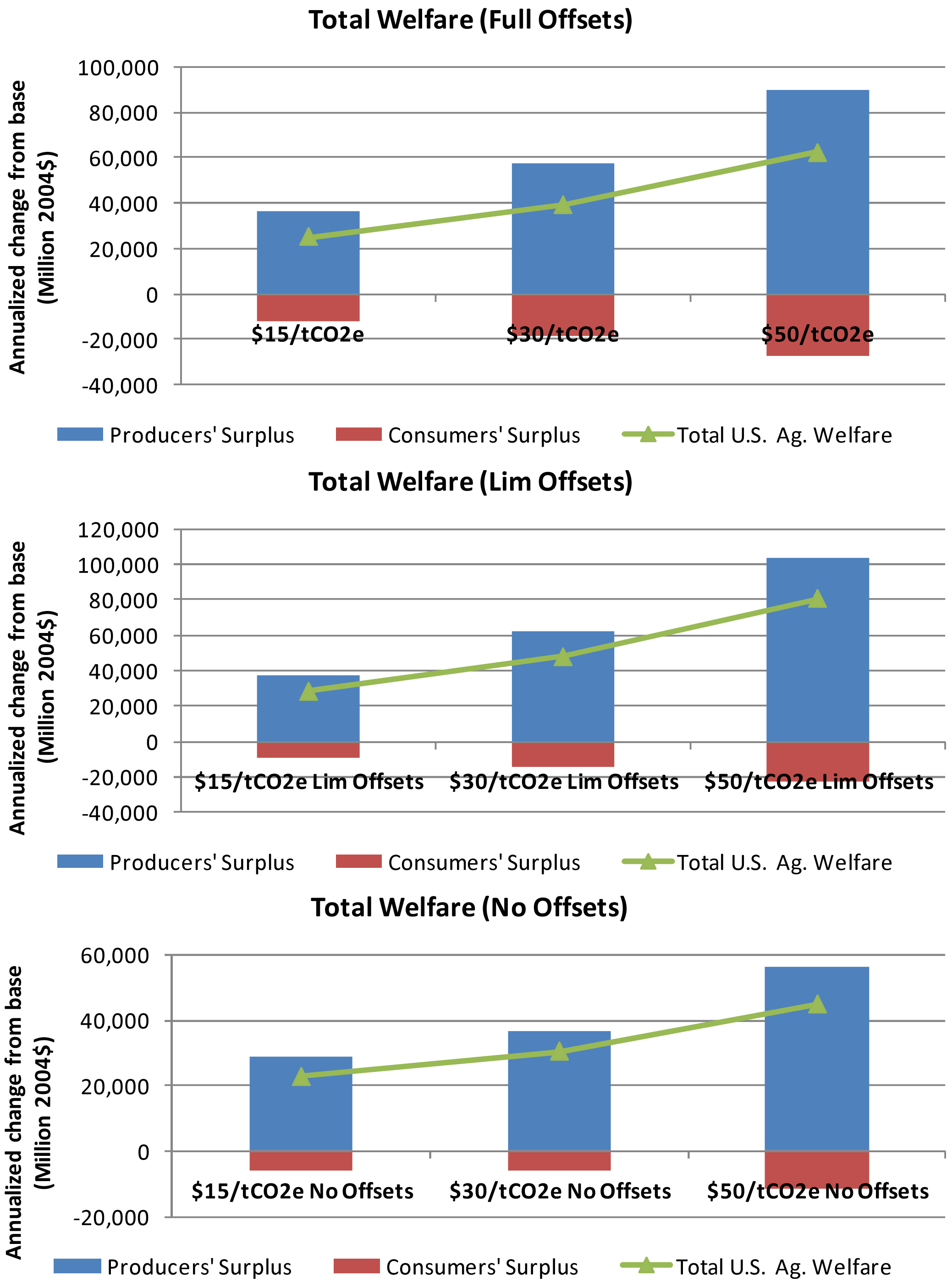

Figure 40: Total change in U.S. agricultural welfare across all mitigation scenarios[60]

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[60] Variable or scenario definitions are found in the Nomenclature section

7.2.2.3 Disaggregating Welfare Flows by Source and Policy

To illustrate the breakdown of welfare flows between direct and indirect sources and by policy, consider Figure 41. Here, I have taken information from simulation output presented in the bioenergy expansion and climate mitigation chapters, respectively. This figure illustrates how welfare changes can be disaggregated by policy, and into direct and indirect sources. The direct policy contribution from the RFS2 is broken down into biofuel processing revenue (the value of processed biofuels), indirect revenue from higher commodity prices, and consumer losses under new market conditions.

Welfare flows are then disaggregated further for climate policy scenarios to distinguish between agricultural GHG mitigation payments, bioelectricity revenue, indirect revenue from commodity market shifts, and consumer losses from climate mitigation. The results show that there is significant revenue potential from the sale of offsets and bioenergy feedstocks. This figure also indicates that pursuit of mitigation through offsets that take land out of production can reduce AF consumer welfare more acutely than bioenergy expansion policies as prices rise sharply. Biofuel mandates, terrestrial GHG mitigation incentives, and use of AF biomass for electricity generation can provide a substantial flow of economic benefits to landowners and producers.

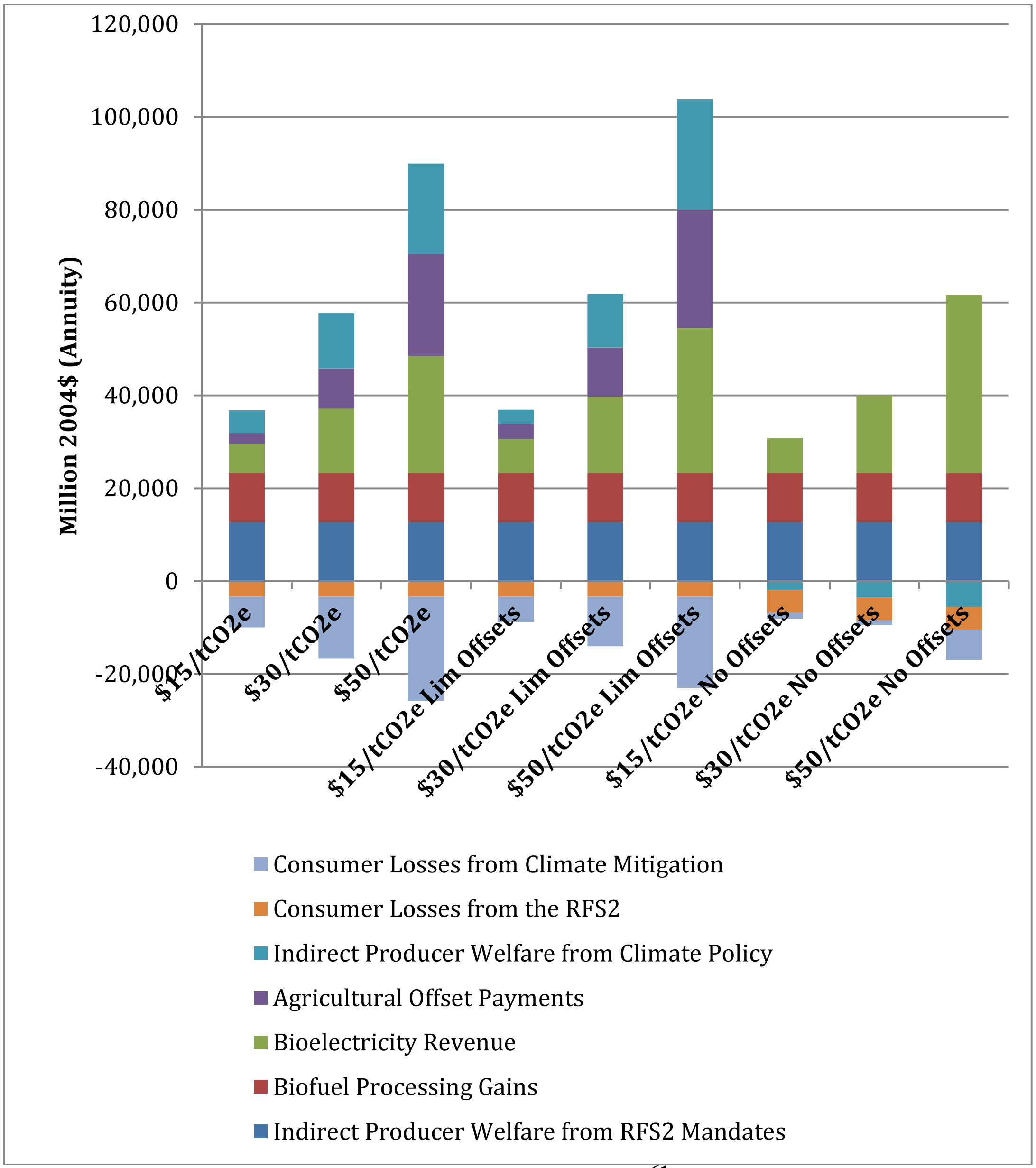

Figure 41: Policy contributions to welfare changes[61]

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[61] Variable or scenario definitions are found in the Nomenclature section

7.2.3 Land Use/Land Use Change

Note, however, that while simulation results show substantial mitigation potential and welfare gains for the US-AF across climate mitigation scenarios, such results are not achievable without significantly altering the way land resources are managed.

7.2.3.1 Full Offset Scenario

- Cropland initially expands, and then contracts significantly. Expansion is caused by the RFS2 mandates and bioelectricity feedstock production at lower CO2e prices. Cropland contraction, prevalent at the $30 and $50/tCO2e cases, is caused by reduced cropland deforestation, and afforestation shifts for carbon sequestration credits.
- Forest use expands substantially (24-48 million acres, annualized) as forests are managed for carbon and agricultural land is afforested (Figure 42).
- Allowing CRP recultivation increases the cropland stock by 3.6-7.4 million acres relative to the mitigation scenarios with no reversion (annualized).
- CRP reversion increases total forestland as well (1-3.5 million acres, annualized). Here, the model is bringing additional cropland into production that was formerly in CRP in regions with no forestry opportunities (Great Plains, Southwest), allowing additional afforestation and bioenergy in other regions.

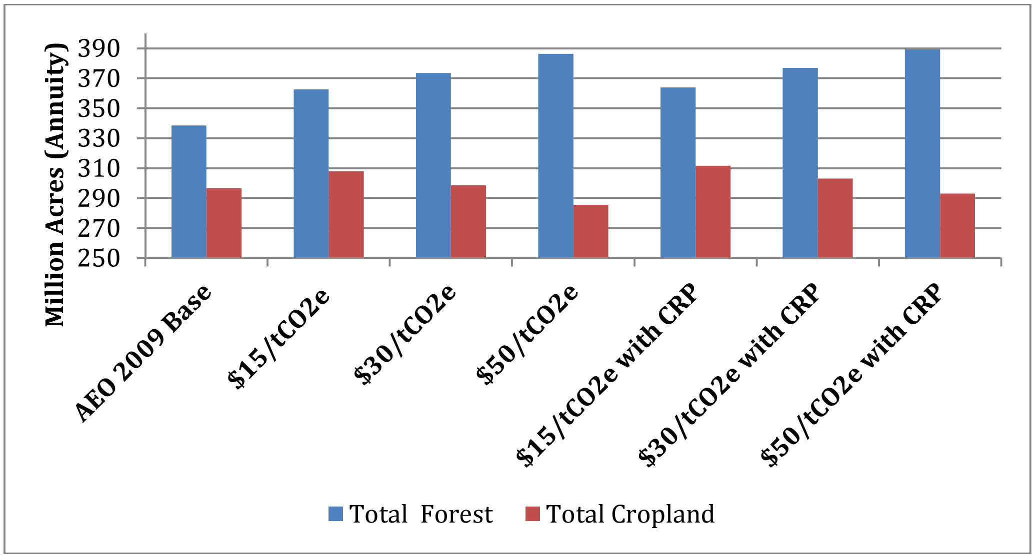

Figure 42: Annualized cropland and forest stocks across full offset mitigation scenarios (million acres)[62]

7.2.3.2 Limited Offset Scenario

- For the limited offset scenario, cropland expands even further at the $15/tCO2e case. The difference in annualized cropland between the full and limited offset cases at $15/tCO2e is approximately 7.5 million acres.
- Forestland increases substantially as well due to afforestation incentives (20-46 million acres annualized), but this is lower than under the full offset case, as there are no avoided deforestation or forest management incentives to keep existing stocks intact or lengthen harvest rotations.

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[62] Variable or scenario definitions are found in the Nomenclature section

7.2.3.3 No Offsets Case

- As discussed, the primary mitigation option under the no offset scenario is bioenergy. Results show that the majority of the requisite biomass comes from dedicated energy crops or agricultural residues.
- Annualized cropland increases 22.4-27.8 million acres (Figure 43).
- Forestland use increases as well (2.7-7.6 million acres, annualized), stimulated by bioenergy feedstock demand although this change is only marginal compared to the full and limited offsets scenario

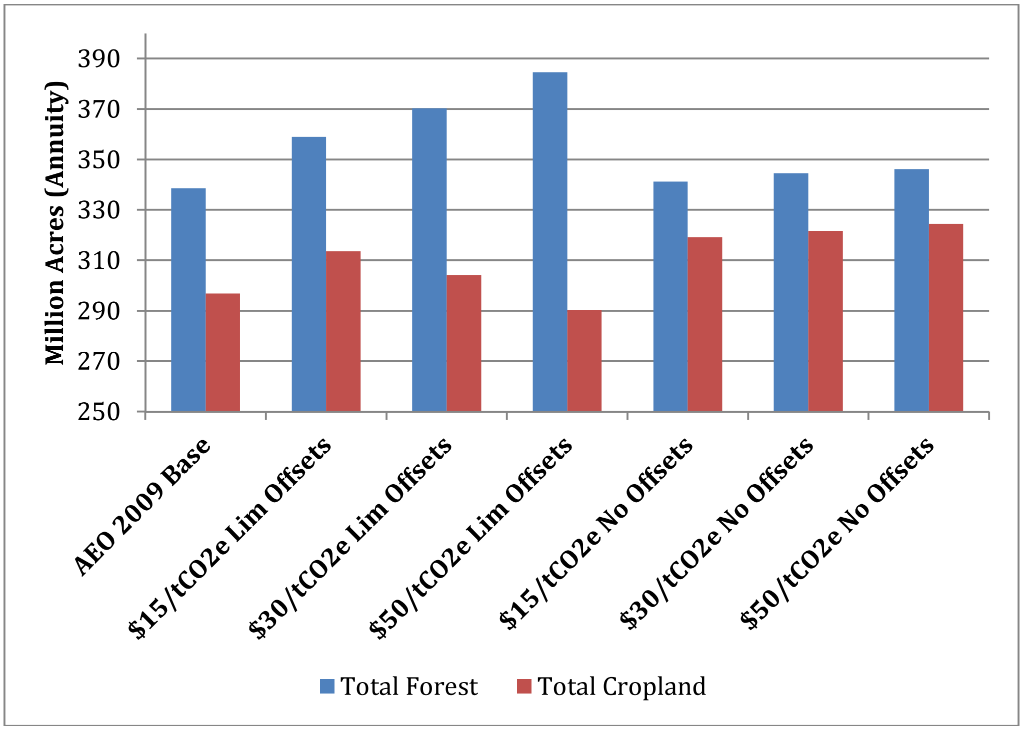

Figure 43: Annualized cropland and forest stocks across limited and no offset mitigation scenarios (million acres)[63]

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[63] Variable or scenario definitions are found in the Nomenclature section

Figure 44 and Figure 45 display long-term trends in forest and cropland use, respectively, to further illustrate land use disposition over time. Total forest use is lowest for the baseline, but declines in the long term across all scenarios after increasing initially under the carbon offset incentive regimes. Total cropland use declines throughout the projection under the baseline and expands to a level of ~325 million acres under the no offsets scenarios. Under full offset eligibility, total cropland decreases initially then expands once again beyond 2050. Here, land is afforested initially, then deforested for crop production in later time periods. Under limited eligibility, cropland expands initially for dedicated energy crop acreage, and afforestation rates are lower initially. With no forest management offsets, forestry rents are lower than in the full offset case, so the model is hesitant to move additional cropland over in early periods. Consistent with the previous chapter, CRP recultivation brings an additional 5-6 million acres back into production across the simulation horizon.

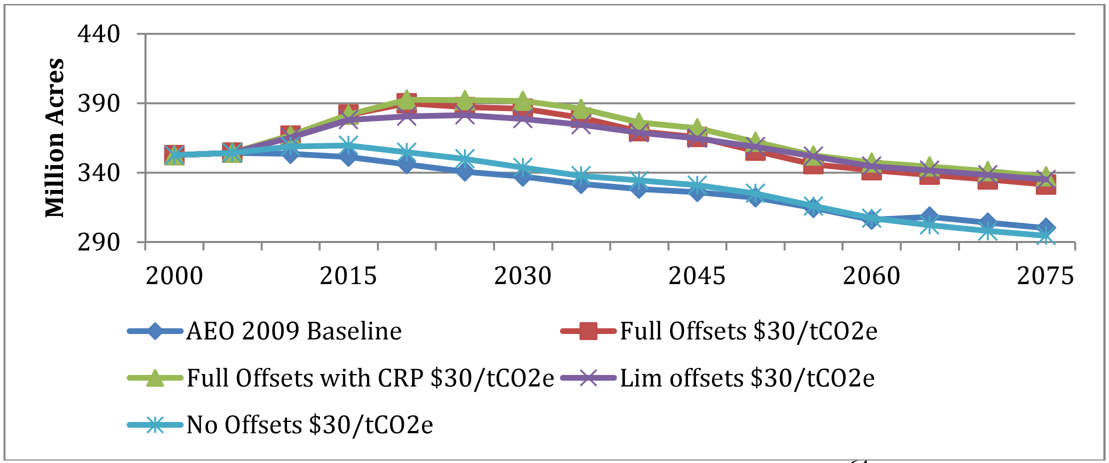

Figure 44: Forest use over time by offset scenario ($30/tCO2e)[64]

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[64] Variable or scenario definitions are found in the Nomenclature section

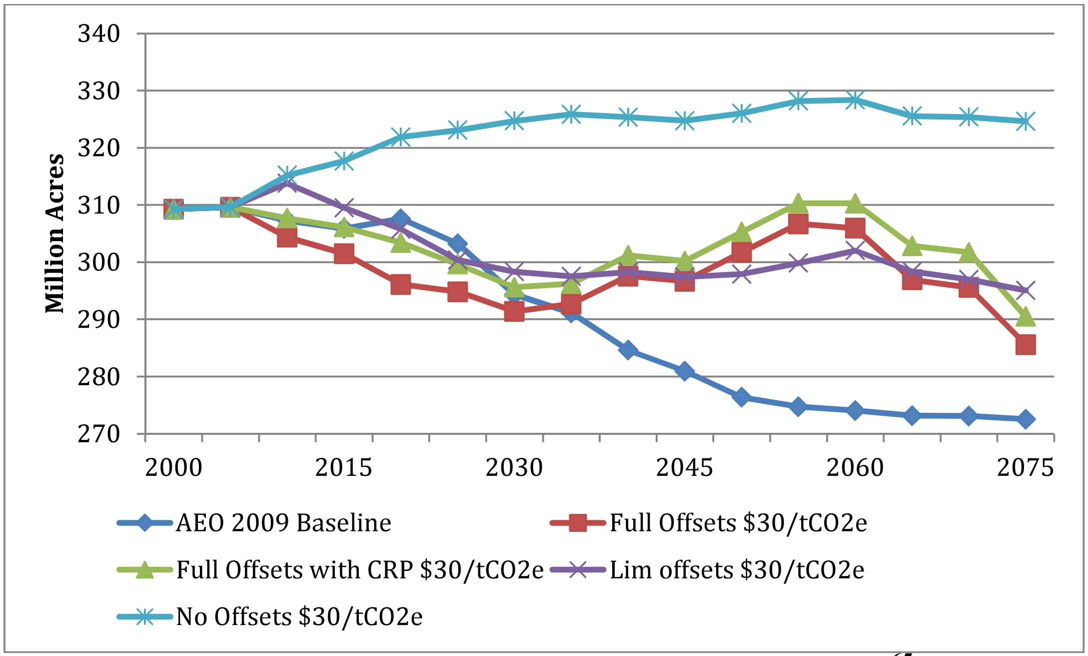

Figure 45: Cropland use over time by offset scenario ($30/tCO2e)[65]

7.2.3.4 Land Use Change

Tables 26 and 27 display cumulative transitions between major land use categories at different CO_2e[66]. The following important observations are made regarding these data:

Full offset eligibility

- GHG pricing decreases cropland and pasture deforestation in the near term, but can boost long-term deforestation rates as previously afforested land is harvested

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[65] Variable or scenario definitions are found in the Nomenclature section

[66] Note that pasture afforestation movements include both cropland pasture to forest shifts (pure afforestation) and grazed forest shifts into timberland (not afforestation per se, but a shift in land management that improves carbon sequestration.

and sustained increases in commodity prices induce a shift back to crop production,

  - CRP reversion reduces near-term deforestation further

- Cumulative cropland and pasture afforestation increases substantially, ranging 52-67 million acres by 2020 and 67-97 million acres by 2050[67],
- Pasture to cropland shifts increase under the full offset scenario by more than 25%,
- CRP recultivation rises with the carbon price. At $50/tCO2e, total recultivation is roughly 60% of the current CRP stock

Restricted offset eligibility

- The limited offsets case has a negligible effect on cropland deforestation in the near-term (though forest to cropland shifts increase marginally at $15/tCO2e)
- With no mitigation incentives for forestry, cropland rents are higher relative to forestry, so there is less incentive to afforest (especially at lower CO_2e prices). This is also driven by changing livestock production practices, as will be discussed,
- The no offsets case significantly increases cropland deforestation and pasture to cropland shifts relative to the base and at greater rate than is observed in the other mitigation scenarios

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[67] Note, this is a cumulative shift, and not a constant shift; land can move into agriculture over time to replace afforested acreage.

- Pasture afforestation still persists, but cropland afforestation is reduced to zero for the no offset case with higher GHG prices.

7.2.3.5 Regional Cropland Use

- Cropland shifts vary widely by FASOMGHG region , GHG price, and offset eligibility scenario (Figures 46 and 47). Areas with significant afforestation potential see reductions in cropland. In the South Central, this occurs at relatively low CO2 prices, and increase with the price of carbon. In regions where cropland is more valuable such as the Corn Belt and Lake States, high levels of cropland aforestation only occur when the price if carbon is sufficiently high.
- The highest increase in acreage from base occurs in the Southwest region, and this is consistent across all policy combinations,
- With CRP reversion total cropland use in the Great Plains and Rocky Mountains expands significantly, which allows additional afforestation (and cropland reductions) to occur in the South Central and Lake States
- Under limited offset eligibility, cropland use expands even further in the Southwest region, but only shifts marginally in other regions,
- Under no offset eligibility, cropland use expands considerably in most productive regions except for the Great Plains, where growth in renewable energy is limited by low bioelectricity market penetration potential.

Table 26: Cumulative LUC across Full Offset Eligibility Mitigation Scenarios, Absolute and Percent Change from Base (Thousand Acres[68])

LUC across full offset mitigation scenarios

	$15/tCO2e		$30/tCO2e		$50/tCO2e	
	2020	2050	2020	2050	2020	2050
Cropland Deforestation	**8,746.04**	**29,318.15**	**6,799.09**	**28,373.20**	**6,494.06**	**25,613.91**
	-28.03%	*30.55%*	*-44.05%*	*26.35%*	*-46.56%*	*14.06%*
Cropland Afforestation	**7,872.70**	**10,953.18**	**17,653.03**	**22,902.40**	**22,359.18**	**49,336.04**
	422.67%	*267.55%*	*1071.99%*	*668.53%*	*1384.44%*	*1555.56%*
Pasture Deforestation	**403.85**	**1,552.60**	**723.69**	**1,867.33**	**737.82**	**1,821.15**
	-29.48%	*-47.77%*	*26.36%*	*-37.19%*	*28.83%*	*-38.74%*
Pasture Afforestation	**44,121.54**	**45,830.29**	**46,168.92**	**47,583.75**	**44,810.97**	**47,294.25**
	87.54%	94.80%	96.24%	102.25%	90.47%	101.02%
Pasture to Cropland	**12,282.40**	**12,282.40**	**13,737.50**	**13,737.50**	**14,015.68**	**14,015.68**
	25.83%	25.83%	40.74%	40.74%	43.59%	43.59%
CRP to Cropland	**5,320.71**	**5,320.71**	**5,320.71**	**5,320.71**	**5,320.71**	**5,320.71**
	45.76%	45.76%	45.76%	45.76%	45.76%	45.76%

LUC across full offset mitigation scenarios with CRP

	$15/tCO2e		$30/tCO2e		$50/tCO2e	
	2020	2050	2020	2050	2020	2050
Cropland Deforestation	**8,219.23**	**29,438.49**	**6,559.69**	**27,775.50**	**6,492.78**	**26,323.82**
	-32.37%	31.09%	-46.02%	23.68%	-46.57%	17.22%
Cropland Afforestation	**9,296.98**	**12,063.59**	**20,016.22**	**28,700.72**	**26,093.07**	**59,065.68**
	517.23%	304.82%	1228.89%	863.10%	1632.33%	1882.05%
Pasture Deforestation	**409.69**	**1,558.43**	**721.08**	**1,864.73**	**737.82**	**1,810.29**
	-28.46%	-47.58%	25.91%	-37.27%	28.83%	-39.10%
Pasture Afforestation	**43,545.33**	**45,838.51**	**46,164.38**	**47,579.41**	**41,108.03**	**47,312.60**
	85.09%	57.40%	96.22%	63.38%	74.73%	62.46%
Pasture to Cropland	**9,761.00**	**9,761.00**	**12,307.96**	**12,307.96**	**11,752.55**	**13,906.27**
	0.00%	0.00%	26.09%	26.09%	20.40%	42.47%
CRP to Cropland	**13,775.33**	**13,775.33**	**16,689.65**	**16,689.65**	**19,973.66**	**19,973.66**
	277.38%	277.38%	357.22%	357.22%	447.19%	447.19%

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[68] Variable or scenario definitions are found in the Nomenclature section

Table 27: Cumulative LUC across Restricted Offset Eligibility, Absolute and Percent Change from Base (Thousand Acres)

LUC across limited offset mitigation scenarios with CRP	$15/tCO2e		$30/tCO2e		$50/tCO2e	
	2020	2050	2020	2050	2020	2050
Cropland Deforestation	**12,341.06**	**27,222.98**	**11,910.87**	**22,406.32**	**12,081.80**	**17,506.98**
	1.53%	21.20%	-2.01%	-0.24%	-0.60%	-22.05%
Cropland Afforestation	**4,167.82**	**9,233.87**	**13,115.35**	**20,381.41**	**21,118.95**	**48,032.17**
	176.70%	212.92%	770.73%	590.68%	1302.09%	1527.71%
Pasture Deforestation	**1,259.16**	**4,114.36**	**1,152.06**	**3,010.59**	**-23,529.12**	**-29,145.77**
	119.87%	38.32%	101.16%	1.22%	-4208.47%	-1079.87%
Pasture Afforestation	**46,897.68**	**48,312.70**	**46,428.62**	**47,843.87**	**9,761.00**	**9,761.00**
	50.95%	34.52%	49.44%	33.21%	-68.58%	-72.82%
Pasture to Cropland	**13,737.50**	**13,737.50**	**14,275.50**	**14,275.50**	**-3,647.46**	**-3,647.46**
	-1.27%	-1.27%	2.60%	2.60%	-126.21%	-126.21%
CRP to Cropland	**5,320.71**	**5,320.71**	**5,320.71**	**5,320.71**	**5,320.71**	**5,320.71**
	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

LUC across no offset mitigation scenarios	$15/tCO2e		$30/tCO2e		$50/tCO2e	
	2020	2050	2020	2050	2020	2050
Cropland Deforestation	**13,909.50**	**27,786.40**	**14,289.06**	**28,348.21**	**15,443.86**	**30,313.99**
	14.43%	*23.71%*	*17.56%*	*26.21%*	*27.06%*	*34.97%*
Cropland Afforestation	**772.90**	**1,085.46**	**0.00**	**0.00**	**0.00**	**0.00**
	-48.69%	*-63.22%*	*-100.00%*	*-100.00%*	*-100.00%*	*-100.00%*
Pasture Deforestation	**523.98**	**3,403.22**	**501.51**	**1,822.16**	**717.75**	**1,917.94**
	-8.51%	*14.42%*	*-12.43%*	*-38.74%*	*25.33%*	*-35.52%*
Pasture Afforestation	**35,815.33**	**39,756.77**	**37,274.85**	**43,679.47**	**45,417.54**	**46,831.97**
	15.28%	27.97%	19.98%	40.59%	46.19%	50.74%
Pasture to Cropland	**14,346.41**	**14,346.41**	**16,014.75**	**16,014.75**	**13,737.50**	**14,016.50**
	3.11%	3.11%	15.10%	15.10%	-1.27%	0.74%
CRP to Cropland	**5,320.71**	**5,320.71**	**5,320.71**	**5,320.71**	**5,320.71**	**5,320.71**

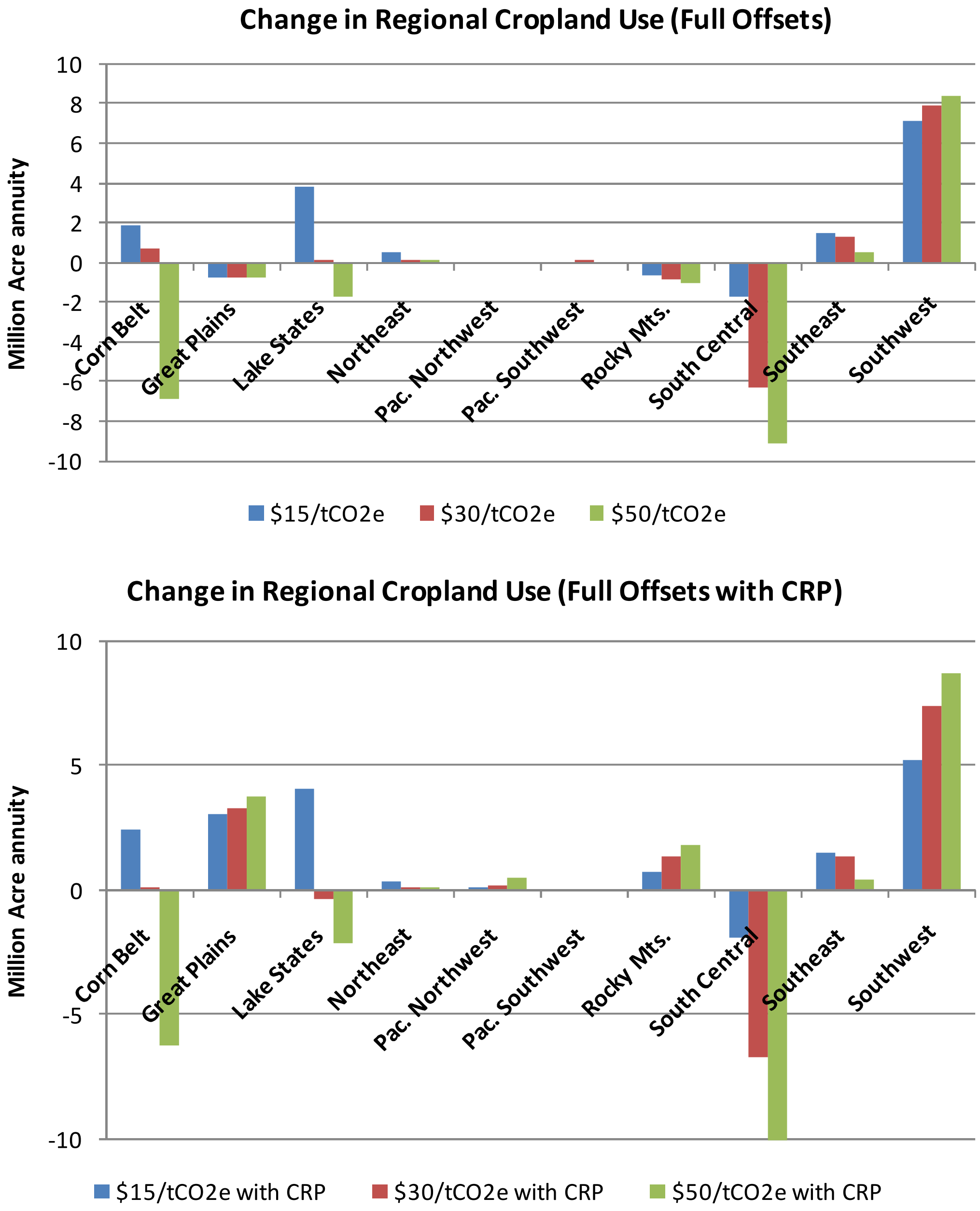

Figure 46: Change in regional cropland use (full offset eligibility)[69]

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[69] Variable or scenario definitions are found in the Nomenclature section

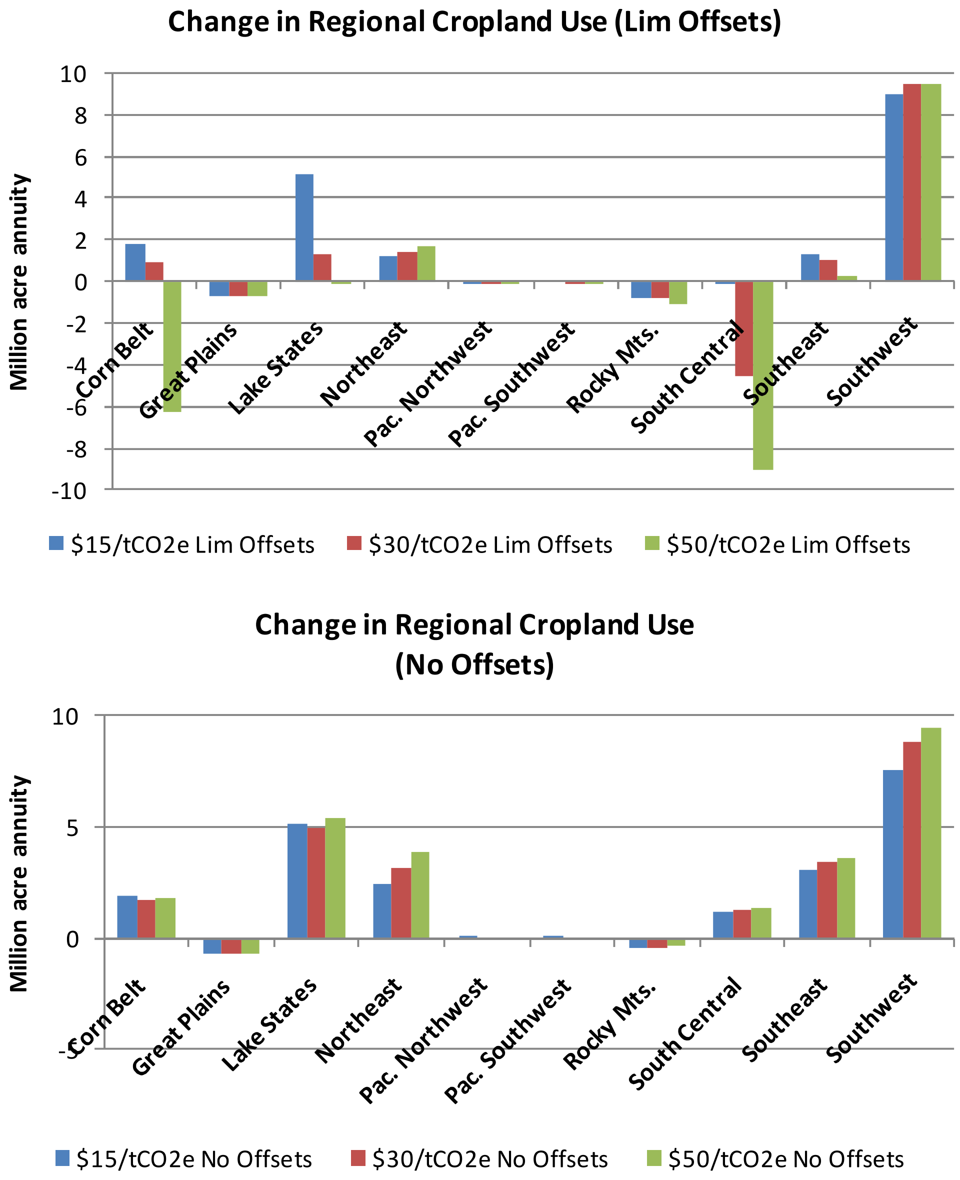

Figure 47: Change in regional cropland use (restricted offset eligibility)[70]

7.2.4 Commodity Production Implications

- Shifting land use patterns affect crop mix and livestock management strategies (Tables 28). The following observations can be made.

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[70] Variable or scenario definitions are found in the Nomenclature section

7.2.4.1.1 Crop Production and Land Use

Table 28 displays regional cropland use by crop and scenario. Specifically, results indicate:

- Corn acreage decreases only marginally for the full and limited offsets scenarios, and expands considerably under no offset eligibility relative to the baseline,
- Soybean acreage changes only slightly from the AEO 2009 baseline, but declines noticeably across the offset eligibility cases relative to the RFS2 projection (10-12%), explaining the high commodity price effect on soybeans,
- Rice and wheat acreage decrease at a high proportion relative to the AEO and RFS2 bases (12%-26% relative to the RFS2 for rice, and 2%-7.5% for wheat),
- Cotton acreage declines relative to the base for all scenarios
- Meanwhile, dedicated energy crop production increases considerably, with the highest growth seen in switchgrass.
    - Switchgrass acreage increases from approximately 7 million acres from the RFS2 scenario, driven by the demand for bioelectricity feedstocks,
    - Hybrid poplar and willow play a role in the portfolio for no offsets case, solely for bioelectricity. However, poplar and willow are used to supplant pulp and paper mills in the full offset scenarios as forests are managed for carbon.

Table 28: Crop Acreage by Mitigation Scenario (Million Acre Annuity)[71]

Conventional Crops	AEO 2009 Base	$30/tCO2e	$30/tCO2e with CRP	$30/tCO2e No Offsets	$30/tCO2e Lim Offsets
Corn	69.40	68.91	69.47	72.43	69.1
Cotton	11.58	11.18	11.10	11.22	11.34
Sorghum	9.94	10.75	10.82	11.58	11
Soybeans	66.33	65.30	66.45	72.22	67.03
Rice	3.13	2.14	2.14	2.52	2.3
Wheat	64.32	58.38	59.77	62.04	60.2
Energy Crop Acres	**AEO 2009 Base**	**$30/tCO2e**	**$30/tCO2e with CRP**	**$30/tCO2e No Offsets**	**$30/tCO2e Lim Offsets**
Hybrid Poplar	0.00	0.91	0.92	1.31	0.71
Switchgrass	0.59	12.07	12.21	15.50	12.67
Willow	0.03	0.56	0.55	0.12	0.12

7.2.4.1.2 Livestock Production

Livestock production practices respond to the mitigation policies in a number of ways. For the full offsets case, livestock production responds directly to mitigation incentives for manure management or improved enteric fermentation, and higher energy costs, and indirectly to higher feed costs that depend on changes in crop production. For limited offsets, livestock producers face higher costs, and manure management incentives, but no payments for improved enteric fermentation. For the no offsets case, livestock producers face only higher costs of production.

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[71] Variable or scenario definitions are found in the Nomenclature section

Table 29 displays absolute and percent deviations from base for several important classification groups (in 1,000 head) for al offset eligibility scenarios and at \$30/tCO_2e. Results show that across these mitigation efforts livestock production practices could respond considerably. For the full offset case, total cattle production (cow/calf) falls ~12%. Stocker calves, yearlings, and heifers are reduced nearly to zero at \$30/tCO_2e. The stocker phase of production occurs when cattle are grazed for a certain portion of time (typically 9 months to a year) before being sent to a feedlot operation. Here, the stocking phase is essentially eliminated, but feedlot calves increase considerably. This is a by-product of incentivizing reduced enteric fermentation and shift use of grazing lands. One mitigation option is to feed the animals more heavily at a younger age, thus reducing lifespan and net GHG emissions per-unit meat. This raises serious concerns regarding the treatment of animals and the environmental co-effects of large-scale feeding operations, but we do not account for that in this analysis. Hog and poultry operations are also reduced, but only marginally so when compared to cattle (this is an indirect response to higher costs of production). CRP reversion has a very small effect on these results.

The limited offset scenarios see a much smaller reduction in livestock head (5.7%), but a similar response in reduced grazing (due to pasture afforestation and cultivation). Other livestock practices see little movement. The no offsets case sees only a slight reduction in total production (though practices change significantly) driven by higher costs of production.

Table 29: Absolute and Percent Change in Livestock Production (Thousand Head)[72]

	$30/tCO2e	$30/tCO2e (% Diff)	$30/tCO2e with CRP	$30/tCO2e with CRP (% Diff)	$30/tCO2e Lim Offsets	$30/tCO2e Lim Offsets (% Diff)	$30/tCO2e No Offsets	$30/tCO2e No Offsets (% Diff)
Sheep	**254.50**	*5.26%*	**151.85**	*3.14%*	**217.41**	*4.49%*	**270.99**	*5.60%*
Cow/Calf	**-4,716.06**	*-11.77%*	**-4,464.30**	*-11.14%*	**-2,275.92**	*-5.68%*	**-1,348.23**	*-3.37%*
Feedlot Yearlings	**-14,250.32**	*-97.98%*	**-14,350.55**	*-98.67%*	**-1,422.89**	*-9.78%*	**-3,088.43**	*-21.24%*
Feedlot Calves	**9,510.55**	*36.68%*	**9,836.98**	*37.94%*	**30.27**	*0.12%*	**2,254.04**	*8.69%*
Dairy	**-377.85**	*-5.94%*	**-338.87**	*-5.33%*	**-198.04**	*-3.12%*	**-45.18**	*-0.71%*
Farrow Hog	**526.67**	*4.20%*	**869.12**	*6.93%*	**512.70**	*4.09%*	**438.85**	*3.50%*
Feeder Pig	**-266.27**	*-4.42%*	**-269.49**	*-4.47%*	**-445.48**	*-7.39%*	**-113.19**	*-1.88%*
Pig Finishing	**-5,346.03**	*-4.60%*	**-5,414.86**	*-4.66%*	**-8,697.55**	*-7.48%*	**-2,069.51**	*-1.78%*
Horses and Mules	**-210.20**	*-3.49%*	**-215.43**	*-3.58%*	**-94.52**	*-1.57%*	**-73.16**	*-1.22%*
Steer Calf (Stocker)	**-11,375.88**	*-89.56%*	**-11,493.42**	*-90.49%*	**-280.03**	*-2.20%*	**-1,687.74**	*-13.29%*
Heifer Calf (Stocker)	**-2,758.37**	*-100.00%*	**-2,758.37**	*-100.00%*	**-1,614.25**	*-58.52%*	**-1,554.09**	*-56.34%*
Steer Yearling (Stocker)	**-11,997.97**	*-87.58%*	**-12,127.22**	*-88.52%*	**-297.21**	*-2.17%*	**-1,750.56**	*-12.78%*
Heifer Yearling (Stocker)	**-2,920.25**	*-100.00%*	**-2,920.25**	*-100.00%*	**-1,692.83**	*-57.97%*	**-1,628.26**	*-55.75%*
Turkey	**323.46**	*0.16%*	**962.37**	*0.47%*	**409.12**	*0.20%*	**1,716.34**	*0.84%*
Broiler	**-136,995.85**	*-1.84%*	**-129,936.88**	*-1.74%*	**-113,834.96**	*-1.53%*	**-27,013.79**	*-0.36%*
Egg	**-6,806.59**	*-2.08%*	**-5,673.98**	*-1.73%*	**-4,291.00**	*-1.31%*	**-2,129.81**	*-0.65%*

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[72] Variable or scenario definitions are found in the Nomenclature section

7.2.4.2 Import and Export Market Implications

Long-term shifts in land use and production patterns impact international agricultural markets, as U.S. exports would be expected to decline under GHG mitigation efforts (Table 30). As suggested in the previous chapter, shifting global trade patterns have serious implications for land use change in international regions. Results suggest that U.S. exports of major grain and meat commodities would decrease substantially under all mitigation scenarios considered. Grain exports decrease at the highest rate, with soybeans seeing the greatest movement (coincidentally, soybean expansion in the Brazilian Amazon is a key concern in the land use change arena). These results reflect export shifts in response to the RFS2, in addition to those stimulated by land shifting to carbon sequestration or bioenergy. The concluding chapter provides more detail comparing export responses to the RFS2 and mitigation scenarios.

Table 30: Percent Change in Annualized Exports across Mitigation Scenarios ($30/tCO2e)[73]

	$30/tCO2e Full Offsets	$30/tCO2e Full Offsets with CRP	$30/tCO2e Lim Offsets	$30/tCO2e No Offsets
Corn	-14.74%	-13.47%	-12.68%	-7.01%
Soybeans	-43.52%	-40.97%	-39.71%	-33.54%
Wheat	-6.59%	-2.88%	-4.85%	-1.41%
Cotton	-18.26%	-8.81%	-8.81%	-12.98%
Sorghum	-44.43%	-41.65%	-41.57%	-36.48%
Rice	-38.99%	-38.79%	-31.91%	-22.54%
Fed Beef	-6.85%	-6.25%	-3.43%	-1.48%
Pork	-3.27%	-3.16%	-5.45%	-0.91%
Chicken	-2.72%	-2.45%	-2.11%	-0.24%

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[73] Variable or scenario definitions are found in the Nomenclature section

Production and exports from international regions show significant upward movement across mitigation scenarios. Figure 48 shows export index values, measured as the annualized change in exports relative to the base (observed) period; values below 100 indicate an expected decline in exports from these regions in the baseline. Essentially, these data illustrate the additional supply of important grain commodities to the world market originating from the regions listed on the horizontal axis. International exports from the regions modeled increase for all mitigation scenarios evaluated, substantially so for some regions (such as Brazil, Argentina and China). Export changes are lowest in all regions for the no offset scenario where production expands considerably in the U.S.

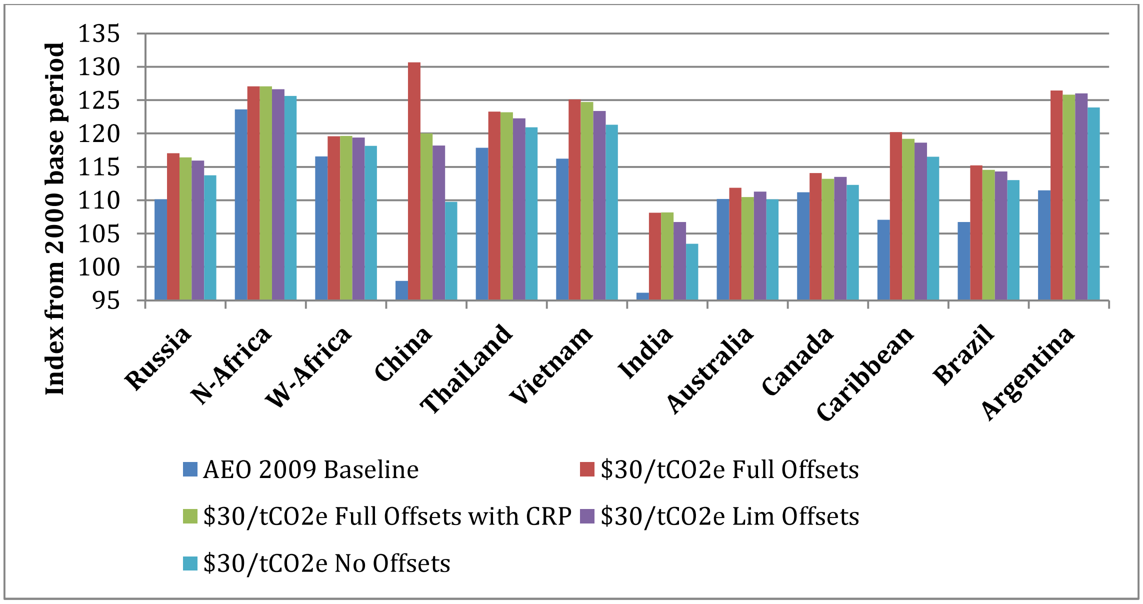

Figure 48: Export change by international region and mitigation scenario (2000 base export level for all crops = 100)[74]

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[74] Variable or scenario definitions are found in the Nomenclature section

7.2.5 Management Intensity and Water Resource Implications

To tell a complete story of shifting land use and production patterns under reduced carbon efforts, one must consider management intensity responses to the low carbon policies in addition to what happens on the extensive (land use) margin.

7.2.5.1 National and Regional Water Use Response to GHG Pricing

Under the influence of bioenergy mandates, irrigation water consumption increases nationally and for most regions. Pattanayak et al. (2005) show that GHG mitigation can improve water quality locally, but this study was performed before national biofuel mandates were under consideration. When GHG mitigation is included in addition to the RFS2, water use declines relative to the baseline, but only marginally. Under full offset eligibility, net water consumption declines 0.5-1.5 million acre feet, or 0.9%-2.5% of total water consumed Figure 49. Water use declines due to higher pumping costs across the mitigation schemes, reduced cropland acreage, and crop mix shifts. However, this is relatively small shift, especially when compared to the total amount of cropland projected to leave conventional production in the full offset mitigation scenarios.

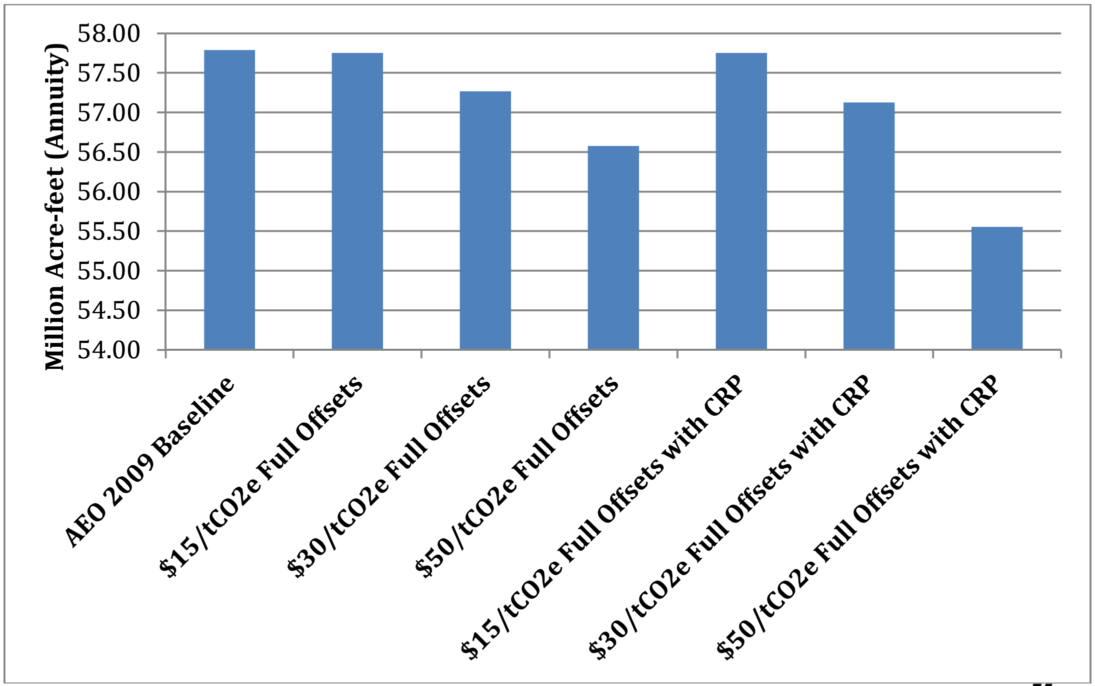

Figure 49: Total water use across mitigation scenarios (full offset eligibility)[75]

CRP reversion brings additional land into production, but also reduces net water consumption further. For the CRP mitigation scenarios, net water consumption declines at a lower rate at the $15/tCO2e case, but at a much higher rate for the $30 and $50/tCO2e scenarios (0.1%-3.9% from base levels). This effect shows that movement to the extensive margin can relax management intensification.

For the restricted offset eligibility scenarios, water use also contracts (Figure 50). Across the limited offset scenarios, annualized reductions in water use range 1.1%-4%. Similar to the full offset case, reductions are caused by higher energy prices, shifting crop mixes, and reduced cropland stocks. For the no offset case, annualized water use

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[75] Variable or scenario definitions are found in the Nomenclature section

declines 0.7%-3.6%, driven by energy prices and a shift out of irrigated production of conventional crops and into non-irrigated perennial crops.

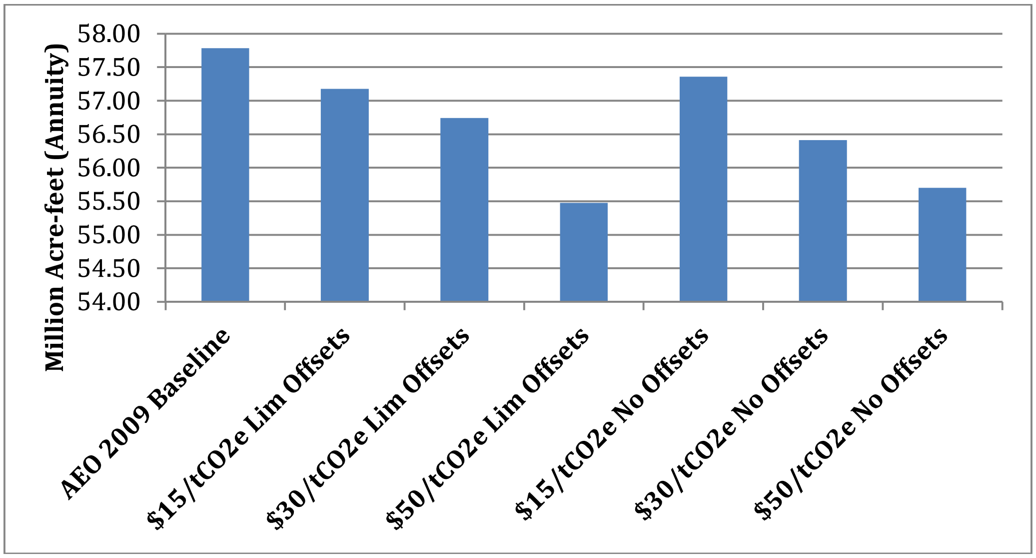

Figure 50: Total water use across mitigation scenarios (limited and no offset eligibility)[76]

7.2.5.1.1 Incidence of Water Leakage

Further examination of water use at the regional level reveals that water use does not decrease consistently for all agricultural regions modeled. If climate mitigation or renewable energy efforts induce land use shifts in the in the in important agricultural regions, indirect production responses in less productive regions and incidence of leakage are possible outcomes.

Table 31 displays percentage deviations in annualized water consumption from baseline (million acre feet). Notice that for some regions, this flux is positive, indicating

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[76] Variable or scenario definitions are found in the Nomenclature section

a net increase in water use. For some regions with existing water scarcity problems such as the Great Plains and Southwest, water consumption increases at a high rate. Thus, when viewed at a national scale, it appears that GHG mitigation efforts can reduce total water consumption, but when viewed regionally shifting production patterns push water use to the intensive margin for regions with little GHG mitigation potential. This is essentially "water leakage," as reducing water consumption and improving quality locally has the residual impact of boosting irrigation elsewhere.

For the restricted offset eligibility scenarios, limited offsets have a similar effect on water consumption, as the Southwest and Great Plains, and Rocky Mountain regions see marginal increases in consumption, while water use changes very little in other regions (Table 32). However, in the no offsets scenarios, water use in the Great Plains declines at higher CO2e prices. This is further evidence of the water leakage phenomenon in reverse order. Here, cropland expansion occurs for most regions, relaxing some commodity prices. Irrigators are thus faced with higher energy costs stimulated by the climate policy, but do not realize the indirect benefits of higher output prices as with the previous offset eligibility scenarios. This encourages a distinct management shift away from irrigated production in the Great Plains where water-pumping costs directly related to energy prices. If climate mitigation or renewable energy policy efforts induce land use or management shifts in the most productive agricultural regions in the U.S., then incidence of leakage or intensification responses in other regions are possible outcomes.

Table 31: Absolute and Percentage Deviations from Base in Regional Water Use under Full Offset Eligibility (Million Acre-feet Annuity)[77]

	$15/tCO2e	$30/tCO2e	$50/tCO2e	$15/tCO2e with CRP	$30/tCO2e with CRP	$50/tCO2e with CRP
Corn Belt	**0.01**	**0.01**	**-0.02**	**0.01**	**0.00**	**-0.02**
	3.96%	*3.01%*	*-7.50%*	*2.10%*	*1.19%*	*-7.36%*
Great Plains	**0.39**	**0.57**	**0.55**	**0.71**	**1.04**	**0.89**
	3.17%	*4.64%*	*4.50%*	*5.79%*	*8.53%*	*7.25%*
Lake States	**-0.04**	**-0.15**	**-0.22**	**-0.05**	**-0.19**	**-0.27**
	-10.70%	*-36.96%*	*-54.59%*	*-12.55%*	*-49.15%*	*-68.99%*
Northeast	**0.00**	**-0.01**	**-0.01**	**0.00**	**-0.01**	**-0.01**
	-2.64%	*-10.38%*	*-10.57%*	*-6.04%*	*-10.75%*	*-15.47%*
Pac. Northwest	**0.09**	**0.15**	**0.15**	**0.03**	**0.09**	**0.16**
	6.06%	*9.75%*	*9.31%*	*2.21%*	*5.70%*	*10.07%*
Pac. Southwest	**-0.02**	**-0.08**	**-0.23**	**0.00**	**-0.07**	**-0.16**
	-0.29%	*-1.19%*	*-3.50%*	*-0.07%*	*-1.06%*	*-2.40%*
Rocky Mts.	**0.19**	**0.28**	**0.36**	**0.42**	**0.46**	**0.48**
	0.85%	*1.28%*	*1.66%*	*1.94%*	*2.10%*	*2.19%*
South Central	**-1.80**	**-2.69**	**-3.83**	**-1.82**	**-2.69**	**-3.95**
	-25.84%	*-38.66%*	*-55.12%*	*-26.17%*	*-38.66%*	*-56.91%*
Southeast	**0.03**	**0.07**	**0.06**	**0.04**	**0.07**	**0.03**
	2.71%	*5.84%*	*5.22%*	*3.41%*	*5.95%*	*2.79%*
Southwest	**0.62**	**0.62**	**0.62**	**0.62**	**0.62**	**0.62**
	9.67%	*9.67%*	*9.67%*	*9.67%*	*9.67%*	*9.67%*

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[77] Variable or scenario definitions are found in the Nomenclature section

Table 32: Absolute and Percentage Deviations from Baseline Water Use Levels under Limited and No Offset Eligibility (Million Acre-feet Annuity)[78]

	$15/tCO2e Lim Offsets	$30/tCO2e Lim Offsets	$50/tCO2e Lim Offsets	$15/tCO2e No Offsets	$30/tCO2e No Offsets	$50/tCO2e No Offsets
Corn Belt	**0.01**	**0.00**	**-0.02**	**0.01**	**0.00**	**-0.02**
	4.27%	*0.53%*	*-7.92%*	*3.57%*	*0.11%*	*-5.71%*
Great Plains	**0.42**	**0.43**	**0.24**	**0.32**	**-0.09**	**-0.18**
	3.39%	*3.51%*	*1.99%*	*2.61%*	*-0.77%*	*-1.43%*
Lake States	**-0.03**	**-0.14**	**-0.23**	**-0.10**	**-0.20**	**-0.22**
	-7.69%	*-36.05%*	*-57.80%*	*-26.41%*	*-50.62%*	*-56.56%*
Northeast	**0.01**	**0.01**	**0.01**	**0.04**	**0.06**	**0.05**
	11.51%	*16.60%*	*19.25%*	*76.98%*	*104.91%*	*90.38%*
Pac. Northwest	**0.06**	**0.11**	**0.10**	**0.02**	**0.01**	**0.11**
	3.58%	*7.11%*	*6.53%*	*1.58%*	*0.86%*	*6.90%*
Pac. Southwest	**-0.01**	**-0.06**	**-0.11**	**0.01**	**-0.01**	**-0.16**
	-0.12%	*-0.86%*	*-1.58%*	*0.17%*	*-0.22%*	*-2.34%*
Rocky Mts.	**-0.05**	**0.11**	**0.28**	**0.04**	**-0.19**	**-0.45**
	-0.23%	*0.50%*	*1.28%*	*0.17%*	*-0.85%*	*-2.05%*
South Central	**-1.65**	**-2.19**	**-3.25**	**-1.45**	**-1.66**	**-1.91**
	-23.76%	*-31.60%*	*-46.74%*	*-20.84%*	*-23.95%*	*-27.52%*
Southeast	**0.02**	**0.06**	**0.03**	**0.06**	**0.09**	**0.07**
	1.57%	*5.20%*	*2.66%*	*4.54%*	*7.29%*	*5.55%*
Southwest	**0.63**	**0.63**	**0.63**	**0.63**	**0.63**	**0.63**
	9.69%	*9.68%*	*9.69%*	*9.69%*	*9.69%*	*9.69%*

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[78] Variable or scenario definitions are found in the Nomenclature section

7.2.5.2 National and Regional Energy and Nutrient Use Response to GHG Pricing

In addition to water, shifting land management patterns can boost intensity of production and use of fossil fuels and nutrients that are also valuable inputs in the production process. Tables 33-36 display annualized percent changes in input use, regionally and nationally, in total and per-acre terms. Given the amount of data presented here, I choose to display intensity effects for the \$30/tCO$_2$e case only.

- Fossil fuel use decreases across most region/mitigation scenario combinations in response to higher fuel costs imposed by the policy.
    - Electricity use declines significantly in some regions, but is boosted by higher irrigation rates in others (Southwest and Great Plains)
    - Total diesel and gasoline use decline significantly nationally and for most regions under full and limited offset scenarios (the Southwest is the one exception here, as cropland expansion in this region induces additional input use).
    - These results are mostly consistent on a per-acre basis, as energy intensity per-acre falls at a national level for all fuels but electricity (increased per-acre electricity use is driven in part by groundwater pumping in the Southwest region)

- Total N fertilizer use increases significantly across all offset eligibility scenarios, ranging 3-9%. Phosphorous and potassium use increase substantially, ranging 9.6%-18% and 21.4%-32%, respectively.
    - The Lake States and South Central regions reduce N use overall but use higher levels of P and K, primarily driven by a higher proportion of soybean production (soybeans typically have lower N application rates than other major grain commodities)
    - Unlike the change from baseline to the RFS2 where cropland expansion was accompanied by a reduction in per-acre N intensity, mitigation boosts per-acre intensity nationally and for most regions. The implication here is that cropland contraction is accompanied by absolute and marginal shifts in nutrient application, or movement from the extensive margin to the intensive margin on the production frontier.

Table 33: Percent Change in Total Input Use under Full Offset Eligibility[79]

Percent change in regional input use at $30/tCO2e with full offset eligibility (annualized)

	Nitrogen	Phosphorous	Potassium	Diesel	Electricity	Gasoline	Natural Gas	Water
Corn Belt	4.53%	18.53%	25.46%	-6.55%	-9.86%	-3.89%	5.73%	3.01%
Great Plains	2.10%	2.20%	69.31%	-2.57%	3.39%	-0.07%	-0.34%	4.64%
Lake States	-4.14%	4.48%	38.82%	-12.15%	-33.52%	-22.47%	-41.21%	-36.96%
Northeast	6.36%	-5.53%	-4.10%	-2.81%	-11.51%	-22.93%	0.00%	-10.38%
Pac. Northwest	2.09%	4.95%	195.41%	-4.94%	8.61%	-0.10%	0.00%	9.75%
Pac. Southwest	2.71%	4.63%	105.63%	-14.89%	-94.64%	-0.77%	0.00%	-1.19%
Rocky Mts.	-0.72%	2.61%	34.04%	-12.47%	-0.89%	-2.71%	2.36%	1.28%
South Central	-20.66%	-9.09%	-16.04%	-38.34%	-34.35%	-27.40%	-44.28%	-38.66%
Southeast	17.84%	23.16%	16.98%	-4.88%	7.71%	-0.85%	0.00%	5.84%
Southwest	43.49%	54.43%	216.86%	-0.57%	12.15%	22.41%	0.00%	9.67%
TOTAL	3.25%	9.62%	22.36%	-8.88%	-1.64%	-7.43%	-37.37%	-2.10%

Percent change in regional input use at $30/tCO2e with full offset eligibility and CRP (annualized)

	Nitrogen	Phosphorous	Potassium	Diesel	Electricity	Gasoline	Natural Gas	Water
Corn Belt	3.63%	17.55%	24.03%	-7.06%	-10.78%	-4.61%	3.57%	1.19%
Great Plains	7.21%	7.90%	73.16%	2.98%	7.57%	8.85%	5.12%	8.53%
Lake States	-5.76%	2.79%	36.54%	-13.93%	-46.52%	-23.97%	-52.45%	-49.15%
Northeast	5.54%	-6.20%	-4.74%	-3.68%	-11.91%	-23.33%	0.00%	-10.75%
Pac. Northwest	5.42%	9.27%	215.54%	-1.61%	4.18%	2.86%	0.00%	5.70%
Pac. Southwest	2.81%	4.68%	95.59%	-14.39%	-94.68%	-0.24%	0.00%	-1.06%
Rocky Mts.	6.14%	8.41%	42.45%	-6.48%	1.36%	4.25%	5.15%	2.10%
South Central	-22.11%	-10.23%	-17.29%	-40.11%	-33.27%	-29.60%	-44.75%	-38.66%
Southeast	17.21%	22.95%	16.77%	-4.44%	7.19%	-0.94%	0.00%	5.95%
Southwest	40.09%	52.24%	209.17%	-2.51%	10.99%	13.51%	0.00%	9.67%
TOTAL	4.41%	10.93%	21.45%	-7.47%	1.08%	-6.39%	-38.10%	-1.15%

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[79] Variable or scenario definitions are found in the Nomenclature section

Table 34: Percent Change in Total Input Use under Restricted Offset Eligibility[80]

Percent change in regional input use at $30/tCO2e with limited offset eligibility (annualized)

	Nitrogen	Phosphorous	Potassium	Diesel	Electricity	Gasoline	Natural Gas	Water
Corn Belt	4.81%	18.65%	25.78%	-5.91%	-10.97%	-3.21%	2.77%	0.53%
Great Plains	2.14%	1.82%	57.36%	-2.48%	2.05%	-0.54%	-1.13%	3.51%
Lake States	-5.97%	9.04%	45.04%	-5.97%	-32.07%	-17.43%	-40.99%	-36.05%
Northeast	34.16%	22.09%	25.07%	20.25%	15.77%	8.79%	0.00%	16.60%
Pac. Northwest	1.64%	3.82%	195.92%	-4.85%	6.75%	-0.09%	0.00%	7.11%
Pac. Southwest	2.29%	4.37%	101.16%	-11.83%	-94.47%	-0.62%	0.00%	-0.86%
Rocky Mts.	-1.46%	2.21%	35.36%	-12.86%	-0.57%	-4.47%	-5.04%	0.50%
South Central	-17.40%	-4.77%	-12.08%	-36.23%	-24.30%	-26.11%	-38.32%	-31.60%
Southeast	14.80%	19.19%	13.78%	-4.19%	5.80%	-4.27%	0.00%	5.20%
Southwest	46.78%	62.34%	234.74%	1.51%	9.92%	21.25%	0.00%	9.68%
TOTAL	4.06%	11.48%	24.57%	-7.37%	-1.61%	-6.60%	-32.99%	-1.81%

Percent change in regional input use at $30/tCO2e with no offsets (annualized)

	Nitrogen	Phosphorous	Potassium	Diesel	Electricity	Gasoline	Natural Gas	Water
Corn Belt	5.02%	18.42%	22.23%	-0.84%	-10.15%	-2.90%	2.32%	0.11%
Great Plains	1.78%	1.43%	44.48%	-1.97%	-3.41%	-2.21%	-1.27%	-0.77%
Lake States	4.66%	20.65%	55.40%	14.63%	-48.47%	-12.25%	-53.48%	-50.62%
Northeast	134.97%	118.45%	125.11%	111.87%	105.45%	102.99%	0.00%	104.91%
Pac. Northwest	0.64%	0.57%	134.14%	-0.26%	1.78%	0.21%	0.00%	0.86%
Pac. Southwest	1.85%	4.42%	92.42%	-3.64%	-94.68%	-0.15%	0.00%	-0.22%
Rocky Mts.	-2.12%	3.80%	45.01%	-13.60%	-1.44%	-10.31%	-21.48%	-0.85%
South Central	-1.60%	15.05%	3.85%	-4.25%	-19.08%	-17.70%	-28.51%	-23.95%
Southeast	30.85%	42.61%	32.97%	17.29%	10.94%	19.53%	0.00%	7.29%
Southwest	41.08%	59.03%	221.28%	14.88%	9.95%	8.65%	0.00%	9.69%
TOTAL	8.99%	18.00%	31.98%	2.22%	-4.55%	-2.32%	-26.20%	-2.38%

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[80] Variable or scenario definitions are found in the Nomenclature section

Table 35: Percent Change in Per-acre Input Use under Full Offset Eligibility[81]

Percent change in per acre regional input use at $30/tCO2e with full offset eligibility (annualized)								
	Nitrogen	Phosphorous	Potassium	Diesel	Electricity	Gasoline	Natural Gas	Water
Corn Belt	3.31%	14.73%	9.36%	-14.55%	5.49%	-8.89%	16.05%	1.79%
Great Plains	3.09%	-0.86%	70.78%	-42.95%	81.22%	-44.86%	80.74%	1.88%
Lake States	-8.20%	13.81%	21.97%	-27.98%	-7.69%	-16.01%	-30.00%	-3.02%
Northeast	-18.03%	15.25%	-16.79%	16.80%	-24.24%	1.73%	0.00%	-23.13%
Pac. Northwest	2.39%	2.50%	188.21%	-67.02%	229.29%	-69.66%	0.00%	1.97%
Pac. Southwest	2.74%	1.84%	101.91%	-57.85%	-87.29%	680.55%	0.00%	-1.24%
Rocky Mts.	2.62%	-0.01%	34.06%	-34.70%	51.79%	-35.90%	59.70%	1.13%
South Central	-9.02%	-0.07%	-15.98%	-26.62%	-10.54%	-18.84%	-31.35%	-12.73%
Southeast	9.47%	12.51%	3.97%	-8.52%	17.74%	-15.79%	0.00%	1.61%
Southwest	1.79%	51.73%	108.84%	-52.39%	135.56%	-48.04%	0.00%	-0.19%
TOTAL	0.56%	9.01%	12.24%	-18.82%	21.16%	-23.60%	-18.02%	0.57%
Percent change in per-acre regional input use at $30/tCO2e with full offset eligibility and CRP (annualized)								
	Nitrogen	Phosphorous	Potassium	Diesel	Electricity	Gasoline	Natural Gas	Water
Corn Belt	1.45%	15.87%	7.04%	-13.17%	2.75%	-7.17%	11.57%	-0.62%
Great Plains	8.25%	-0.33%	73.73%	-40.72%	81.47%	-40.02%	75.25%	0.46%
Lake States	-19.24%	27.29%	7.27%	-19.76%	-33.35%	14.08%	-58.32%	-1.43%
Northeast	-54.34%	105.42%	-53.63%	107.72%	-57.59%	80.79%	0.00%	0.25%
Pac. Northwest	5.43%	3.65%	204.44%	-67.68%	222.37%	-68.09%	0.00%	0.45%
Pac. Southwest	2.81%	1.82%	92.09%	-55.43%	-88.06%	735.38%	0.00%	-0.96%
Rocky Mts.	8.08%	0.31%	42.02%	-34.15%	53.93%	-32.27%	55.26%	0.56%
South Central	-24.77%	19.32%	-30.68%	-13.61%	-22.76%	-8.85%	-39.39%	-2.09%
Southeast	-7.66%	33.15%	-12.30%	8.97%	-1.64%	0.71%	0.00%	0.92%
Southwest	1.37%	50.19%	105.86%	-52.64%	134.37%	-51.57%	0.00%	-0.24%
TOTAL	-3.81%	15.32%	5.32%	-12.15%	15.05%	-18.64%	-23.92%	0.85%

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[81] Variable or scenario definitions are found in the Nomenclature section

Table 36: Percent Change in Per-acre Input Use under Restricted Offset Eligibility[82]

Percent change in per acre regional input use at $30/tCO2e with limited offset eligibility (annualized)

	Nitrogen	Phosphorous	Potassium	Diesel	Electricity	Gasoline	Natural Gas	Water
Corn Belt	3.59%	14.54%	9.82%	-14.32%	3.91%	-6.85%	10.33%	-0.67%
Great Plains	3.13%	-1.27%	59.38%	-38.81%	66.79%	-40.37%	65.80%	0.78%
Lake States	-9.95%	21.08%	19.78%	-21.50%	-13.47%	-4.58%	-38.16%	-1.62%
Northeast	3.39%	18.09%	5.92%	13.54%	1.97%	6.68%	0.00%	0.01%
Pac. Northwest	1.94%	1.85%	190.55%	-67.25%	226.00%	-69.35%	0.00%	-0.48%
Pac. Southwest	2.32%	2.00%	97.21%	-55.29%	-87.64%	703.82%	0.00%	-0.92%
Rocky Mts.	1.86%	0.35%	34.89%	-35.40%	53.92%	-37.93%	53.00%	0.35%
South Central	-5.28%	0.54%	-12.55%	-27.08%	3.81%	-28.82%	-13.35%	-2.68%
Southeast	6.65%	11.76%	1.81%	-5.89%	12.43%	-14.86%	0.00%	1.00%
Southwest	4.12%	55.91%	114.69%	-52.72%	132.47%	-47.84%	0.00%	-0.17%
TOTAL	1.35%	10.00%	13.25%	-18.21%	20.30%	-22.36%	-13.69%	0.87%

Percent change in per-acre regional input use at $30/tCO2e with no offsets (annualized)

	Nitrogen	Phosphorous	Potassium	Diesel	Electricity	Gasoline	Natural Gas	Water
Corn Belt	2.81%	15.18%	6.12%	-6.56%	-3.84%	0.97%	1.33%	-32.78%
Great Plains	2.76%	-1.29%	46.37%	-33.02%	44.22%	-32.19%	45.60%	5.18%
Lake States	-10.31%	34.53%	15.52%	-0.77%	-48.07%	68.99%	-72.47%	-29.09%
Northeast	1.66%	114.89%	4.76%	102.25%	1.58%	99.83%	0.00%	142.26%
Pac. Northwest	0.64%	-0.07%	134.30%	-57.43%	139.08%	-58.09%	0.00%	-48.76%
Pac. Southwest	1.85%	2.52%	87.69%	-48.66%	-89.63%	863.23%	0.00%	-64.68%
Rocky Mts.	-0.34%	4.15%	39.24%	-37.94%	58.82%	-43.53%	39.05%	-47.65%
South Central	-4.95%	21.04%	-14.20%	11.60%	-27.49%	13.49%	-37.01%	-7.57%
Southeast	3.09%	38.34%	-3.88%	22.02%	-9.08%	31.47%	0.00%	-26.37%
Southwest	2.08%	55.79%	106.23%	-44.29%	97.37%	-44.95%	0.00%	-28.77%
TOTAL	0.42%	17.51%	12.32%	-8.99%	4.88%	-6.86%	-20.76%	-30.70%

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[82] Variable or scenario definitions are found in the Nomenclature section

7.2.5.3 Implications for Water Quality

As with the previous chapter, it is important to keep in mind that minor changes in regional nutrient use can significantly impact nutrient constituents in ground and surface water supplies at different rates than the overall change in nutrients applied. For instance, under the full offset case I find evidence of increased nutrient use, but subsequent pollution decreases (Table 37) at higher CO_2 prices. This is due to the regional distribution in changing crop management practices. Notice that N and P use decline substantially in the South Central (or Mississippi Delta) regions, where nutrient runoff is quite high.

However, under the limited and no eligibility scenarios, nutrient use and pollution are impacted heavily by the magnitude of the carbon price. At lower prices ($15-$30), cropland expansion under the limited eligibility regime increases pollution, but this effect is reversed completely at \$50/tCO_2e. Sources of nutrient pollution increase significantly under the no offsets case, but taper off at \$50/tCO_2e, reflecting higher input costs. This result indicates that a strong push for bioelectricity derived from AF sources could exacerbate existing water quality concerns.

Table 37: Environmental Impacts of Mitigation Scenarios (Annualized Percent Deviation from Base)[83]

	N Subsurface Loss	**NO3 Loss Runoff**	**Percolation N Loss**	**P Loss in Runoff**	**P Loss Sediment**
Full Offset ($15/tCO2e)	-0.51%	-0.57%	-2.51%	-0.52%	0.24%
Full Offset ($30/tCO2e)	-4.39%	-5.38%	-7.97%	3.21%	-18.40%
Full Offset ($50/tCO2e)	-10.56%	-13.90%	-14.14%	2.62%	-38.14%
Full Offset with CRP ($15/tCO2e)	0.60%	0.39%	-1.55%	-0.72%	1.21%
Full Offset with CRP ($30/tCO2e)	-2.88%	-4.59%	-6.28%	2.88%	-16.42%
Full Offset with CRP ($50/tCO2e)	-8.71%	-13.36%	-12.44%	1.06%	-35.15%
Lim Offset ($15/tCO2e)	11.23%	1.38%	-0.59%	2.33%	3.50%
Lim Offset ($30/tCO2e)	13.89%	-2.89%	-5.38%	8.79%	-16.53%
Lim Offset ($50/tCO2e)	-11.19%	-12.91%	-12.62%	7.52%	-34.92%
No Offset ($15/tCO2e)	47.03%	2.65%	3.85%	7.07%	7.75%
No Offset ($30/tCO2e)	45.76%	2.40%	3.87%	8.84%	6.82%
No Offset ($50/tCO2e)	30.96%	-1.93%	1.39%	8.92%	-4.03%

7.3 Conclusions

The results found here imply that:

- AF can play a significant role in the U.S. GHG abatement portfolio, but not fully pricing all forms of emissions and sequestration not only reduces mitigation potential, but it can lead to indirect environmental co-effects,
- Forest management and afforestation incentives appear necessary to achieve high domestic abatement levels
- Cropland contraction and adoption of mitigation strategies pressure commodity markets, boosting output prices and producer welfare
- Consumers would likely face higher food prices under a cap-and-trade regime, in addition to higher energy prices

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[83] Variable or scenario definitions are found in the Nomenclature section

- Higher prices and adoption of mitigation activities change long-term management strategies, reduce exports, and influence global agricultural markets (likely leading to leakage internationally) For some crops such as corn and wheat, export changes here are twice as great as those brought on by the RFS2 alone
- Depending on the scope of the mitigation policy pursued, cropland use can expand or contract; forestland will likely increase,
- Land use change is also affected by mitigation strategies; internalizing the carbon costs of land use transitions can reduce forest to cropland transitions, but boost cultivation of pasture and conservation lands. Cropland and pasture afforestation transitions are extremely valuable mitigation options, but reduced output domestically raises international leakage concerns,
- Water use declines at a national level, but mitigation efforts boost water use intensity in regions with existing water scarcity concerns,
- Other management intensity responses include increased N, P, and K applications, both in absolute and per-acre terms.

CHAPTER VIII

ASSESSING THE IMPACT OF BIOFUEL MANDATES AND OFFSET ELIGIBILITY RESTRICTIONS ON THE COSTS OF COMPREHENSIVE CAP-AND-TRADE: AN INTEGRATED MODELING APPROACH

8.1 Introduction

This chapter extends the previous mitigation results of the previous chapters to illustrate how the total costs of economy-wide GHG abatement in the U.S. under comprehensive climate legislation can be affected by biofuel mandates and offset eligibility restrictions. To understand how policy factors that limit terrestrial mitigation potential could change the full costs of GHG abatement, a reduced form emissions trading model of the U.S. economy is developed. This model combines important information from other sector-wide economic simulation models and be can be used to simulate GHG abatement, permit trading, and offset purchases under two recently proposed climate bills with unique provisions, HR 2454 or Waxman-Markey (W-M), and S 1733, or Kerry-Boxer (K-B). The following section provides some background on GHG emissions trading and the welfare effects of policies impacting offset supply or compliance obligations.

8.2 Background and Study Objectives

The following diagrams provide a conceptual basis for this modeling approach. Figure 51 displays a case in which in overall cap is placed on emissions where one emitter with a marginal abatement cost schedule (MAC) and emissions compliance obligations defined as the difference between baseline emissions and the cap. In an economy represented by one aggregate emitter, total abatement costs will be equal to the area under the marginal abatement cost curve for the full range of emissions compliance (represented by area *A*).

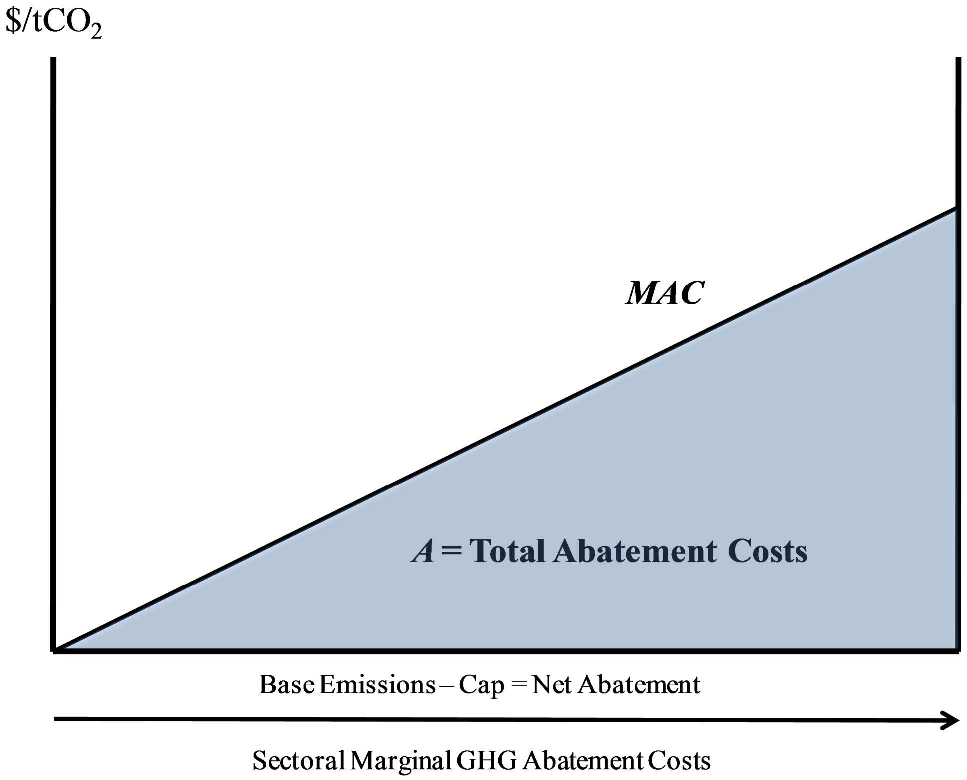

Figure 51: Abatement costs without emissions trading

Now, consider a case more consistent with comprehensive climate legislation. In the presence of a cap-and-trade system economic theory dictates that trading will commence until the marginal abatement costs of all emitters have been equilibrated. This equilibrium point represents the market price for pollution permits. The logic is similar in the case of offsets, as marginal abatement costs from the representative emitter should equilibrate to the market price for offsets (assuming no restrictions on offset provisions).

Figure 52 displays this scenario in a simple form in which there is one emitter with a marginal abatement cost curve (*MAC*), and one offset supply source (OS_1). The distance between the two vertical axes represents the total emissions reduction that must occur for the emitter to be in compliance under the cap (the difference between base emissions and the cap). In the absence of an offset market, the emitter would bear the full costs of compliance, or the entire area under the MAC curve (represented by the sum of areas *A*, *B*, and *C*). In the presence of an offsets market, the emitter has the option to purchase offset credits, thereby reducing total costs of compliance. The total costs of abatement in such a case would be the sum of the area underneath the MAC curve (*A*) and offset supply curve (*B*), respectively. This increases economic welfare by the area *C*.

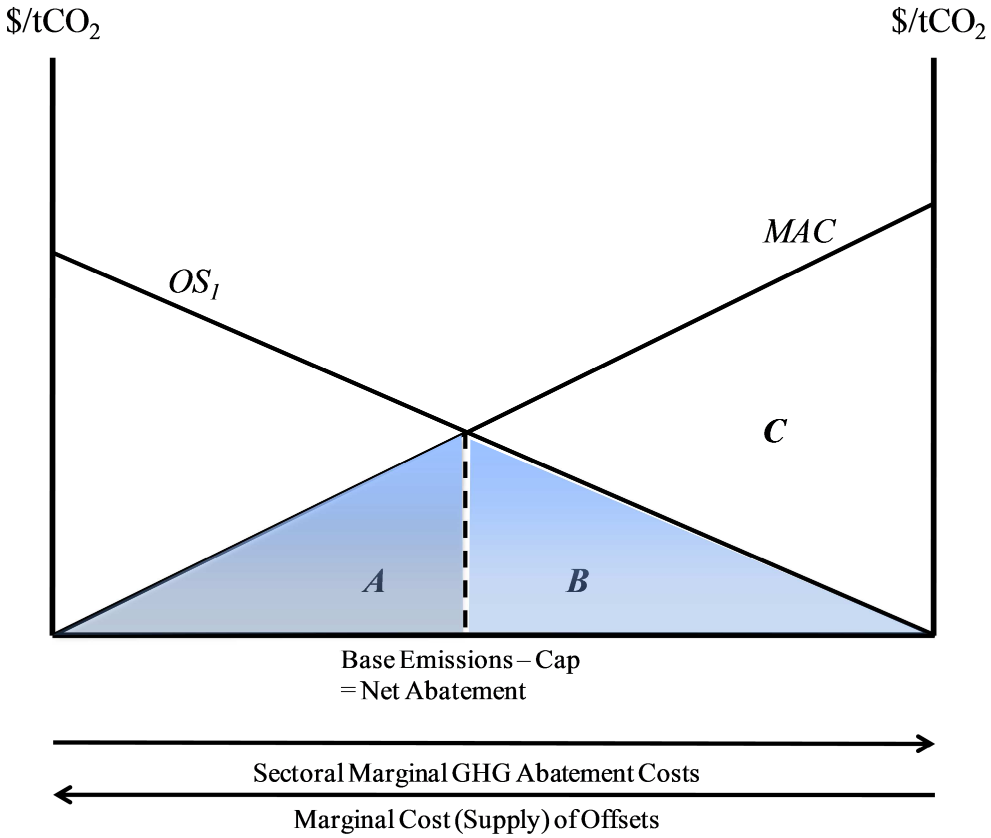

Figure 52: Equilibrium condition for allowance and offset markets

Using this framework, policy efforts that boost the marginal costs of supplying offsets will raise total mitigation costs (unless the policy simultaneously and equivalently decreases abatement costs for the emitter). As Figure 53 shows, more expensive offsets (i.e., increasing the slope of the offsets curve to OS_2) increase total abatement costs by the area C_1 relative to the prior case.

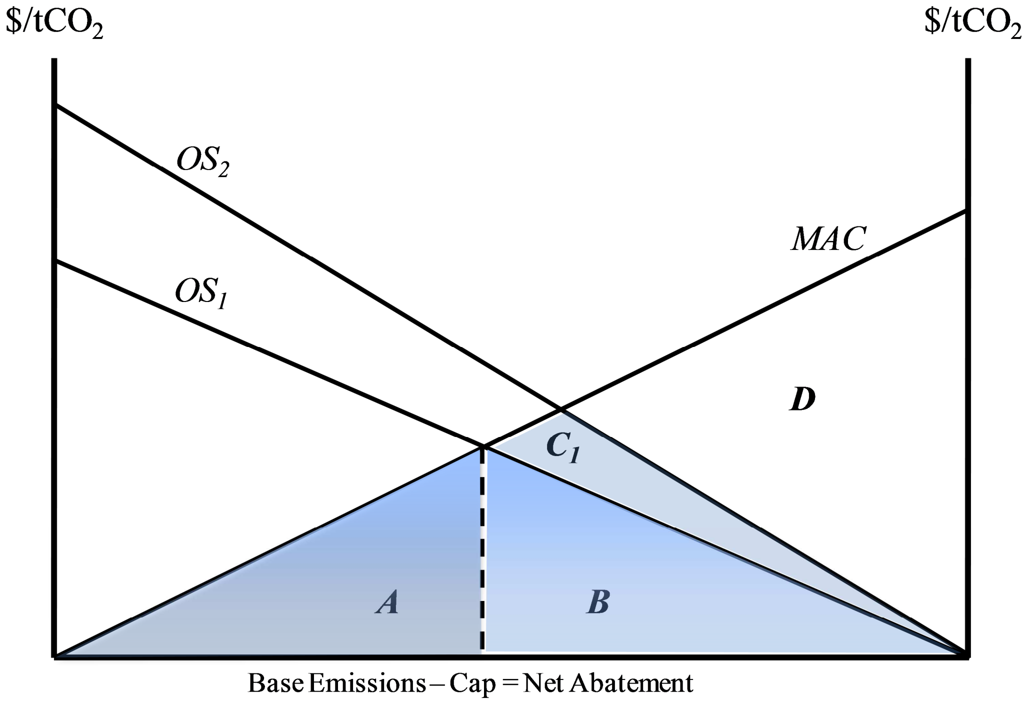

Figure 53: The effect of higher offset costs on total abatement costs

Now consider a restriction on total offset supplies, such as legislative provisions in the W-M and K-B bills that limit total offset use for compliance purposes. This scenario is illustrated by Figure 54. If the use of offsets for compliance purposes is restricted, it is possible that this introduces a price discontinuity between the offset price (*OP*) and the allowance price (*AP*). Such a restriction raises total abatement costs relative to a scenario where offsets are unrestricted as a higher portion of the mitigation portfolio will come from abatement actions taken by the emitter. Abatement costs under a "low cost" offset regime are *A*+*B*+*C*+*D*. Raising the marginal costs of offsets increases total abatement costs further (by area *E*), but notice that this relative shift in total costs is smaller when offsets are restricted than when left unrestricted. Thus, legislative provisions limiting total use of offsets for compliance can impact GHG abatement costs in addition to policy-induced shifts in the supply of offsets. However, such limits also serve as a buffer against over-reliance on offsets, which can be fraught with problems such as violations of additionality criterion.

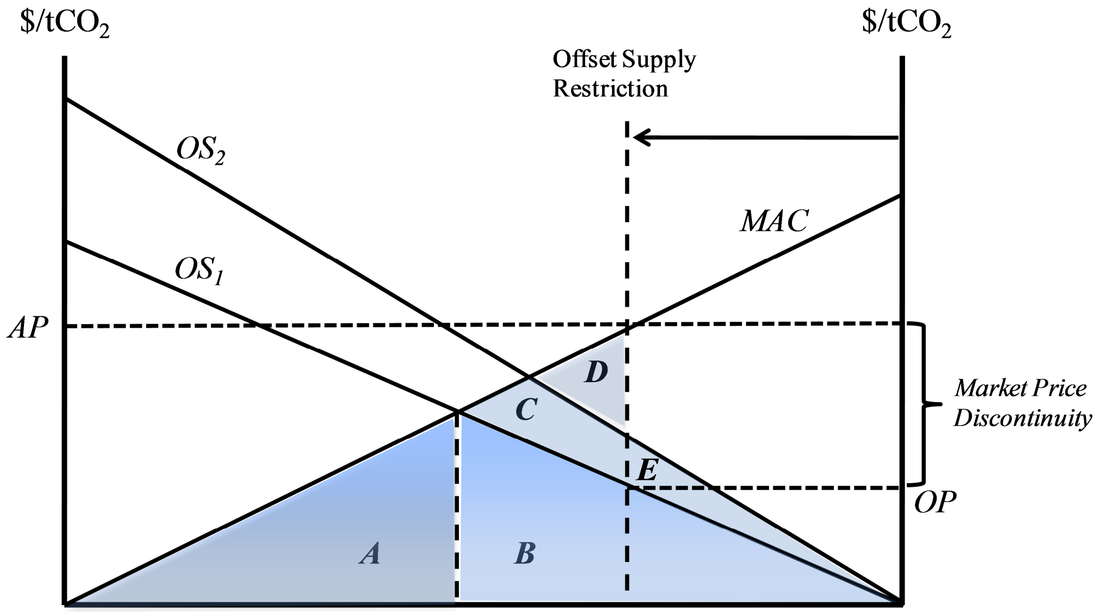

Figure 54: Restricting total offsets

Now, consider a case in which the external policy affects the marginal cost of offsets and overall compliance costs simultaneously. This dissertation has shown that biofuel expansion can increase the cost of domestic offset supplies, but the existence of such mandates should reduce emissions relative to a no policy condition. In this case, two welfare effects must be considered, 1) the offset cost impact of biofuel mandates, and 2) decreased abatement costs from lower compliance obligations for the transportation sector when biofuels are mandated (henceforth referred to as the biofuel emissions reduction effect). This scenario is illustrated by Figure 55. The top portion of the figure represents abatement costs under business as usual conditions. Notice here that compliance obligations are higher than the RFS2 scenario depicted by the bottom portion of the figure as there is no emissions reduction effect of biofuels (thus, a greater source of abatement is required in the baseline to meet the cap). With biofuel mandates (represented by the bottom figure), compliance obligations are lower as baseline emissions are reduced by the emissions reduction of biofuels. However, the marginal costs of offsets increase. Total abatement costs are reflected by $A_2 + B_2 + C_2$. Thus, one must compare areas $A_1 + B_1$ with $A_2 + B_2 + C_2$ to determine the welfare effects of a mandate when baseline emissions are adjusted by the emissions reduction of biofuels.

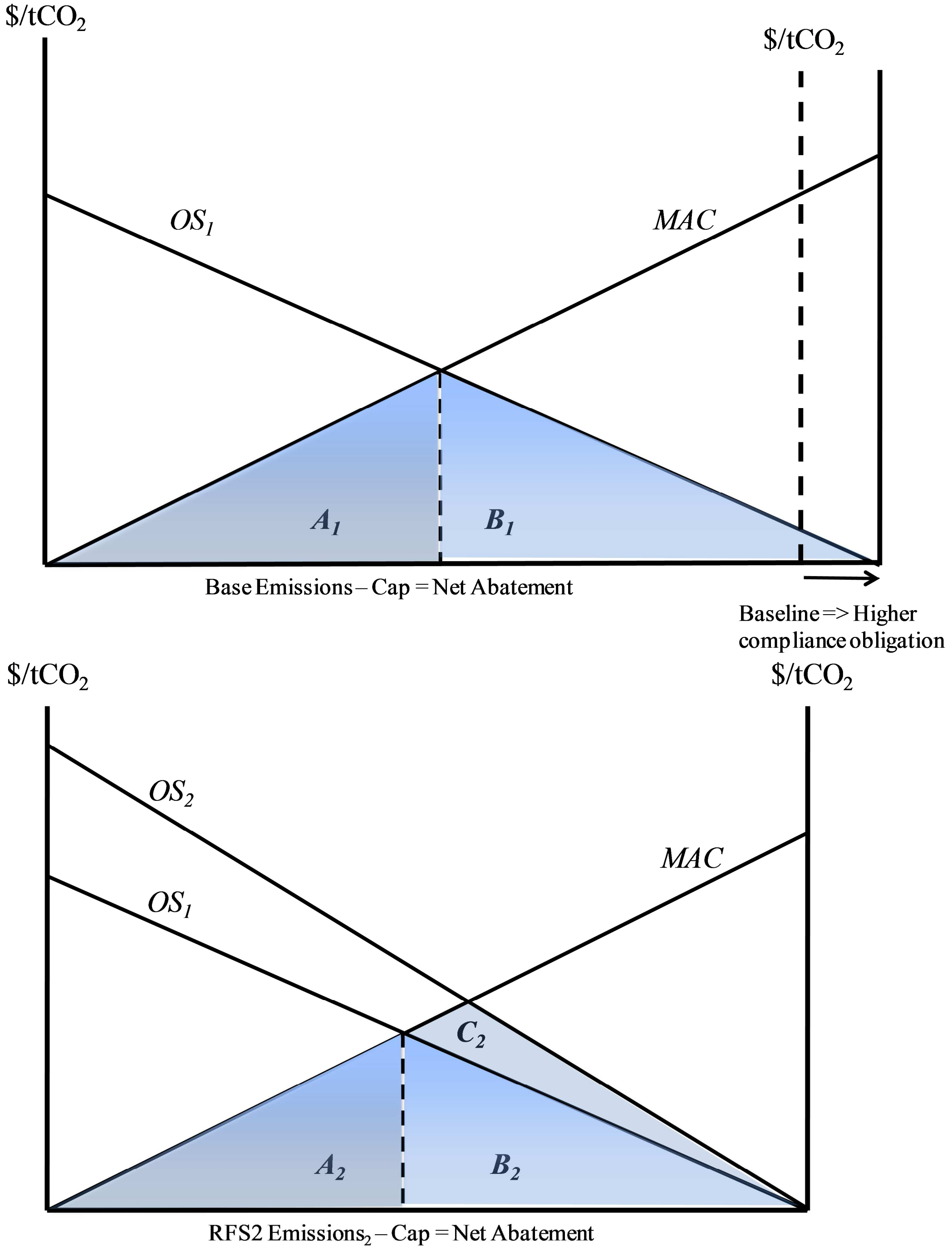

Figure 55: The abatement cost implications of a policy impacting different offset supply and total compliance obligations

8.2.1 Objectives

In this study I directly measure the impact of biofuel mandates or offset eligibility restrictions on the compliance costs of cap-and-trade legislation using a reduced form model of GHG mitigation in the U.S. economy. The problem with concentrating solely on the implications of biofuel policies on natural resource systems and markets is it ignores the economic welfare implications such policies present in other markets and/or sectors of the economy. For example, there is an emerging literature that discusses the welfare effects of various biofuel expansion policies on fossil energy markets and overall fossil fuel consumption (de Gorter and Just, 2009). However, FASOMGHG cannot isolate any of these welfare impacts as it is a partial equilibrium model with no energy sector representation. Other partial equilibrium models offer a very detailed look at the energy and transportation sectors (such as the National Energy Modeling System, or NEMS), but fail to provide a general equilibrium view and do not explicitly account for external mitigation from offsets. Furthermore, models such as FASOMGHG and NEMS usually require some exogenous policy input variable to simulate abatement responses to carbon price incentives (thus, allowance prices are not solved for endogenously).

Computable general equilibrium models can avoid this shortcoming by capturing welfare effects of policies that crossover multiple sectors of the economy (EPA, 2010b; EPA, 2009). In a climate mitigation context, such models can solve for sectoral abatement and implied allowance prices endogenously once an economy-wide cap on emissions has been imposed. However, these models do not contain the level of sectoral specificity and abatement options represented in partial equilibrium models, and generally do not fully capture resource consumption and investment decisions.

This study attempts to bridge this modeling gap by incorporating the most recent data available on mitigation opportunities in fossil-fuel intensive economic sectors and offset availability in agriculture and forestry into a reduced form model of the U.S. economy that simulates emissions trading. Specifically, I use the Duke University Emissions Trading Model (DUET) to simulate emissions trading using sectoral abatement costs and offset supply information supplied by the Nicholas Institute version of NEMS (NI-NEMS) and FASOMGHG model, respectively. This study is a unique attempt to isolate the effects of biofuel policies and offset market restrictions on the costs of GHG abatement within the U.S.

8.3 **Duet Model Overview**

DUET is fully dynamic and can simulate economy-wide GHG emissions trading in the U.S. under alternative cap-and-trade schemes by allowing flexibility in different legislative provisions such as cap stringency, offset provisions, or sectoral inclusion/exclusion from the cap. DUET minimizes the total costs of economy-wide abatement inter-temporally by allowing pure mitigation (emissions reduction), emissions permit trading between capped sectors, and the purchase of offset credits from domestic and international sources. In addition, DUET allows for banking and borrowing of emissions permits. Consistent with legislative provisions, entities can bank emissions permits (credits) indefinitely, and can borrow from future compliance periods (though these must be paid back at a premium at a later date). As the model operates in a discrete-time optimal control fashion, the stock of banked credits that can be used for compliance and baseline emissions from each sector are treated as state variables. Allowing banking and borrowing gives the model a solution in which equilibrated permit prices rise at the internal rate of discount (in this case, 5%).

8.3.1 DUET Mathematical Structure

Use of MAC curves to simulate emissions trading patterns across comprehensive cap-and-trade policies has been prominent in the economics literature (Atkinson and Tietenberg, 1991; Boehringer et al., 2004; Rose et al. 1998; Rose and Zhang, 2004; Stevens and Rose, 2002). DUET follows a similar conceptual structure as other existing models used to simulate emissions trading through the use of exogenously determined marginal abatement cost curve parameters. Ellerman and Decaux use country-specific MAC curves derived from the MIT-EPPA model to simulate emissions trading in a post-Kyoto Protocol environmental under a number of different policy assumptions (including an all-inclusive global trading scheme compared to trading among OECD or Annex B countries only). Boehringer et al., 2004 develop a static emissions-trading model used in the European Union, also with country-specific MAC curves.

DUET's inclusion of banking and borrowing possibilities mirror the dynamic structure of the emissions trading model presented by Rubin, 1996, an optimal control model developed to illustrate the effectiveness of banking and borrowing provisions at reducing compliance costs of a cap-and-trade system, as well as lowering social damages of a pollutant[84]. Other analyses have employed dynamic emissions trading models with country-specific MACs to address international climate mitigation potential under alternative post-Kyoto scenarios (Brandt and Rose, 2002; Rose and Zhang, 2004). This study employs a similar empirical approach at a national level to address the costs of U.S. mitigation under alternative policy and market futures.

The DUET model has a flexible mathematical structure that allows for emissions trading over some time interval *t*, between different sectors of the economy (*j*), and offsets are supplied to the market from multiple sources (*k*). Currently, the *j* capped sectors of the economy include residential, commercial, industrial, petroleum refining, and transportation. This sectoral disaggregation includes all major sectors that would fall under recent climate mitigation proposals, and which are the sources of the overwhelming majority of anthropogenic GHG emissions in the U.S. NI-NEMS has a detailed representation of fossil energy consumption in these sectors, and explicitly accounts for emissions from those activities.

Offset supply sources currently include domestic (U.S.) and international to be consistent with legislative provisions restricting the total use of offsets for compliance purposes. Offsets include those from AF and non-AF activities. Each offset source (domestic and international) has a separate supply function that depicts the marginal cost and legislative provision (restriction) of each source.

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[84] DUET operates in discrete time, while analytical model operates in continuous time.

Several parameters are included in DUET to depict different conditions that vary with specific climate legislation provisions or external policies impacting the marginal costs of offsets (such as biofuel expansion or offset eligibility restrictions). Emissions from biofuels are accounted for explicitly in the transportation sector baseline, consistent with EIA projections. Important parameters in DUET include:

1. **CAP_t** = Aggregate emissions cap for the entire U.S.
2. CAP projections come from EPA estimates, and can vary from bill-to-bill
3. **$Base\_Emit_{jt}$** = Baseline (projected) emissions by sector and over time
4. Emissions projections come from the U.S. Energy Information Administration (EIA, 2009)
5. **$Target_{jt}$** = This is an arbitrary initial allowance endowment used to initiate trading and sectoral abatement decisions. This distributes the emissions cap evenly across all sectors of the economy based on each sectors proportion of total baseline emissions.
6. **$Off\_available_{kt}$** = Sets a limit on the number of offset credits that can be purchased from each offset source (domestic, international).
7. These values are set exogenously to mimic offset provisions in legislation (e.g. HR 2454 allows for 50-50 split between domestic and international offsets with a 2 billion tonne CO_2 limit annually, Kerry-Boxer is 75:25 domestic:international split, with the same total cap on offsets)

8. α_j = Marginal abatement cost curve parameters consistent with the estimated abatement portfolio of each sector. MAC cuves can take a variety of functional forms. DUET has options for linear, logarithmic, and polynomial MAC functions.
9. β_k = Offset supply parameters
10. φ = Premium placed on emissions borrowed from future compliance periods.
11. In HR 2454 W-M, this is 8% for permits borrowed in years 2-5 (no premium for year one)
12. ***r*** = Discount rate (5%)

DUET operates in an optimal control fashion, and includes state variables that evolve dynamically according to chosen abatement activities (including the emissions "bank" as described below). Endogenous variables in DUET include:

1. $\boldsymbol{Abate_{jt}}$ = Efficient level of abatement, or pure emissions reduction in time period *t* for each sector.
2. $\boldsymbol{Permit\_sell_{jt}}$ = Emissions permits sold by the j^{th} sector for compliance in another sector. The variable transfers the right to emit from one sector to another.
3. $\boldsymbol{Permit\_use_{jt}}$ = Emissions permits bought by the j^{th} sector and used for compliance purposes in time *t.*
4. $\boldsymbol{Permit\_bank_{jt}}$ = Emissions permits bought by the j^{th} sector and banked for compliance purposes in later time periods.

5. ***SR_borrow*$_{jt}$** = Emissions permits borrowed from short run periods for compliance purposes in period *t* (in Waxman-Markey and Kerry-Boxer, emitters can borrow one year into the future without paying a premium for borrowed allowances in the following year). Borrowed emissions permits must be paid back in the future compliance period from which the emitter borrowed. So, in the case of short run borrowing, the emitter faces a baseline emissions profile that includes borrowed permits from period t-1 in addition to baseline compliance obligations.
6. ***LR_borrow*$_{jt}$** = Permits borrowed from long run periods (in W-M case, these are permits borrowed in periods $t+2, \ldots, 5$). There is an 8% premium for borrowing these permits—1 permit borrowed for use in time *t* reduces availability of 1.08 permits in the future compliance period from which the permit was borrowed). Thus, this is a compliance transaction where "interest" is paid in credits.
7. ***Offset_use*$_{jt}$** = Offsets bought by the j^{th} sector and used for compliance purposes in time *t*.
8. ***Offset_bank*$_{jt}$** = Offsets bought by the j^{th} sector and banked for compliance purposes in later time periods.
9. ***Bank_use*$_{jt}$** = Permits or offsets bought and banked in previous time periods (t = t-M , . . . , t) used for compliance purposes in time period t
10. ***Bank_Stock*$_{jt}$** = Sets aside permits or offset credits to be used at a later date. This stock changes over time.
11. ***Offset_sell*$_{kt}$** = Offsets sold by the k^{th} source in time period *t*

12. ***MAC_{ijt}*** = Marginal abatement cost in period t for the ij^{th} sector

13. ***$Offset\_P_{kt}$*** = Offset price by source for time period t

14. ***$Permit\_P_t$*** = Market-Clearing emissions permit price at time t (in $/tCO$_2$)

The following algebraic structure solves for market-clearing conditions in DUET:

- **Emissions for Compliance Obligation**: Equates baseline emissions plus any additional compliance obligations due to short or long-term borrowing. Here, baseline emissions are exogenous parameters, but total emissions for compliance obligations (Cap – Emissions) evolve according to the amount of emissions permits borrowed (short or long run). Thus, emissions reductions occur relative to a revolving baseline that is a function of borrowing decisions over the time horizon.

(Equation 28) $$Total\_Compliance_t = \sum_{j=1}^{J} \left[\begin{array}{l} Base\_emit_{jt} + SR\_borrow_{j(t-1)} \\ + \left(\sum_{\bar{t}=t-5}^{t-2} LR\_borrow_{jt} (1.08)^{\bar{t}} \right) \end{array} \right] \quad \forall t$$

- **Permit Balance:** Balances permits purchased in time t with permits sold, ensuring no excess supply or demand of tradable emissions permits on the market in all time periods (Walrasian equilibrium)

(Equation 29) $$\sum_{j=1}^{J} \left(Permit\_use_{jt} + Permit\_bank_{jt} \right) = \sum_{j=1}^{J} Permit\_sell_{jt} \quad \forall t$$

- **Offset Balance:** Balances Offsets purchased with those sold in time *t*.

(Equation 30)

$$\sum_{j=1}^{J}\left(Offset\_use_{jt} + Offset\_bank_{jt}\right) = \sum_{k=1}^{K} Offset\_sell_{kt} \quad \forall t$$

- **Abatement Function:** Determines the efficient level of abatement for the j^{th} sector using a parametric representation of marginal abatement costs. This expression says that at a particular level of abatement for the j^{th} sector, the corresponding marginal abatement cost (equivalent to the allowance price) would be MAC_{jt}.

(Equation 31)

$$MAC_{jt} = \alpha_j Abate_{jt} \quad \forall j,t$$

- **Offset Price Function:** Similar to the previous equation, this Here, we use a general parametric function describing the supply of offsets that would be available at price $Offset\_P_{kt}$

(Equation 32)

$$Offset\_P_{kt} = \beta_k Offset\_sell_{kt}$$

- **Offset Price Discontinuity:** As domestic and international offset sources are subject to legislative provisions, it is possible that the supply of one of the two offset source could be exhausted in this modeling framework. To handle this discontinuity, I add an arbitrary variable restricted to the positive domain that allows the domestic offset price to continue to grow even after the allowable supply of cheapest source of offsets has been consumed:

(Equation 33) $$Offset\_P_{"Domestic"t} = Offset\_P_{"International"t} + \lambda_{1t}$$

- **Permit Price Function:** This equation denotes a market-clearing permit price that is equilibrates marginal abatement costs and offset prices across all sectors/sources (*Permit_P*$_t$). To account for the possibility that emitters exhaust the total source of offsets as stipulated by policy, another arbitrary variable is included here to deal with this potential discontinuity in prices between offset and emissions permit markets.

(Equation 34) $$MAC_{ijt} = Offset\_P_{kt} + \lambda_{2t} = Permit\_P_t$$

- **Max Offsets :** Sets a limit on offset sales by source to be consistent with legislative restrictions.

(Equation 35) $$Offset\_sell_{kt} \leq Off\_available_{kt} \quad \forall k, t$$

- **Bank Stock Equation:** Here, the stock of permits banked by capped sectors is treated as a state variable. As each sector can bank permits or offsets purchased in any given *t* and store them indefinitely, this equation illustrates the dynamics of permit "banking". Beginning with the previous period's (*t-1*) stock of banked emissions permits, the rate of change in stocked permits is equal to the amount of permits coming in, less those that are consumed for compliance purposes in time period *t*.

$$Bank\_stock_{jt} = \begin{bmatrix} Bank\_stock_{j(t-1)} - Bank\_use_{jt} \\ +Permit\_bank_{jt} + Offset\_bank_{jt} \end{bmatrix} \quad \forall j,t$$

(Equation 36)

- **Net Emissions Balance:** This summarizes all abatement and permit/market offset activities. For borrowing, I sum over all long-run borrowing in the preceding 5-2 years, and divide by 4, which is a more tractable programming approach than trying to assign long-term borrowing to specific years.

(Equation 37)

$$Net\_emit_{jt} = \begin{bmatrix} Base\_emit_{jt} \\ -Abate_{jt} \\ -Permit\_use_{jt} - Offset\_use_{jt} - Bank\_use_{jt} \\ -SR\_borrow_{jt} - LR\_borrow_{jt} \\ +SR\_borrow_{j(t-1)} + \left(\sum_{\bar{t}=t-5}^{t-2} LR\_borrow_{jt} (1.08)^{-\bar{t}} \right) \\ +Permit\_sell_{jt} \end{bmatrix}$$

- **Emissions Cap Balance:** This equation ensures that the economy-wide cap on emissions binds. Thus, net emissions across all sectors are equal to the cap (net emissions includes all deviations from the baseline—including abatement, offsets, and permits, banked or borrowed).

$$\sum_{j=1}^{J} Net\_emit_{jt} \leq Cap_t \quad \forall t$$

(Equation 38)

- **Objective Function:** Minimize the net present costs of abatement:

(Equation 39)

$$\min\left(Total\_Cost\right)=\sum_{t=0}^{T}\left[\begin{array}{l}\displaystyle\sum_{j=1}^{J}\int_{0}^{Abate_{ijt}^{*}}\left(\alpha_{j}Abate_{jt}\right)dAbate_{jt}\\ \displaystyle\sum_{k=1}^{K}\int_{0}^{Offset\_sell_{kt}^{*}}\left(\beta_{k}Offset\_sell_{kt}\right)dOffset\_sell_{kt}\end{array}\right](1+r)^{-t}$$

8.3.2 Data and Development

The DUET model uses explicit information on projected emissions for multiple sectors of the economy that are consistent with Energy Information Administration projections and projected emissions caps provided by proposed legislation. Since NI-NEMS can only simulate time horizons ending in 2030, projected emissions were extrapolated beyond using the average percentage change in emissions by sector projected between 2012 and 2030. Figure 56 displays the projected emissions (for all capped sectors in the U.S.) over time, relative to the caps imposed by W-M and K-B. The difference between projected and capped emissions in 2050 represents a shift of approximately 6 Gigatons of CO_2, more than an 80% reduction in total projected emissions.

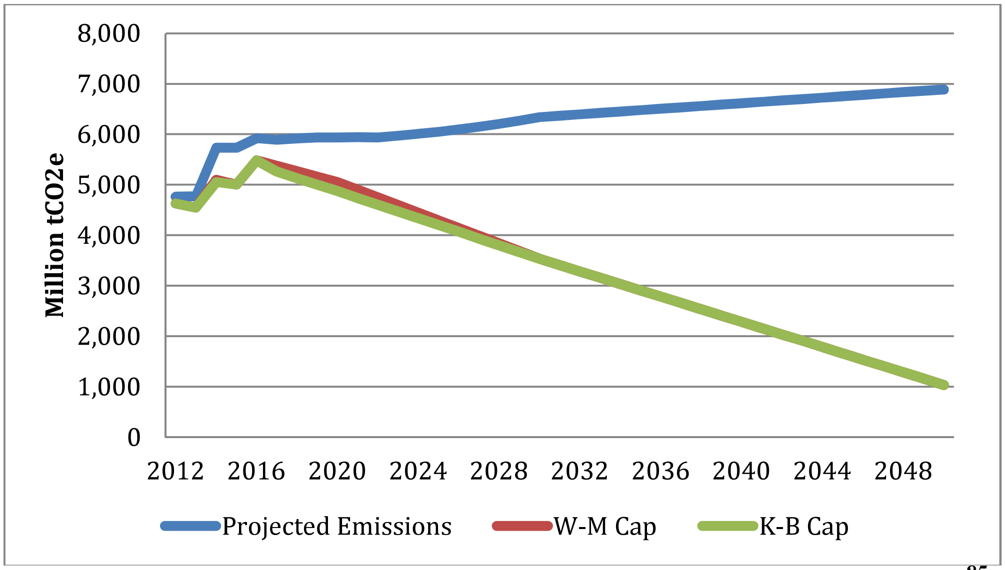

Figure 56: Net emissions projections relative to the W-M and K-B caps[85]

To derive marginal abatement cost curve (MAC) parameters for each sector, the following steps were taken:

1) NI-NEMS was used to assess mitigation in the residential, commercial, industrial, and transportation sectors in response to a carbon price signal[86]. Mitigation in NEMS includes energy switching, adoption of renewable energy, direct reductions in energy consumption, technology switching in power generation, and retrofitting of power plants for carbon capture and storage adoption. Seven different mitigation scenarios were run through NEMS to provide a comprehensive assessment of mitigation potential at various points in time for different magnitudes of the CO_2 price (initial CO_2

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[85] Variable or scenario definitions are found in the Nomenclature section

[86] NEMS is a widely applied model in energy policy. For more information, please refer to: http://www.eia.doe.gov/oiaf/aeo/overview/

prices were varied arbitrarily from \$5-\$36/tCO_2). Prices were imposed beginning in 2012, rising at 5%. This provides a comprehensive range of CO2 prices consistent with recent climate policy analyses.

2) Total mitigation potential for the U.S. was disaggregated into the economic sectors mentioned previously.
3) The difference in baseline (projected) emissions and computed emissions across simulations were captured for each scenario and sector to match total abatement with each exogenous CO_2 price point.
4) Marginal abatement cost curves parameters were derived by regressing the CO2 price on total sectoral abatement. Several functional forms were tested, as were time trends. For simplicity and consistency across sectors I use linear MAC curve specifications, with the intercept set to the origin. Parameters are listed in Table 38:

Table 38: Linear MAC Parameters Estimated Using NEMS (EIA, 2009)[87]

	Linear MAC Coefficient
Transportation	0.7899
Residential	0.1528
Commercial	0.1405
Industrial	0.2667
Refining	1.1544

**Dependent variable = Price (\$/tCO_2e)*
**Explanatory variable = Abatement quantity (Million tCO_2e)*

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[87] Variable or scenario definitions are found in the Nomenclature section

Data points used to estimate MAC parameters are displayed by Figure 57. The highest marginal costs of abatement are found in the refining and transportation sectors (which includes emissions from residential vehicle use), due to the amount of fossil energy consumed in these sectors and the high costs of infrastructure improvement required to achieve meaningful emissions reductions. Industrial processes also face relatively steep abatement costs. Residential and commercial entities have the lowest abatement costs as significant emissions reductions are often possible with low-cost (or cost-saving) improvements in energy efficiency. To achieve an efficient level of abatement, high cost emitters in the refining and transportation sectors could purchase emissions credits from the low-cost emitters, essentially subsidizing emissions reductions or efficiency improvements in those sectors.

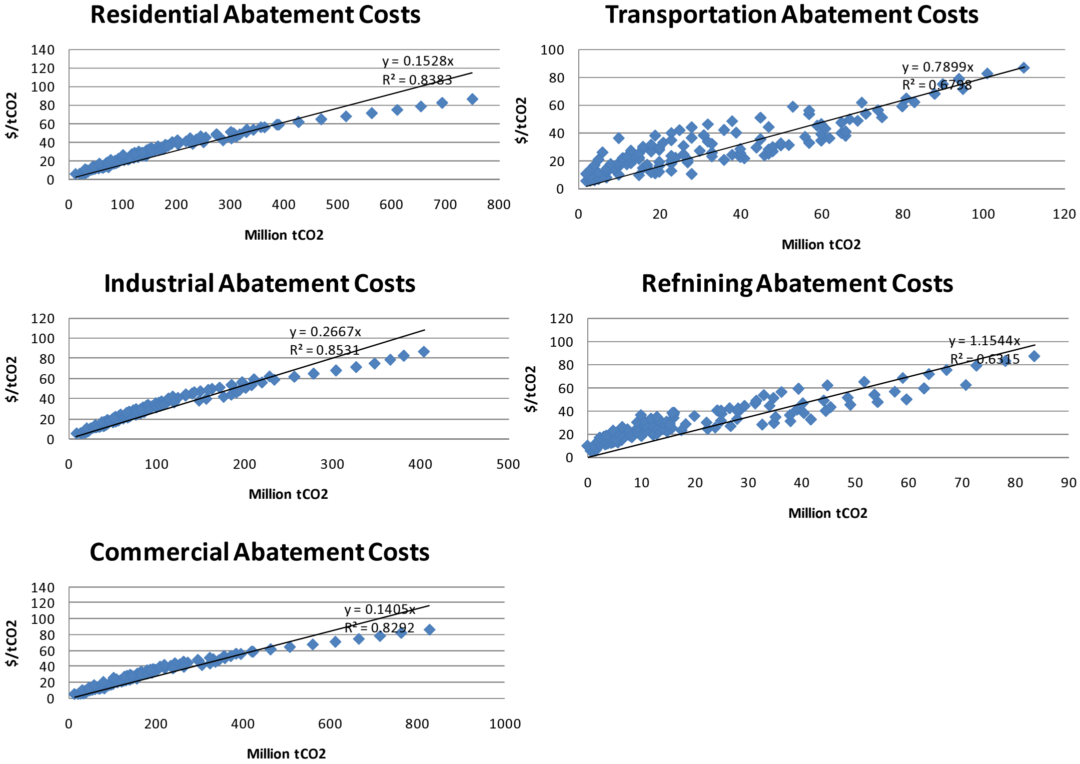

Figure 57: DUET marginal abatement cost curves by sector[88]

A similar approach was taken to develop domestic offset supply curves. I use mitigation results derived directly from a set of runs evaluated in previous chapters (Full offset eligibility with the RFS2, and Limited offset eligibility with the RFS2), plus a specialized set of mitigation runs without the influence of the RFS2 to develop offset supply curves from US AF. The mitigation potentials from offset activities only (excluding emissions reductions from bioelectricity and reduced fossil fuel use) are summarized in Table 39. Notice that the existence of the RFS2 reduces total GHG offset potential by more than 20% at $15 and $30/tCO$_2$e and by approximately 8% at

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[88] Variable or scenario definitions are found in the Nomenclature section

\$50/tCO$_2$e. This is a significant loss in GHG abatement, and illustrates an external cost on the GHG market from an exogenous policy factor brought on by biofuel mandates. That is, when mandatory biofuel expansion is enacted with a comprehensive offset market, it consumes resources that could ultimately be used for mitigation (offset) purposes, which raises the costs supplying offsets. Restricting offset eligibility on top of the RFS2 decreases mitigation potential and raises the costs of offsets further. The implication is that not including forestry offsets (among others) into the allowable abatement portfolio reduces mitigation potential by more than 50% in the low CO$_2$ price range.

Table 39: Total Mitigation Potential from Offsets by Scenario (Million tCO2e Annuity)[89]

	\$15/tCO2e	**\$30/tCO2e**	**\$50/tCO2e**
Full Offset Eligibility (without the RFS2)	376.26	617.80	742.24
Full Offset Eligibility (with the RFS2)	300.07	483.86	683.34
(% difference)	*-20.25%*	*-21.68%*	*-7.94%*
Limited Offset Eligibility (with the RFS2)	148.79	272.92	419.38
(% difference)	*-60.46%*	*-55.82%*	*-43.50%*

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[89] Variable or scenario definitions are found in the Nomenclature section

In addition to AF, there is potential for domestic offsets generated from activities such as reduced methane form landfills, petroleum, and natural gas operations. The US-EPA as documented the potential of such offset sources and the marginal costs of each. I include the supply of other non-AF offsets into the general offset supply function for a comprehensive accounting of domestic offsets. From \$5-\$50, the supply of non-AF offsets ranges 69-119 million tCO_2e $year^{-1}$. Non-AF offset supplies are added to the FASOMGHG generated supply curves for AF offsets to expand the scope of domestic offsets. To generate AF offset supplies at \$5/tCO2e, I multiply the estimated \$15 level by 0.33.

Offset supply for U.S. AF are generated for the three aforementioned scenarios by regressing price on annualized mitigation potential. Curves are plotted through the origin. The estimated parameter is incorporated into DUET to represent the marginal cost of supplying domestic agricultural and forestry offsets across the three mitigation scenarios simulated Figure 58.

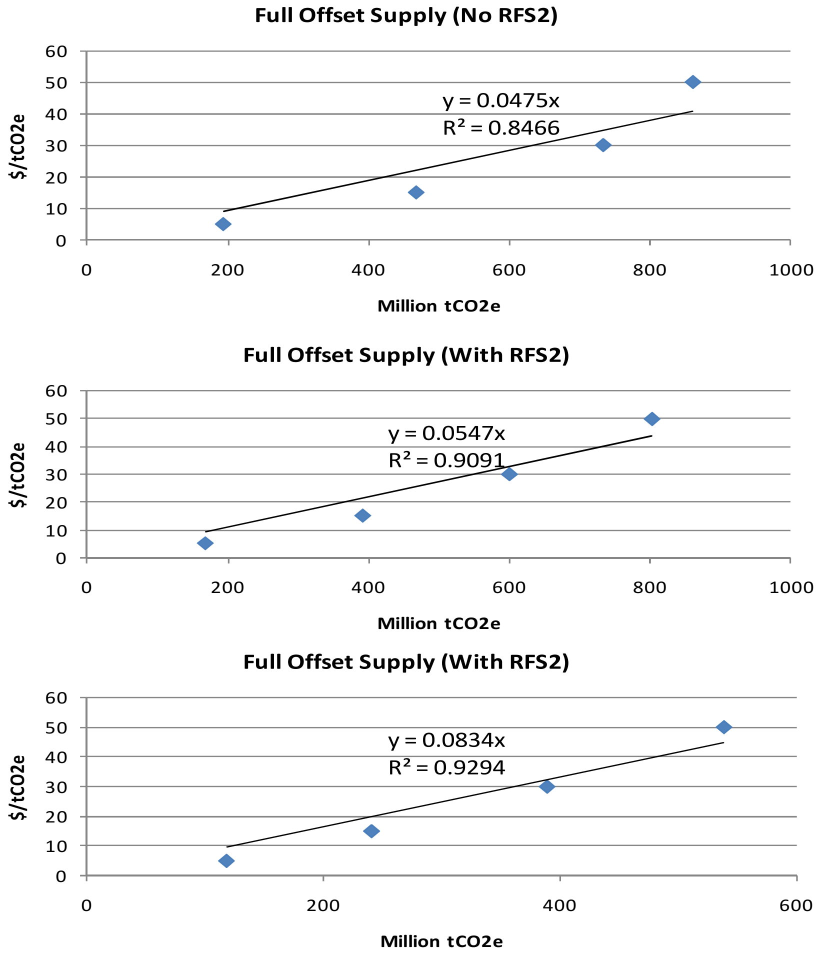

Figure 58: Offset supply curves across FASOMGHG mitigation scenarios evaluated[90]

For international offsets, I use data compiled by the US-EPA through personal communication (Alan Fawcett, personal communication, 2010; US-EPA, 2006). Similar data on international offsets are used in EPA analyses on the economics of climate change mitigation policies (EPA, 2009). The data are compiled by EPA from several independent modeling efforts using similar modeling techniques at various scales to

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[90] Variable or scenario definitions are found in the Nomenclature section

develop marginal abatement cost curve estimates at international scales. The bulk of international offsets come from changes in forestry practices (namely, avoided tropical deforestation). Notice that the sheer abundance of international offsets available implies extremely low marginal abatement costs (Figure 59). In general, the computed international offset supply parameter implies a source of offsets that more than 90% less expensive on the margin than domestic offsets.

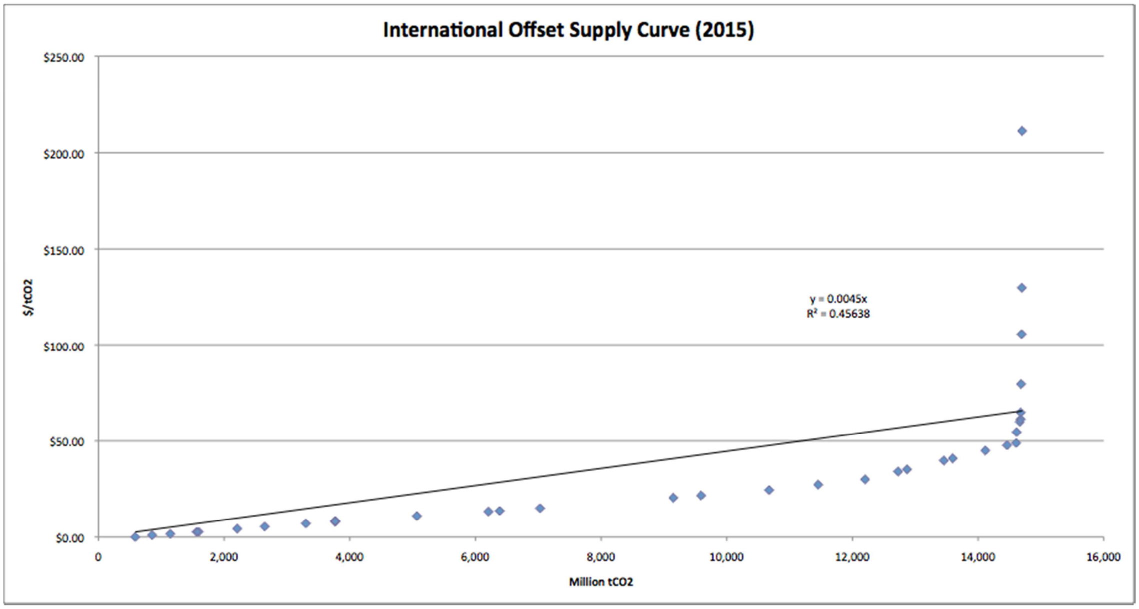

Figure 59: International offset supply and DUET parameter (Source: EPA, 2010)

8.3.2.1 Scenarios Tested

A number of factors can influence total abatement costs in a model like DUET, including MAC and offset supply function parameters, the stringency of the overall cap, assumptions about baseline emissions, and policy regulations regarding offsets. The following scenarios provide a general look at the sensitivity of full-economy abatement costs to a comprehensive range of possible policy outcomes.

8.3.2.1.1 Offset and Biofuel Scenarios

This test for the influence of the RFS2 and offset eligibility restrictions on overall mitigation costs. The base case represents full offset eligibility with no RFS2 mandates. Instead, biofuel projections consistent with the previous energy bill (RFS1) are imposed on the model at rates consistent with those discussed in the previous chapters. Then, the RFS2 mandates are imposed (also at rates discussed in previous chapters). Finally, I restrict offset eligibility, limiting forest management and non-CO2 offsets in agriculture, consistent with scenarios applied in the previous chapter.

8.3.2.1.2 Climate Policy Scenarios

Cap projections, the phasing in of certain sectors into the cap, and offset provisions are modeled in accordance with two recent climate bills—H.R. 2454 (Waxman-Markey, or W-M) and an alternative (but similar) bill proposed in the Senate in the Fall of 2009 by Senators Kerry and Boxer (referred to as Kerry-Boxer, or K-B). Major differences include the level of the cap in early periods of the bill, and most important to this analysis, domestic and international offset provisions. Both W-M and K-B allot a total of 2 billion t CO_2 of offsets to be purchased for compliance purposes by capped entities, but the ratio of domestic to international in W-M (1:1) is less than in K-B (3:1). Thus, international offset provisions are not allowed to exceed 500 million tCO_2 in K-B. As international offsets are expected to be less expensive than domestic following estimates in the literature, reducing international offset potential would increase the cost of offsets and overall compliance costs.

8.3.2.1.3 Emissions Adjustment Scenarios

Since biofuels present a reduced carbon fuel alternative to fossil transportation fuels, it is important to account for the emissions displaced by biofuel consumption in the transportation sector under the RFS2. However, there is some ambiguity as to how transportation fuel consumption and emissions would evolve under an RFS2 regime—recent evidence points out that such mandates can increase fossil energy consumption and emissions (de Gorter and Just, 2009). With this in mind, I present three cases for transportation emissions in the baseline, 1) unadjusted emissions consistent with EIA projections, and 2) adjusted emissions where the net biofuel emissions reduction of transportation fuels under the RFS2 is deducted from transportation sector emissions, and 3) adjusted emissions with 50% leakage from increased fuel consumption.

This effectively raises emissions in the baseline to reflect a case where RFS2 mandated biofuels are replaced with fossil fuel equivalents on a one-one basis (thus raising baseline emissions for the transportation sector). Increasing baseline emissions in transportation will add to the full compliance obligations of the sector (and economy), thus increasing the total costs of abatement. Emissions reduction thresholds for biofuels as stipulated by the RFS2 (20% for corn ethanol, 40% for biodiesel, and 60% for cellulosic ethanol) are applied. I compute the difference in biofuel production by fuel type between the RFS2 and AEO baseline cases (generated by FASOMGHG), then multiply this fuel volume by the aforementioned GHG thresholds, and the per gallon

CO_2 equivalence of gasoline and diesel (0.0089 and 0.0099, respectively). The total emissions difference is then added to the transportation sector baseline, reflecting a case where baseline emissions are greater without the RFS2. The net difference adds approximately 3% to baseline transportation emissions over the long-term.

The second adjusted emissions scenario considers 50% leakage in transportation emissions. That is, I consider a case where 50% of the emissions displaced by biofuels are outweighed by emissions gains from increased transportation fuel consumption (a case illustrating another potential leakage effect of biofuel policies, whereby stringent renewable fuels mandates increase net fuel consumption and hence emissions).

8.4 **Results and Discussion**

First, consider CO2 price paths under two example simulations. Under W-M conditions, estimated CO2 price points begin in the range of \$14.91-\$19.28 per tCO2 (Table 40). This is similar to EPA's analysis of the W-M Bill, which produced allowance price points ranging\$13-\$17 per tCO2 in 2015 (EPA, 2009). Results also compare favorably to the EIA analysis of HR 2454, which ran multiple sensitivity analyses around the W-M cap (EIA, 2009). Using the NEMS model, the EIA analysis estimated an initial allowance price of \$17.93[91]. The difference in my estimates is due to assumptions regarding in technological advancement and abatement costs for capped entities between the NI-NEMS model and general equilibrium models applied by the EPA for climate mitigation analysis (ADAGE and IGEM). When emissions are adjusted

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[91] Allowance prices rise at a rapid rate of 7.4% in the EIA analysis due to a high discount rate in NEMS.

in the transportation sector, however, initial price points in the absence of the RFS2 increase to \$16-\$20.29/tCO_2. The 50% leakage case results in a initial CO2 price that is very similar to the RFS2 unadjusted case under W-M, meaning that a leakage effect that reduces biofuel emissions reduction by 50% has roughly the same impact on equilibrium allowance prices as the increased costs of offsets brought on by the RFS2.

For the K-B bill, initial price points are 30-33.4% higher than under W-M, due to more stringent cap requirements in early periods, and reduced international offset provisions. Holding baseline transportation emissions constant, the RFS2 increases the initial CO_2 price point relative to the base by ~4-5%. Allowance prices in all scenarios rise at the internal discount rate of 5% as banking and borrowing of emissions credits are allowed; this is typical Hotelling behavior found in dynamic models. Under exponential price increases, minor differences in initial CO_2 price points can create large differences in total mitigation costs as the price wedge between scenarios increases over time, as indicated by Figure 60.

Table 40: Estimated Allowance Prices for the Initial Time Period ($/tCO2e)[92]

	W-M Initial Allowance Price ($/tCO$_2$e)	K-B Initial Allowance Price ($/tCO$_2$e)
No RFS2 (Full Offset Eligibility)	14.91	19.28
No RFS2 (Full Offset Eligibility with Adjusted Transportation Emissions)	16.00	20.29
No RFS2 (Full Offset Eligibility with 50% Adjusted Transportation Emissions)	15.45	19.78
With RFS2 (Full Offset Eligibility)	15.56	20.24
With RFS2 (Limited Offset Eligibility)	17.63	20.30

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[92] Variable or scenario definitions are found in the Nomenclature section

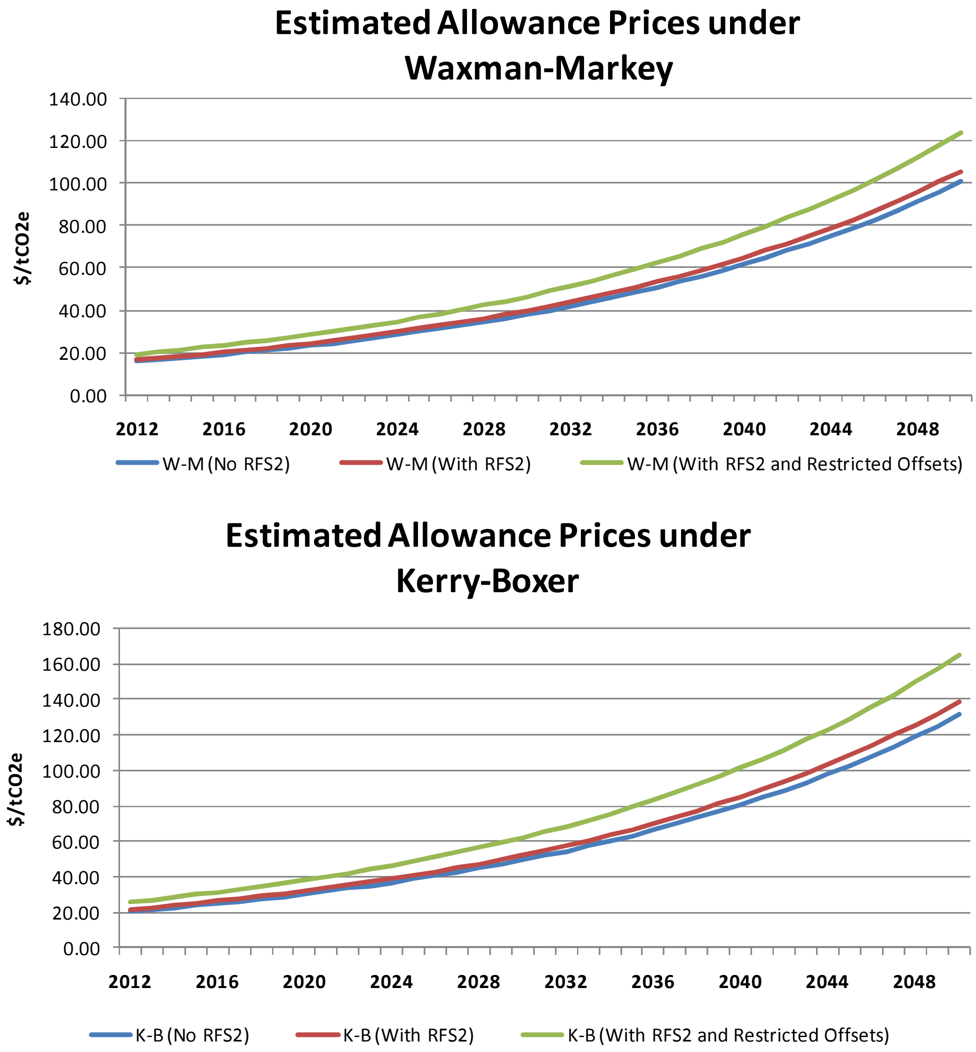

Figure 60: Estimated allowance prices across climate mitigation and offset scenarios

8.4.1 Difference in Total Mitigation Costs

When the RFS2 is included, the increased price of domestic offsets affects the efficient allowance price path, and increases costs of abatement 5.58% under the RFS2 and W-M scenarios (Table 41). This cost increase rises to approximately 6.4% under the K-B scenarios. The implication of this result is without the emissions reduction effect of biofuels, the existence of the RFS2 can significantly affect long-term abatement costs by consuming resources that could be used more efficiently for abatement purposes. As K-B restricts use of international offsets for compliance purposes, this puts additional pressure on domestic offset supplies, further amplifying abatement cost increases of the RFS2. Adding restrictions to offset eligibility on top of RFS2 mandates magnify abatement cost increases even further. Here, restricting forest management and non-CO_2 offset eligibility in the U.S. will boost total mitigation costs by more than 20% under base emissions.

Adjusting emissions for biofuel reduction relaxes this effect to an extent. These results illustrate the importance of an inclusive offset policy. Forest management activities present a number of institutional complications in terms of verification, monitoring, and enforcement, but could ultimately play a large role in the domestic U.S. offset portfolio. As agricultural resources and land available for mitigation purposes is ultimately constrained by the existence of RFS2 mandates, including forestry activities into the mitigation portfolio is important.

Table 41: Effects of Simulation Scenarios on Total Abatement Costs[93]

		Baseline Emissions		Adjusted Emissions		50% Adjusted Emissions	
		W-M	**K-B**	**W-M**	**K-B**	**W-M**	**K-B**
Full Offset Eligibility with the RFS2	Absolute Cost Difference from the no-RFS2 Baseline (Million $ Annuity)	1,004	1,887	-997	-674	22	623
	(% Difference)	***5.58%***	***6.42%***	***-4.98%***	***-2.11%***	***0.11%***	***2.03%***
Limited Offset Eligibility with the RFS2	Absolute Cost Difference from the no-RFS2 Baseline (Million $ Annuity)	4,097	7,652	2,095	5,090	3,092	5,765
	(% Difference)	***22.76%***	***26.03%***	***10.48%***	***15.93%***	***16.40%***	***20.83%***

This study has made an initial attempt to explicitly quantify the effects of biofuel mandates and domestic offset eligibility restrictions on economy-wide GHG abatement costs. Additional work is needed to refine sectoral MAC curves, more accurately model the expected change in baseline transportation (and refining) emissions under the RFS2, and understand the impact of U.S. biofuel policies on the costs of international offsets. This last point is particularly important, and represents the most natural extension of this analysis. As U.S. biofuel expansion drives land use competition domestically and

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[93] Variable or scenario definitions are found in the Nomenclature section

internationally, this will raise the costs of international offsets from sources such as avoided deforestation.

In summary, biofuel mandates increase the costs of supplying domestic AF offsets, which increases overall compliance costs of cap-and-trade. Restricting AF offsets further amplifies this cost increase. However, adjusting baseline transportation emissions by the emissions reduction of biofuels under the RFS2 adds to the compliance obligations for transportation and other sectors of the economy. In this case, the RFS2 actually decreases costs of emissions, implying that the higher costs of offsets (by >10%) are outweighed by the impact of reduced compliance obligations in transportation (by ~3%). This result is driven by the relatively high marginal abatement costs of transportation. If leakage reduces the emissions reduction effect by 50%, there is no discernible change in abatement costs for a bill like W-M. Further work is needed to explore this affect with additional sensitivity around the emissions reduction under the RFS2.

CHAPTER IX

CONCLUSIONS

This dissertation has analyzes the trade-offs between biofuel and carbon price based GHG mitigation policy. More specifically the dissertation sought to improve the understanding of how the aforementioned policies would affect the domestic AF sectors in terms of production patterns, export market conditions, water use, welfare, land use, and management intensity using conceptual and empirical modeling procedures. Several major results emerged from this effort and can be classed into conceptual and empirical findings:

9.1 **Conceptual Modeling Results**

First, a static conceptual was developed and used to show that:

- Biofuel production mandates and biofuel type targets directed toward achieving GHG reductions can alter land use allocation and influence management intensity for energy and food cropping systems. Such policies raise prices of conventional commodities, and can induce leakage-- increasing GHG emissions from conventional production.
- GHG carbon equivalent prices that are sufficiently high can reverse cropland expansion trends caused by the energy mandates; leading to higher net returns for landowners. However this boosts conventional and bioenergy prices further, increasing the potential for international leakage.

- Biofuel mandates and GHG intensity thresholds are competitive with the supply of GHG reductions from the land-based activities.
- If land shifts into carbon sequestration and the subsequent commodity price feedback are large enough, landowners might respond by intensifying production (and hence emissions) to boost yield.
- When extended to multiple regions, the model shows that intensification and land use change (with an accompanying sequestered carbon loss) can occur in less productive regions as a result of cropland contraction and land reallocation in more productive regions.

However, while useful for policy discussion, static analytical models ultimately ignore the dynamics of the system plus abstract form a lot of on the ground realities. Simulation analysis using an extended version of FASOMGHG was used to evaluate long-term commodity price, welfare, production, and natural resource consumption trends under a variety of low carbon futures. Many important findings emerged from this simulation analysis, as summarized below in subsequent sections.

9.2 Empirical Results on Production and Land Use Change

Simulation results indicate that crop and livestock production could be affected greatly, especially across mitigation scenarios where dedicated bioenergy feedstocks and carbon sequestration replace some conventional commodity production. This especially affects livestock production as reduced carbon policies incentivizes land use shifts out of cropland, and reduces the supply of feed-grains.

- The RFS2 stimulates long term cropland use above baseline levels, drawing land into cultivation from forests, pasture, and the CRP positive income and negative GHG effects,
- When all offsets are eligible for payment, cropland use contracts and forest use expands substantially. At higher CO_2eq prices, this contraction effect reduces cropland below baseline (no RFS2) levels,
- Limiting offset eligibility causes smaller land shifts as the reduced emission benefits of moving out of cropland are not eligible and thus ony only contracts the cropland base below baseline levels at higher CO_2eq prices.
- Pursuit of bioelectricity as a mitigation option (instead of offsets) raises the value of cropland, often pushing grazing and CRP lands into production.
- Restricting offsets and incentivizing bioenergy also boosts deforestation in early years of the time horizon, but this effect disappears in later periods.
- The RFS2 could pressure on the CRP, leading to a significant loss in conservation acreage. Re-cultivating conservation lands can help to relax land value, commodity price and trade impacts of the mandates.
- CRP continuation contributes to mitigation efforts by adding additional land resources for carbon sequestration or dedicated bioenergy production.

In general, I have shown that land use patterns in AF are highly sensitive to alternative energy and mitigation policy scopes. Land use patterns, particularly for cropland, differ significantly by region. One of the important results of this dissertation is that evaluating aggregate or broad analytical effects of a policy tells an incomplete story. Regional shifts in production and strategy choice can have acute effects in regions with existing resource scarcity or environmental degradation potential. Additional work is needed to improve our understanding of the optimal role of land resources in a reduced carbon and enhanced biofuel economy.

9.3 **Management Intensity and Water**

Results concerning water consumption:

- While recent literature has raised concerns regarding the effect of biofuel mandates on water resources, I find that the aggregate shift in irrigation water consumption is minimal at a national scale, but could be problematic at a local scale.
- Aggregate water use declines under most mitigation scenarios, but the regional distribution of impacts warrants attention. Production shifts drive water consumption indirectly in regions such as Texas, the Great Plains, and the Pacific Southwest, which is troubling given those regions' pre-existing water shortages.

For management intensification I found that:

- Nutrient use expands significantly under the RFS2, especially in regions such as the Corn Belt and South Central United States where N and P pollution through runoff and leaching are significant environmental concerns.
- Aggregate input use declines across most GHG carbon equivalent price scenarios, though I find evidence of per-acre intensification in nutrient use (and energy use in some instances). Altered production patterns stimulated by

terrestrial mitigation efforts imply higher use of nutrients per unit land in production, which counters previous claims that the existence of climate mitigation incentives could improve water quality (Greenhalgh and Sauer, 2005). However, this result is consistent with theory; a cropland contraction shift due for carbon sequestration can push production to the intensive margin.

- Shifts in aggregate input use affect national indicators of environmental degradation; the RFS2 increases N and P pollution significantly (illustrating nonlinear pollution returns to increased nutrient application).
- Mitigation only alleviates these concerns under the full offset eligibility case. Pursuit of dedicated bioenergy across the restricted offsets boosts indicators of water quality degradation.

9.4 Commodity Markets, Welfare, and Exports

Perhaps the most policy relevant set of results to emerge from this study is the implications of low carbon policy efforts on agricultural commodity prices, producer and consumer welfare, and export markets, including the following key results:

- Commodity price effects of the RFS2 are generally lower than those found in previous studies, partly due to cropland expansion and intensification.
- However, offset markets and bioenergy incentives boost prices significantly further reducing production and exports, suggesting that the “Food vs. Carbon” debate has merit if domestic offsets are to play a predominant role in a reduced carbon economy. Taking land out of production for mitigation can

have greater downstream land use effects than allocating land to biofuel production.

- For welfare, the most important result from this study is that AF producers and landowners have the opportunity to see substantial long-term welfare benefits from renewable energy and climate policy while consumers lose considering AF consumption related welfare only (ignoring benefits of less imported fuel and climate change). The direct flow of offset payments and bioenergy revenue far outweighs the fossil fuel related input cost increases, refuting the claim of many agricultural stakeholders that comprehensive climate policy would significantly cost farmers. When compared to a future where real commodity prices continue to fall, economic prospects for producers and landowners appear much brighter under reduced carbon and biofuel policies.
- Welfare gains vary by region and producer groups (with livestock producers bearing the brunt of feedstock price increases).
- Consumers of AF commodities are worse off under climate mitigation regimes. Commodity price impacts faced by consumers should be more carefully weighed within the context of the general economy to truly understand the net effect of these impacts but that is beyond the scope of this study.
- Exports are lowered significantly relative to the baseline. The effect of mitigation efforts is much more pronounced on exports than the RFS2, again

supporting the notion that productivity decreases under a full offset market could imply much greater leakage effects than biofuel mandates.

9.5 Effects of AF Policies on the Costs of GHG Abatement

In the context of economy-wide GHG abatement, results show that:

- AF can provide a significant source of offsets to capped entities at a relatively low cost, so policies that influence those costs can impact total abatement costs for the general economy.
- The full costs of AF offsets depend greatly on the existence of the RFS2 and which offset activities will be considered eligible under a comprehensive climate bill. The RFS2 alone can increase the marginal costs of offsets by about 20%, but the net effects on total abatement costs depend on assumptions of baseline emissions in the transportation sector, and international offset provisions.
- With a full emissions displacement effect, reduced abatement costs resulting from lower compliance obligations in the transportation sector outweigh the higher costs of offsets caused by the biofuel mandates
- Limiting offset market participation by excluding forestry activities or limiting payment eligibility increases total abatement costs substantially (>20%).

9.6 Research Limitations and Future Research Directions

There are a number of limitations to this study that should be emphasized. Each provides a unique future research project:

9.6.1 AF Only Concentration

The focus of this work has been squarely on AF welfare, with little regard to residual economic impacts caused by the policies in other sectors of the economy. While food prices and consumer welfare are captured endogenously, this fails to capture the potential substitution or income effects of such price shocks in a general economy framework. Such a shortcoming might underestimate the full economic costs of AF GHG mitigation.

9.6.2 Biofuel Market Penetration Assumptions

This analysis uses exogenous parameters to represent total biofuel market production, with and without the RFS2 mandates in place. Then, mandates are locked in beyond the maturation of the RFS2 (in 2022). This procedure inherently ignores the possibility that the market and infrastructure necessary for biofuels could grow beyond or limit the RFS2 mandates. It is currently not well known how biofuel markets could evolve over time, both in the absence of policy, or beyond policy mandated levels. Without such information, additional sensitivity analysis is needed that tests the effect of alternative biofuel market growth trajectories.

9.6.3 Direct Linkages with International Production Systems

The U.S. is a world leader in agriculture, producing more than 40% of the corn consumed globally. One must keep in mind that under current legislative proposals to reduce GHG emissions in the U.S., domestic offsets would compete to an extent with exports and international offsets. A more global analysis is needed.

9.6.4 No Direct Feedback from Groundwater Systems

One weakness of this analysis is there is no direct feedback from water consumption on the stock and depletion rates of groundwater resources. Groundwater depletion from excessive agricultural withdrawals is a highly problematic, especially in regions where simulation analysis reveals agricultural expansion (the Southwest and Great Plains). While the empirical model used in this study is dynamic in many variables, stock and depletion effects of groundwater consumption are ignored. Future work will incorporate regional groundwater dynamics directly into FASOMGHG to model such a scenario.

9.6.5 No Transportation MAC Adjustment without Biofuels

As the previous chapter showed, the slope of the MAC parameter for the transportation sector drives much of the full abatement cost results. Transportation sector emissions are adjusted based on potential displacement value of biofuel replacement of fossil transportation fuels (following policy-imposed GHG reduction thresholds), but shifts in abatement costs caused by removing biofuel mandates are currently ignored. Presumably, removing the mandates could lower abatement costs in the transportation sector, but additional information is needed to accurately model the magnitude of this effect.

9.7 **General Conclusions**

This dissertation assesses some of the intersections of biofuel mandates and comprehensive cap-and-trade by considering potential natural resource implications of these various policy drivers. The US AF sectors have the opportunity to contribute greatly to federal renewable energy or GHG mitigation targets. However, such contributions could dramatically alter the AF landscape by influencing land management decisions. Also, domestic GHG mitigation efforts in conjunction with the RFS2 can pressure agricultural commodity markets, leading to international leakage through land use change. This also raises concerns that the per-capita costs of climate mitigation may have been understated in previous economic analyses of U.S. climate bills that did not fully account for increased household food costs expenditures brought on by a successful domestic GHG offset market. Indirect consequences of domestic biofuel expansion merit policy attention, but have perhaps have been overstated in previous analyses. However, results indicate that comprehensive climate mitigation efforts and domestic offsets can potentially induce leakage at far greater rates than biofuel mandates. This result reinforces the notion that international offsets should play a critical role in domestic climate mitigation efforts as a buffer against international leakage caused by the combined market forces of domestic biofuel expansion and offset provisions.

Domestic biofuel mandates and policies targeted at production systems that ensure GHG reduction thresholds could have indirect consequences in addition to leakage, such as reducing the available supply of terrestrial GHG offsets. This is the first study to directly model the influence of increased competition for land resources on climate mitigation costs. Perhaps a preferred policy would be one that sets a mandate without stringent GHG reduction thresholds and combines this with a market for carbon offsets. This would increase the total supply of offsets (reducing total abatement costs) and could influence the reductions in intensity desired by biofuel policies.

Pursuit of climate mitigation and movement to a renewable energy portfolio are lofty, achievable, and important policy goals that we should continue to pursue. However, managing land for food, energy, and carbon with a growing population and rapidly emerging global economies will not come without significant economic sacrifice. In order to maximize returns to land resources to satisfy these growing demands, technological advancement and enhanced global yield growth is imperative. Additionally, intensity-based incentives that credit GHG reductions and productivity improvements in the same metric could help alleviate leakage concerns by improving productivity (Murray and Baker, 2010).

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SELECTED RECENT PUBLICATIONS

- Murray, Brian C. and **Justin S. Baker**. 2011. "An Output-Based Intensity Approach to Crediting Greenhouse Gas Mitigation in Agriculture: Explanation and Policy Implications." *Greenhouse Gas Measurement and Management*. Vol. 1(1): 27-36.
- Robert B. Jackson and **Justin S. Baker.** 2010. "Opportunities and Constraints for Forest Climate Mitigation." *BioScience.* Vol. 60 (9): 698-708.
- **Baker, Justin S.**, Bruce A. McCarl, Brian C. Murray, Steven K. Rose, Ralph J. Alig, Darius Adams, Greg Latta, Robert Beach, Adam Daigneault. 2010. "Net Farm Income and Land Use under a U.S. Greenhouse Gas Cap and Trade" *Policy Issues.* P17. April 2010.

SELECTED EXTERNAL FUNDING

- David and Lucile Packard Foundation- GHG and Nitrogen Emissions Scenarios for U.S. Agriculture and Global Biofuels: An Integrated Assessment Approach

SELECTED FELLOWSHIPS AND AWARDS

- Texas Water Resources Institute. Mills Scholarship Program. 2007.
- Outstanding Master's Thesis. Western Agricultural Economics Association. 2006. Title: "Transboundary water resource management and conflict resolution: A Coasian strategic negotiations approach."
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