Relating Land Use and Select Environmental Impacts to U.S. Consumption with a Focus on Agricultural Products

Submitted in partial fulfillment of the requirements for

the degree of

Doctor of Philosophy

in

Civil and Environmental Engineering

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December 2010

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Acknowledgements

My grandmother has a favorite story about my childhood. The story goes that at age 4 I was working on a difficult puzzle and I got really frustrated and upset and through sobs I yelled, "I'll never learn." That spirit of curiosity and desire for knowledge has been a driving force and occasional burden throughout my life. When I started my undergraduate education earning a doctorate degree was a distant dream. Very few people in my life had gone to college let alone completed graduate education. Completing this degree is professionally and personally a considerable accomplishment. It has happened partly due to choices I've made but at least as much this accomplishment is due to the amazing people I've been fortunate enough to stumble upon.

First, thanks to my committee and the faculty and students in Green Design. The Green Design program enamored me during my search for a graduate program and I was not disappointed upon arrival. Scott: thank you for encouraging me to pursue a PhD during my M.S. studies, your assistance throughout my research and the occasional pep talk. Mike: thank you so much for your support, incisive counter-points and helping me to work toward "keeping the main point the main point." Amy: thank you for allowing me to build upon your research, your friendship, and openness to new ideas. Chris W.: without your help with input-output modeling I never would have finished this degree and thanks for being a good friend over these years. Chris H.: thank you for being a role model for a well-balanced life, it's been a pleasure to be a teaching assistant for your classes.

Misha thank you for tolerating all of my crazy and apparently loving me anyway. Thank you so much for never asking me to sacrifice my goals and dreams, believing in me when I don't believe in myself, driving countless miles to see me over these last four years, for your endless curiosity and intelligence, for being able to fix anything, without you I would have no working appliances, probably would still not have a cell phone, and would still not have visible equations in this dissertation.

Thanks to my parents who are proud of me even though they wonder if I'll ever get a ‘real’ job. You set an example of hard work and perseverance that has stuck with me throughout my life. To my sister, Betty: your generosity, kindness, strength and a level-headedness are very inspiring. Thank you for all of the late night gchats while I pseudo-worked. To my brother, Mike: thanks for making me laugh, working hard, and for being strong through personal challenge.

Deb and Hal, thank you for raising such a wonderful son and for being so supportive of both me and Misha over these years. Thanks to the rest of the Kwasniewski, McCausland and Deakin families as well. I feel very lucky to have you all in my life.

To my dear friends Josh, Katie, Angela, Andy, Anu, Bea, Joanna and Susanna thank you for inspiring me to be as awesome as you all are and for endlessly listening and indulging me in all of my rant/rambles. And most importantly thank you for always being down to have fun. Special shout-out to Susanna for reviewing much of this document and providing helpful comments.

Thank you to Tad Radzinski and James Kenney for mentoring me during my undergraduate years and planting the seeds that have led me down this path.

To my wonderful cats, Goat and Piglet, for their unconditional love and for keeping my feet warm at my desk in the winter.

And, finally, I would like to thank the following for financial support: the National Science Foundation, specifically the Materials Use: Science, Engineering and Society (MUSES) Grant 0628084 and Environmental Sustainability Grant 0932484 and the Philip and Marsha Dowd Engineering Seed Fund.

Abstract

Approximately 29 percent (%) of the Earth's surface is used to support humanity. Demand for land use is expected to increase by an additional 33% over the next 100 years. Land suitable for crop cultivation is limited, as are pasturelands, both critical for food production. How we use these lands and all land results in environmental impacts. Environmental impacts associated with land use and land use change are many and various. Land use change can cause runoff and sedimentation of soil, contamination of waterbodies with fertilizers and pesticides and release of carbon to the atmosphere. Paving of surfaces causes changes to the hydrology of an area and can create heat island effects. All of these land uses disrupt habitat for other species.

This thesis addresses the following main research questions: What types and how much land occupied by industry and agriculture, in this thesis defined as land in production, are used to meet demands for consumption in the U.S.? What commodities use the most land? How much land is traded between the U.S. and the rest of the world (ROW)? Are there particular categories of land use that dominate supply chains across sectors? How is land use connected to environmental impacts?

First, land in the United States is related to domestic final demand, including land embodied in U.S. exports. To do this an inventory of land with respect to economic sectors is created. Environmentally Extended Input-Output Analysis (EE-IOA) is used to define connections between land in production and consumed goods and services. It is found that agricultural land use is significant in the majority of economic sectors.

Next, the EE-IOA is expanded to include an additional region representative of the rest of world. This enables estimation of the land embodied in U.S. imports. In many land use studies only agricultural products are considered. Through extending this analysis to include the total supply chain land use embodied in the production of good and services it is shown that land use associated with manufactured goods is significant.

Finally, two analyses are executed to demonstrate the connections between land use and environmental impacts. First, Monte Carlo Analysis is employed to approximate the nitrate output within the Mississippi/Atchafalaya River Basin as a result of increased

demand for biofuels in the U.S. Nitrate output is related to the formation of hypoxia in the northern Gulf of Mexico. Results indicate that with or without biofuels, our current land use and land use management practices are inadequate. Each year a hypoxic zone forms in the northern Gulf of Mexico the additional land in cultivation will exacerbate this situation. Next, the connection between greenhouse gas (GHG) emissions and land use was explored, again using EE-IOA methods.

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1. Introduction

Land is required for virtually every activity in our daily lives. Aside from our connection to the Earth's land surface through gravitational force, the qualities of land provide the means for basic human necessities i.e., food, fiber, shelter, clean water and fuel for fire. Without healthy soil there would be no crops to meet nutritional needs, without timber we would lack basic construction materials or means for cooking and warmth. In addition, the ecosystems on the land surface purify water, attenuate toxicity of pollutants, provide aesthetic experiences, and vegetation to remove carbon dioxide from the atmosphere. If we extend our understanding of land to include the Earth's crust then electricity, electronics, roads, cars…essentially everything that we use in our daily lives is due to the generosity of land. Even if we do not extend our understanding of land to include the crust, extraction of materials from the Earth's crust can irrevocably alters the land surface and causes damage to ecosystems at the land surface.

Global anthropogenic land use has increased rapidly in the last few decades due to population growth and rising affluence [1]. Approximately 29 percent (%) of the Earth's land surface has been converted to agricultural or built-up areas to support human life and projections indicate that an additional 33% of the land surface could be converted for human purposes over the next 100 years [2]. Simultaneously, populations are moving to urban areas; roughly 75% of the global population lives in urban areas [2] where the links between the provisions of land and survival are obscured. In the United States (U.S.) 77%, of the land surface, including Alaska and Hawaii, is used in some way for anthropogenic purposes. Of this land 25% may be described as intensive use, cropland and developed land, and the remaining 75% may be described as less intensive, pasture and timberland. Given the magnitude of current land use and anticipated increases it is important to understand how land and the resources it provides are required to meet demands made by humanity. Further, we must understand how the land that we use is linked to environmental impacts.

Table 1.1. Summary of Land Use in the United States

Land Use Category	Land in Classification Category	Land in Use in 2002
	million hectares	
Forested (Grazed lands, Timberland)	260	200
Cropland (Grains, Oilseeds, Fruits, Vegetables, etc.)	180	140
Grassland/Pasture	240	310[a]
Special Uses (Transportation, Recreation and Wildlife, Farmsteads)	120	15
Urban Land (Residential, Recreational, Commercial, Industrial)	20	12
Miscellaneous (Rural residential, Barren land and Marshland, Mines, Quarries, Commercial, Industrial)	90	5
Total	920	682

Note: (a) The entire grassland/pastureland land use category is assumed to be used to graze cattle, in addition approximately 25 million hectares (Mha) of cropland are used for pasture and 50 Mha of forested land are used for grazing[3].

As we can see in Table 1.1. the majority of land classified as cropland is currently in use. The U.S. has approximately 15 million hectares (Mha) of land classified as unused cropland, cropland is defined based on soil quality and other characteristics conducive to crop cultivation. Note that 25 Mha of cropland are currently used to graze cattle [3]. Current agricultural practices are responsible for approximately 400 teragrams (Tg) of carbon dioxide equivalents (CO_2e) and nitrate output to waterways causes hypoxic conditions in the Gulf of Mexico annually. The Energy Independence and Security Act (EISA) of 2007 mandated the production of 35 billion gallons (Bgal) of biofuel production by 2022. If biofuel mandates are met, population and food consumption increases and export levels remain steady the U.S. will be forced to expand land in cultivation existing cropland exacerbating existing environmental problems or will be required to increase imports of land-intensive crops or goods from elsewhere in the world causing environmental issues elsewhere.

Given the global natures of markets, increased demand for crops in one country can lead to increased production and land use in another country. The potential for this type of cascading increase in land use and land use change has generated a great deal of concern over the last few years. This land transformation can result in carbon emissions which may offset the GHG benefits of replacing fossil energy with biomass-derived energy [4, 5]. The biofuels debate has illuminated the reality that land is a precious and limited resource and asks the question of how we will use a limited amount of land to meet differing consumption goals. The potentially significant GHG emissions associated with indirect land use change demand that researchers connect land use, consumption and environmental impacts in order to compare future consumption choices and associated land use decisions.

The relationships between land use, land use change, consumption and the environment are many and complex. Alteration of the land surface disrupts the function of ecosystems that are arguably required to sustain output for the organisms of the Earth, including humans. These alterations result in many and varied environmental impacts. Determining the full range of impacts is a daunting task. Vitousek et al. describe the significance of land transformation this way: "Human use of land alters the structure and functioning of ecosystems, and it alters how ecosystems interact with the atmosphere, with aquatic systems, and with surrounding land. … Moreover, the effects of land transformation extend far beyond the boundaries of transformed lands" [6]. That is to say, when we alter the land surface we disrupt the natural systems connected to the land in that particular location. When a forested area is cleared for cultivation of crops the hydrology of the area is disrupted, species habitats are destroyed and fragmented, carbon sequestering vegetation is lost, carbon bound in soils is released to the atmosphere and nearby land may be affected by deposition of loosened soils from adjacent land. Subsequent use of this land will also result in impacts to the environment, for example, if crops are fertilized with nitrogen the natural biogeochemical balance will be altered, local and regional water quality will be impacted and nitrous oxide (N_2O) emissions will enter the atmosphere.

To explore these connections the land used to produce goods is related to consumed goods using environmentally extended input-output analysis (EE-IOA), Figure 1.1 depicts the conceptual overview of this approach. The left pie chart represents the organization of land use in terms of production. EE-IOA is the modeling technique used to relate this land in production to consumed goods and services, represented by the pie chart on the right. EE-IOA is a form of Life Cycle Assessment (LCA). LCA is the systematic study of the environmental aspects and potential impacts across a product's life, often described as cradle-to-grave from raw material acquisition through production, use and disposal [7]. Note, however that EE-IOA does not include use and disposal phases. Input-Output Analysis has been used since the 1930s but recently has been used to capture environmental impacts associated with the production of a particular good or service across the entire supply chain of production [8, 9]. The power of IOA is its ability to delineate upstream environmental impacts as a result of including all levels of supply, i.e., the suppliers of the suppliers without cut-off error, a serious issue in LCA. For example, most people purchase processed food goods, few people make their own bread let alone grind wheat to make flour. If we only consider the land occupied by the bread producer we would ignore the relatively large upstream land use associated with the production of wheat. Each step in the supply chain of bread production is represented by a sector in the U.S. economy and each sector occupies an area of land to produce output. Further, the production of any product involves numerous inputs, e.g., energy, raw materials, seeds and in addition to the desired output there are often undesired environmental consequences, e.g., GHG emissions, other air pollutants, excess nutrients.

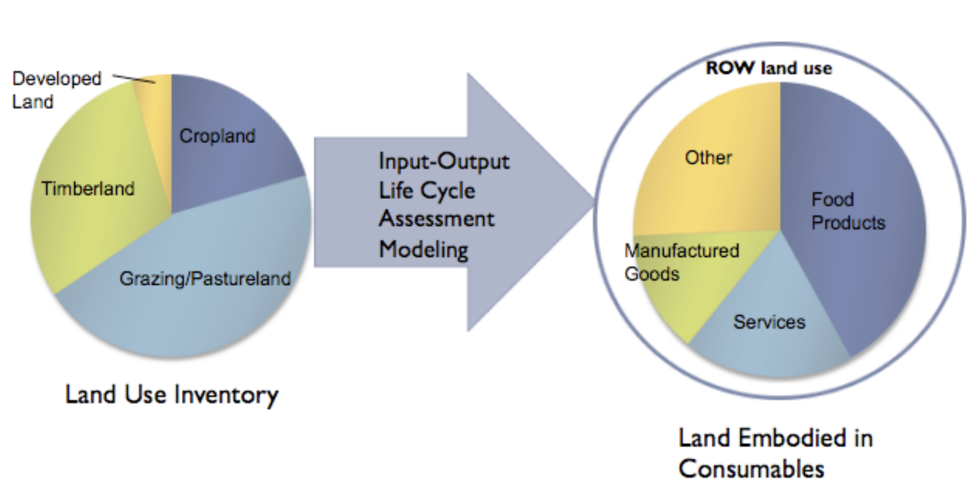

Figure 1.1. Conceptual Overview of Relating Land Used in Production to Consumed Goods through Environmentally Extended Input-Output Analysis.

The chapters in this thesis explore the connection between land used for production and land embodied in goods and services consumed in the U.S., both domestically and internationally. The last two chapters explore environmental impacts associated with land use. First, in Chapter 2, a land use inventory of the U.S. with respect to economic sectors is completed and integrated into an EE-IOA modeling framework in order to relate land in production to consumed goods. Chapter 2 also provides background to the inclusion of land use in life cycle assessment research and a discussion about metric selection. The chapter answers the following research questions: (1) Which economic sectors use the most land to produce output and which sectors are responsible for the most land use from a consumption perspective. (2) What metrics are most useful for considering land use at a large (national or global) scale? (3) Are there land uses consistently present in large quantity in the supply chains of goods and services consumed in the U.S. For example, energy and associated greenhouse gas (GHG) emissions are present in the upstream purchase of most goods and services, is there an analogous land use type?

The contribution from Chapter 2 is that by using EE-IOA we can consider not just the land directly occupied by a facility producing televisions or a farm producing corn, but we can quantify the land upstream of the final producer to better understand the links between goods and services and land use. These links seem obvious for food products, however even for items such as automobiles upstream land use can be considerable due to purchases of leather. This sort of upstream land use would often be overlooked in a land use study. The results of this analysis help to understand how U.S. land in production is required to produce goods and services and also elucidates the importance of considering upstream land use in addition to direct land use.

Since global trade as become so significant to U.S. consumption Chapter 3 expands the IOA to include a Rest-of-World (ROW) region and addresses the research question: How much land is embodied in imported goods? Scenarios are developed to explore the land use required to meet increased demands for ethanol. Additionally scenarios are developed to consider if dietary shifts could potentially allow the U.S. to meet ethanol goals within its borders without increasing cultivated land. Chapter 3 also provides a discussion of methods for assessing environmental impact embodied in trade. The development of a multiplier to represent LU in the ROW is discussed at length, the approach taken was aimed at most accurately estimating the land virtually imported to the U.S. without using global average yields, which is common practice.

Chapters 4 and 5 explore the connection between land use and environmental impact. In Chapter 4 the research question is: How will meeting ethanol goals outlined in the EISA impact the formation of hypoxia in the northern Gulf of Mexico (NGOM). A large amount of nitrogenous fertilizer in used for crop cultivation in the U.S., excess nutrients enter waterways and can lead to hypoxic conditions in waterbodies that disrupt ecosystem functioning. First, nitrate output within the Mississippi and Atchafalaya River Basin (MARB) was estimated using Monte Carlo Analysis based on anticipated production of corn, corn stover, soybeans, and switchgrass to meet EISA goals. Nitrate loading values are used to estimate the subsequent formation of hypoxia in the NGOM.

Chapter 5 uses EE-IOA to relate GHG emissions to land use. Approximately 6% of total U.S. GHG emissions occur due to agricultural activities. Despite this relatively small overall contribution, Agricultural activities are large contributors of methane (CH_4), 31%, and N_2O emissions, 68% [10]. Many of these emissions originate and could be reduced through agricultural land use management. A GHG multiplier organized with respect to the origin of GHG emissions it is possible to determine which GHG emissions are directly related to land use choices. The scenarios developed in Chapter 3 are assessed with respect to GHG emissions. The contribution of these chapters is an attempt to explicitly link land use to environmental impacts at a large scale. Understanding the environmental impact of land use choices is critical to making decisions regarding future land use.

By answering these research questions we gain insight to how land is required to support current consumption in the U.S. The use of land is associated with many environmental costs, however, many of these uses are unavoidable, i.e., suspending food production is not an option. However, the use of biofuels may be deemed unnecessary by society if the environmental costs are too high. It is not the purpose of this thesis to debate the relevance of biofuels, though this thesis does attempt to quantify the amount of land we might expect to employ if biofuel goals are met.

2. Chapter 2: Inventory Development and Input-Output Model of U.S. Land Use: Relating Land in Production to Consumption[1]

In this chapter, a U.S.-centric economic input-output life cycle assessment (EIO-LCA, also referred to as environmentally-extended input-output analysis) framework is used to relate current U.S. land used for production to the goods and services consumed in the U.S. First, a production-based inventory of land use is developed for incorporation with the most recent (2002) U.S. Department of Commerce 428-sector (plus six sectors added by disaggregating the original tables) commodity-by-commodity input-output table [11]. The production-based inventory assigns land area occupied for production to each sector of the economy, e.g., area occupied by corn cultivation is assigned to the Corn farming sector. Secondly, an analysis using EIO-LCA is conducted to estimate the land used both directly and upstream to produce goods and services, also referred to as a consumption-based inventory. The consumption-based inventory provides insight into the most land-intensive goods and services.

To my knowledge no U.S. study has attempted to create a production inventory for all sectors of the economy. This inventory and related results of EIO-LCA provide insight to the quantity of land required to support domestic consumption of goods and services, including U.S. exports. Exploration of the amount of land associated with imports is provided in Chapter 3. Challenges associated with creating the inventory including data availability and allocation to sectors are discussed. This analysis provides an understanding of how actual land areas are required to meet consumption demand for all goods and services in the U.S. economy.

2.1. Life Cycle Assessment and Land Use

For the last fifteen years, LCA and sustainability research communities have been looking to incorporate land use (occupation) and land use change (transformation) in their research efforts [12]. When land is disturbed from its natural state there are often many consequences, for example, soil erosion, loss of species diversity, GHG emissions from

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[1] Much of the text in the chapter is based on a paper submitted for publication.

soil, hydrological disturbances, to name but a few. Communicating all of these impacts individually is difficult and can be cumbersome for non-experts. As such, researchers have been working toward more concise metrics that will not only relay the initial impact but also the ultimate consequences of LU and LUC, however a consensus has not been reached [13-15]. LCAs typically include a quantitative inventory step and a qualitative impact assessment step, e.g., assess how much land has been disturbed and then determine the associated environmental impact typically on a per unit basis. Difficulties arise with both quantitative and qualitative efforts due to lack of data. Concerns specific to qualitative assessments include comparison across ecosystems and the difficulty of assessing impacts over varying time scales [16]. These difficulties are exacerbated when comparing large-scale, i.e., national and global systems [17]. Recently, LU research has focused heavily on the consequential or marginal land use change as a result of increased demand for land-intensive goods, termed indirect land use change. These issues are exemplified by the biofuels debate and a growing interest in comparing the land use and land use impacts of bio-based and fossil fuels. This section provides background literature on efforts to generate inventory and impact assessments of land use within an LCA framework.

2.1.1. Quantitative or Inventory Metrics

Three major efforts to quantify and relate LU to consumption have arisen in the sustainability and LCA fields. First, the ecological footprint method estimates how much land is needed to support consumption, usually on a country basis [18]. Ecological footprinting compares countries on an "equivalent number of earths required" to support consumption. However, these assessments include hypothetical land area (e.g., acres of trees needed to offset CO_2 emissions to produce a good), lack specificity with regard to types of consumption or land type and fail to assign any spatial reference. More importantly, they are not constrained by the quantity or quality of land actually available [19, 20] making it only a useful metaphor for over-consumption. For these reasons, the ecological footprint approach has limited usefulness for practical integration with life cycle assessments seeking to allocate how the land used to produce goods is allocated to final demand. Turner et al. advocate for the use of multi-regional input output methods in lieu of the current inventory-based approach used to calculate Ecological Footprints [21], this approach will be explored in Chapter 3.

Secondly, partial, e.g. the Food and Agricultural Policy Research Institute (FAPRI) [22, 23] and general equilibrium models, e.g. the Global Trade Analysis Project (GTAP) [24], use economic relationships to predict changes in land use due to changes in economic demand. For instance, GTAP has recently incorporated land use to better understand how agricultural land and land use change relates to global climate change analysis [24, 25]. The model was used to project anticipated indirect land use (ILUC) due to increased U.S. biofuel production [26]. While GTAP's recent interest in land use is an important contribution given the breadth of the project, several issues with the model exist. For example, the model is aggregate - with only 57 total industries. Also GTAP only assigns land use to agricultural sectors, including 8 crop sectors, 4 animal (including animal fibers) sectors, 1 fishing sector, and 1 forestry sector resulting in considerable aggregation.

Recently, a third approach has risen incorporating land use into input-output modeling frameworks [8, 9, 27]. Lenzen and Murray created a land use inventory based on land used for the production of goods in Australia and an IOA to relate land used for production to consumed goods similar to the work done herein [8]. Other authors have tracked physical land used in trade by determining a country's "virtual" land use from imports from other countries [9, 20]. Similar methods have been used to consider virtual water use through agricultural trade [28, 29]. The environmental impacts "embodied" in traded goods is a concept often described in climate change research and assigns the environmental impacts to the final consumer of the goods produced rather than the producing country [30-32].

2.1.2. Qualitative or Impact Assessment Metrics

The first step in completing an LCA is typically the aforementioned quantitative inventory. There are two main considerations when assessing land use impacts: impact due to the transformation of the land from one state to another (land use change) and occupation of land for a certain activity (land use) [12]. Land and the ecosystems that have evolved on them provide a number of ecosystem services that are often taken for granted. When land is changed from one state to another or is occupied for human use these services are disrupted. The goal of developing metrics is to better understand how land use and land use change disrupt these services. Lindeijer has assembled a list of ecosystem services of concern for which metrics would ideally be developed [12]:

- Erosion resistance
- Alien substance filter, buffer and transformation capacity
- Groundwater erosion
- Buffer capacity for surface water
- Protection against physical emissions (noise, dust)
- Capacity to improve small-scale climates
- Human resort function
- Productivity for sustainable agriculture/forestry
- Drinking water productivity potential
- Landscape quality
- Habitat resort function

Impact metrics do not exist to assess all of these ecosystem services though a number of summary metrics have been developed. They can be grouped in two ways, those assessing biodiversity and those using weighting schemes. Biodiversity is most simply defined as a measure of the diversity of organisms in a given area. Biodiversity is often chosen as it is considered a proxy for assessing the health of an ecosystem or ecosystem services such as water retention/purification and carbon sequestration [33]. That is, as ecosystem services are impaired biodiversity is negatively impacted. Biodiversity is commonly subdivided into three categories genetic, species, and ecological diversity. Most often biodiversity is assessed in terms of vascular plant species [33] in one case a mixture of plants, mollusks, and moss species were considered [16]. Soil organic matter has also been used to indicate the quality of land largely to assess the potential for agricultural productivity [34].

Change in biodiversity is argued to be an endpoint metric to holistically represent the many activities associated with occupying or transforming land [33]. Koellner groups land use for anthropogenic purposes into three categories: surface use (e.g., developed or agricultural land), abiotic resource extraction (e.g., mining), and biotic resource production [33]. The use of land for these purposes results in a variety of physical, bological and chemical disturbances that can result in ecosystem damage. Koellner refers to these as ‘interventions’ some examples include: fragmentation, direct habitat creation/destruction, physical soil treatment, soil compression, removal of biotic soil cover, fertilization, desiccation/irrigation, and introduction of biocides [33]. These interventions result in midpoint impacts such as occurrence of land cover types (e.g., loss of forest cover), pattern of land cover mosaics, changes in chemical/physical conditions and water availability, all of which ultimately impact the biodiversity of an ecosystem [33]. Therefore, biodiversity or at least change in biodiversity as a result of a decision is thought to be a consistent means to evaluate impacts of land use or land use change [12, 33]. Major limitations to this approach include data availability as well as time required to collect and process the data, spatial resolution, and the subjective nature of valuing biodiversity across varied ecosystems. The latter may be overcome by comparing changes to biodiversity rather than comparison of total values.

A related concept is environmental vulnerability, which is defined as “the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or a stress/stressor” [17]. Environmental vulnerability is measured by rating many (50 or more) items included in an index and has often been done at a national scale. Barnett et al. argue that such vulnerability indices cannot be meaningful when applied to large-scale systems and should only focus on smaller scales of analysis [17].

Land classification and weighting schemes have been proposed to assess the impact of land use and land use change [12]. This approach generally classifies land type in relation to anthropogenic use, a representative example provided by International Union for Conservation of Nature is [12]:

I. Natural systems
II. Modified, often subdivided into intensive and extensive
III. Cultivated
IV. Systems dominated by human buildings
V. Systems degraded by pollution and loss of soil and vegetation.

These classes are then assigned a weighting factor based on the amount of presumed incurred damage by each of these land types. The weighting factors vary based on different perspectives or concerns and are highly subjective. To illustrate, Lindeijer compiled the weighting factors determined by a number of researchers for these five classes of land (Table 2.1). Each column indicates different criteria for assessment. In Table 2.1, higher score represent the least environmental impact. As can be seen in the table, there is not a clear consensus regarding how to assign weights to land uses.

Table 2.1. Proposed Weighting Systems for Five Land Use Classes

Land use class	Biological accumulation	Regeneration time	Panel value	Multicriteria	Two diversity and red lists indicator[a]
II	1	1	1	1	1
III (extensive)	1	0.17	0.84	0.35	0.85
III (intensive)	0.1	0.0047	0.52	0.18	0.49
IV	0.05	0.0004	0.29	0.06	0.15
V	0	0	0	0	0

Note: Table adapted from Lindeijer [12]. (a) This indicator represents the author's prioritization of species diversity and endangered or 'red listed' species.

Similarly, Lenzen and Murray assigned weights for land use based on perceived damage [8]. Developed land was weighted more heavily than cropland and undisturbed land, e.g., forests, are not weighted at all [8]. When used these weights are multiplied by the area utilized in production to create comparable metrics across land uses. Using this scheme developed land area is counted in totality and less disturbed land is discounted.

Weighting schemes provide some insight to the degree of use and implied environmental burdens, however, they do not provide a good sense of how much land is currently dedicated to a particular purpose and may oversimplify actual impact. Connecting total area to consumption allows one to assess how much land or how much intensification of current land use may be required to meet future consumption expectations. In lieu of a weighting scheme, it might be most useful to organize land in terms of production potential or according to agro-ecological zones [24]. These differentiations would allow one to make assumptions about the potential for increased output from land currently in. Impact assessment metrics are often associated with area, therefore un-weighted areas may be coupled with existing impact metrics.

2.2. Input-Output Modeling for Land Use Analysis

EIO-LCA was employed to relate the production-based land use inventory to goods and services to create a consumption-based inventory of direct and upstream land use. Economic input-output analysis (IOA) was originally formalized by Leontief and represents a linear model of all inter-industry or inter-commodity transactions in a national economy [11, 35]. IOA has been used since the 1930s but recently has been used to capture environmental impacts associated with the production of a particular good or service across the entire supply chain of production [8, 9]. The power of IOA is its ability to delineate upstream environmental impacts as a result of including all levels of supply (the suppliers of the suppliers) without cut-off error, a serious issue in LCA. A detailed list of sectors and areas assigned to the production-based inventory can be found in Appendix A.

The EE-IOA model used for this work employs the most recent (2002) U.S. Department of Commerce 428-sectorbenchmark commodity-by-commodity input-output matrix [11]. Six sectors that were added to the model for a total of 434 sectors to provide greater detail in Agricultural sectors are shown in Table 2.2 [36, 37]. Soybean farming was created as it is a major feed source for livestock and is used for biodiesel production. The grain farming sector was disaggregated to create corn, wheat, rice, and all other grain farming. Corn is a major feed source for livestock, is currently the main source of ethanol production, and is the largest consumer of N fertilizer in the U.S. Wheat is also a major staple crop. Rice is not produced on a large scale in the U.S., but it directly results in methane emissions and thus has a relatively different environmental profile than the other grains. The Animal (except Poultry) Slaughtering and Processing sector was disaggregated to isolate cattle from other animals, as cattle are responsible for very large amounts of GHG emissions and have different land use patterns than other animals included in this sector, such as swine. Given the importance of agriculture when evaluating LU, the disaggregation of these sectors will allow for finer assessment of likely environmental impacts.

Table 2.2. Disaggregated Sectors

2002 Benchmark IO Sectors	Disaggregated Sectors
Oilseed farming	Soybean farming
	Other oilseed farming
Grain farming	Corn farming
	Wheat farming
	Rice farming
	Other grain farming
All other crop farming	Hay and pasture farming
	All other crop farming
Animal slaughtering and processing(except poultry)	Cattle slaughtering and processing
	Other animal (except poultry) slaughtering and processing

The following equations represent those used for the IOA:

Equation 2.1. $\mathbf{X} = \mathbf{q} = [\mathbf{I}-\mathbf{A}]^{-1}(\mathbf{Y_{hh}} + \mathbf{Y_{pi}} + \mathbf{Y_{exp}} + \mathbf{Y_{govt}} + \mathbf{Y_{imp}})$

Equation 2.2. $\mathbf{f} = \mathbf{F} \times \mathbf{X}$

Equation 2.3. $\mathbf{A} = \mathbf{Z} \times (\mathbf{X})^{-1}$

Total supply chain requirements, **X**, for a specified final demand, **Y**, can be estimated using Equation 2.1, where **A** is the direct requirements matrix, representing inter-industry transactions, and **I** is the identity matrix. The expression $(\mathbf{I}-\mathbf{A})^{-1}$ represents the solution to the linear system, also called the Leontief inverse [38]. Final demand, **Y**, is separated into four categories in this analysis: $\mathbf{Y_{hh}}$ for demand by personal consumption or households, $\mathbf{Y_{pi}}$ for private fixed investment and changes in private inventories, $\mathbf{Y_{exp}}$ for exports, and $\mathbf{Y_{govt}}$ for government purchases. Note that for demand in imports, $\mathbf{Y_{imp}}$, is only used for the disaggregation calculations described below, land use associated with demand for imports is assessed in Chapter 3. Private fixed investment is defined as investment by industries in equipment, software, and structures [39]. With estimates of average sector land use per dollar (**F**), the inventory of land use associated with making any good or service (**f**) can be calculated using Equation 2.2. The vector **F** was created with the land use inventory as described below and has units of million hectare per million U.S. dollars (Mha/$M). First-tier purchases, **A×Y**, and associated land use **F×A×Y** are also calculated to identify the land associated with direct purchases made by sectors to produce output. The word 'direct' has specific implications in both the land use (e.g., the area immediately supplying a product, usually agricultural) and input-output (i.e., $(\mathbf{I}+\mathbf{A})\times\mathbf{Y}$) research communities. However, in this work, the word direct will be used to refer to first-tiered purchases. Upstream land use is defined as all land use associated with purchases from the second tier ($\mathbf{A}\times\mathbf{A}\times\mathbf{Y}$) and beyond. These distinctions were made to show the importance of considering the upstream impacts in land use LCA analysis.

Disaggregation of sectors entails splitting out new rows and columns to the original **Y** and **A** matrices. The **A** matrix is derived from the **Z** matrix, Equation 2.3. The **Z** matrix is essentially the **A** matrix except that the **Z** matrix is in units of total dollars. In general, disaggregation is done using economic output ratios of the specific good to all goods included in the sector, e.g., corn to all grains in the Grain Farming Sector, using data provided by the BEA [40]. Imported and exported demands are disaggregated using trade data, which itemizes imports and exports by commodity [41]. Rather than disaggregating with economic data, fertilizer purchases by the newly added sectors (i.e., Corn, Wheat, Rice and Other grain farming) were disaggregated using United States Department of Agriculture (USDA) fertilizer consumption data [42]. Corn farming utilizes more fertilizer than any of the other grains in this sector.

More specifically, the final demand matrix, **Y**, is disaggregated first, as these values are required to determine the ratios for disaggregating the **Z** matrix, Equation 2.4. Total output from a given sector, **X** or **q**, must be equal to the total value generated to meet inter-industry demand, **Z**, as well as final demand, Equation 2.1. The economic ratios of agricultural commodities to be disaggregated (corn, wheat, rice, for the grain farming sector) vary considerably for imports, exports, and domestically produced commodities, Table 2.3. The import and export ratios were used to disaggregate $\mathbf{Y_{imp}}$ and $\mathbf{Y_{exp}}$. Detailed commodity data from the BEA were used to disaggregate **q** [40]. To ensure that the disaggregated tables are balanced ratios from Equation 2.4 are used to disaggregate the **Z** matrix and all other elements of **Y**. Note that since this analysis is concerned only with domestically produced goods the inclusion of the import adjustments is only used to ensure that the model is balanced, Equation 2.4. The resulting ratios are presented in Table 2.3.

Equation 2.4. $$r_{balance} = \frac{q_{disag,j} - \left(fd_{disag,ex,j} + fd_{disag,imp,j}\right)}{\sum Z_j + \left(fd_j\left(fd_{ex,j} + fd_{imp,j}\right)\right)}$$

Where:
$r_{balance}$ = adjusted ratio for disaggregating Z and non-trade elements of final demand
q_{disag} = total commodity output disaggregated with detailed item output
$fd_{disag,ex}$ = exported final demand disaggregated with export trade data
$fd_{disag,imp}$ = imported final demand disaggregated with import trade data
Z = total inter-industry demand for original BEA sector
fd = total final demand for original BEA sector
fd_{ex} = exported final demand for original BEA sector
fd_{imp} = imported final demand for original BEA sector
i = disaggregated sector, 1-6, 14, 15, 65, 66
j = original BEA sector, 1, 2, 10, 60

Table 2.3. Disaggregation Ratios

Disaggregated Sector	Import Ratios	Export Ratios	Detailed Item Output	Adjusted Disaggregation Ratio ($r_{balance}$)
Oilseed farming (j=1)				
Soy farming (i=1)	14.3%	96.4%	96.3%	94.5%
Other oilseed farming (i=2)	85.7%	3.6%	3.7%	5.5%
Grain farming (j=2)				
Corn farming	19.1%	53.1%	68.8%	71.3%
Wheat farming	37.1%	37.7%	20.4%	16.5%
Rice farming	0.2%	2.1%	3.1%	3.2%
Other grain farming	43.6%	7.1%	7.7%	8.9%
All other crop farming (j=10)				
Hay and pasture farming	17.4%	32.9%	86.5%	86.7%
All other crop farming	82.6%	67.1%	13.5%	13.3%
Animal (except poultry) slaughtering and processing (j=60)				
Cattle slaughtering and processing	64.0%	60.8%	79.3%	80.0%
Other animal (except poultry) slaughtering and processing	36.0%	39.2%	20.7%	20.0%

Because U.S. input-output accounts do not separate domestic and imported commodities in the use matrix, imports were stripped from the **A** matrix to avoid inclusion of imported goods to industry and directly to final demand, similar to methods described in past work [43]. Similarly, the final demand values were adjusted to consider only demand for domestic goods. The land use associated with imported goods are explored in Chapter 3 using multi-regional input-output modeling [44].

2.3. Creation of Production Inventory

2.3.1. Metric Selection

The metric chosen for this analysis is hectares/$M-yr, which essentially considers the quantitative occupation impacts of LU for a given year. This metric enables a clear understanding of the relationship between land types in terms of quantity currently in use. Some considerations associated with using this metric include divisibility, temporal issues and defining 'use.'

Land use is not divisible in the same way that many environmental emissions are divisible. For example, one can easily imagine dividing total GHG emissions by the total number of cars produced to determine GHG emissions per car produced. However, it is less clear that the land occupied by a car manufacturer should be divided in a similar fashion since the entire facility is required to produce even one car and because the same land is used over an uncertain time period. It is easier to imagine that agricultural land is divisible because we can determine the area required to grow a single onion. However, the same problem of divisibility exists in agriculture, if an additional onion is demanded (assuming yields cannot be increased) an additional farm is required to ensure economic viability. Note that an increase in yield would result in a change in the land use multiplier, i.e., decrease in area per $M.

To further complicate this difficult question, time is not well represented by this metric. While this metric considers a single year, land is typically used for many years. As an illustrative example, consider an automobile manufacturing facility in Lordstown Ohio. The facility occupies 520 ha and produced 14 million cars over 34 years, with annual output varying. Table 2.4 represents some possible metrics given this information. It is not possible to know how many years a facility will produce goods, and further, it is not typically the case that a retired facility is returned to its previous 'natural' state. More often a facility requires many years of environmental remediation or is left unoccupied. Therefore there is little certainty associated with metrics based on an assumed facility life [12, 45]. While this example was presented largely as a thought exercise, the underlying issue of how to address time with regard to land use and associated impacts is considerable.

Table 2.4. Example Quantitative Metrics for Land Use

Entire area of facility (ha/car)	Hectare (ha)/ #cars-yr	ha/#cars-life of facility (32 yr)	ha/ $Million (1997)	ha/ $Million (34 yr)
520	$4e^{-3}$ – $2e^{-3}$	$3.7e^{-5}$	$7e^{-2}$	$4e^{-3}$

Finally, there is an issue of defining land use and disparity of productivity across land use, even land used for the same purpose. These issues are particularly relevant for timberland and pastureland. The degree of impact as a result of using timberland varies year to year. The same hectare of forest cannot be harvested annually as a period of re-growth is required and the duration to the next harvest depends on the tree species. Environmental impacts associated with the initial harvest are diminishing over time as the land is left to re-establish vegetation. Spatial variation in characteristics of the land itself (soil type, geology, and climate, etc.) influence re-growth rate for trees and influence the type and amount of vegetative growth on pasturelands.

This work took a conservative approach by including all land classified as useable for timberland and pastureland. This assumption implies that all acres are treated equally despite varying production potential. For example, in 2002 there were approximately 200 Mha of land classified as timberland in the U.S. [3]. The average area harvested over the years 2001-2005 was approximately 4.4 Mha, with 1.7 Mha clear cut and 2.7 Mha partial cut [46]. By assigning only the area harvested to the sectors Logging - 113300 and Forest nurseries, forest products and timber tracts –1133A0, the area required to sustain annual harvest is not accounted for. Alternately, assigning the total area designated as timberland might overestimate area required to sustain output and implicitly treats all acres, i.e., those harvested in the study year and those harvested 20 years prior to the study year, as equivalent. A more accurate approximation of area required to support annual harvest rates could be completed if detailed area, tree species and associated re-growth rate data were available. Similar issues exist for pastureland; not all areas are grazed with the same intensity and the potential for grazing varies based on land characteristics.

2.3.2. Data Sources

Table 2.5 includes information and references for various data sources consulted for the completion of the production-based inventory. Not all of these data sources were used in the final inventory but are included here in the event that they are useful to other researchers.

The data are generally collected through surveys or satellite imagery. Survey data sources utilized include: Census of Agriculture [47], Agricultural Statistics [48], USDA Major Uses of Land Use Report (MULR) for 2002 [3], Forest Inventory and Analysis [49], Manufacturing Energy Consumption Survey – interior floorspace of buildings [50], Commercial Building Energy Consumption Survey – interior floorspace of buildings [51]. Satellite imagery programs include: Multi-Resolution Land Characteristics (MRLC) Consortium [52], the High Resolution Land Use and Land Cover Mapping (HRLULCM) Project [53] and the Land Cover Trends Project [54], USGS National Land Cover Dataset 1992 and 2001 [55], Land-Cover and Land-Use Change Program [56]. The Global Trade Analysis Project (GTAP) uses data generated by the Center for Sustainability and the Global Environment (SAGE) at the University of Wisconsin-Madison, which uses satellite and survey data, these data are used in Chapter 3.

Table 2.5. Available Data Sources for Land Use Inventory

Economic Land Use Category	Year	Units	Level of Data Available				Source
			National	Regional	State	County	
Agriculture	92-05	acres	x	x	x	x	[3, 47, 48]
Manufacturing	85,88,91, 94,98,02	sq. ft.interior, # bldgs	x	x	-	-	[50]
Commercial	92,95,99,03	sq. ft. interior, # bldgs	x	x	-	-	[51]
Mining	94-05	tons output	x	x	x	-	[55]
Transportation	93,95,97,99-06	miles	x	x	x	x	[57]
Forest/Timberland	Varies	acres	x	x	x	x	[46]
Residential	75-85, biennial to 05	# houses, dist.of lot area	x	x	x	-	[58]
Other – “barren land”	92,01	acres	x	x	x	x	[55]

2.3.3. Assigning Areas to the Inventory

The production-based inventory, required to create the land use vector (**F**), was assembled from several data sources. Land use data in hectares were used wherever possible to assign an area to each sector in the production-based inventory. With the exception of agricultural sectors, the approach to assigning land use to sectors was generally top-down, such as when data specific to an individual sector were not available an aggregate value was allocated to the sectors using other proxy data. This is particularly relevant to developed land and the sectors located on developed land. The primary source used to obtain this aggregate data is the USDA MULR for 2002, which assigns all 920 Mha of U.S. land (including Alaska and Hawaii) to six major categories in Mha: grassland/pastureland, 238; forest, 263; cropland, 179; special uses (e.g., roads, rail, parks, recreational lands), 120; miscellaneous (e.g., rural residential areas, marshes, deserts), 92; and urban land, 24 [3]. The MULR was used to ensure that estimates derived from other sources are reasonable and in the case of timberland, road and air transportation, and commercial and manufacturing industries, the MULR estimates were used directly. A full list of sectors and assigned areas is provided in Appendix A. A summary of data sources and areas assigned to sectors is described in the following paragraphs.

Hectares were assigned to crop and animal production sectors using USDA data, which annually reports area occupied by individual crops and animals [47, 48]. The only exception is Cattle Ranching and Farming, which was assigned the value reported for pastureland in the USDA MULR [3]. The USDA Census of Agriculture reports "land in farms," which does not include some publically owned pastureland [47].

The USDA MULR provides estimates for land classified as timberland, which was used to assign values to the following industries, Logging (#113300), and Forest Nurseries, Forest Products and Timber Tracts (#113A00). The total timberland value was allocated between these sectors using a ratio of the economic output of these two sectors.

Mining industries were assigned areas based on data from the 1992 USGS National Land Cover Dataset (NLCD) [55] and evenly assigned to the 9 mining sectors included in the inventory, with the exception of support activities that were not assigned a value. The 1992 USGS NLCD is the most recently available approximation for national mining land use and represents only surface mining. The Minerals Yearbook is the most comprehensive dataset available for mining statistics in the U.S. and reports economic value and weight of mined minerals annually [59]. Given the large disparity across mined minerals in terms of value, weight, quantity of overburden, there was no logical choice for using any of these quantities as an allocation proxy. Further, there is a lack of data for below-ground mining operations, which may be significant.

Area associated with road transportation industries was taken from the USDA MULR [3]. This area was allocated between personal transportation (Transit and Ground Transportation - 485000) and transportation of goods (Truck Transportation - 484000) using Federal Highway Fee Payment data [60]. Area associated with rail (482000) and air (481000) transportation industries were also taken from the USDA MULR [3]. Area estimated by the USDA for rail uses were divided between two sectors: 482000 (Rail transportation) and 485000 (Transit and ground passenger transportation) using system mileage data for Class I (freight) rail and commuter/passenger rail [57]. Area was estimated for sector 486000 (Pipeline transportation) using linear mileage of pipeline data from BTS, a buffer of 20 feet was assumed, no consideration was given to portions of the system that are underground. Land use for water transportation was assumed to be zero; on-land facilities associated with water transportation, e.g., ports, office space, were also excluded due to lack of data. Additional details about area assumptions for transportation sectors can be found in Appendix A.

There is little data available in units of area for assigning values to Commercial and Manufacturing sectors. The "Urban Land" and "Miscellaneous Land" categories included in the USDA MULR include industrial and commercial land uses. Also included in these categories are residential, recreational, and barren and marsh lands. It was assumed that such lands are not used to produce goods and services. Residential areas were allocated directly to households. Residential, recreational and barren lands were subtracted from the sum of Urban and Miscellaneous land categories, and this remaining area was assumed to approximate the area occupied by industrial and commercial sectors. This area was allocated to sectors at the 6-digit NAICS level using three allocation methods: number of employees, number of establishments (data are available for 2002 at 6-digit NAICS level) [61] and calculated building footprint (derived from floorspace and number of floors data available at 3- to 6-digit level).

Number of employees was considered as an allocation method based on the assumption that a certain quantity of building space is required for each worker. However, manufacturing facilities may have a great deal of space devoted to equipment and have relatively few employees while sky scrapers house many more employees per square foot and also occupy a relatively small footprint. Similarly, the number of establishments might be expected to correlate to area, though again some industries occupy relatively small amounts of space but may have many establishments (e.g., retail stores) while a larger facility (e.g., manufacturing) may have a smaller quantity of establishments.

Building footprint estimates for manufacturing facilities were estimated from the 2002 Manufacturing Energy Consumption Survey [50]. Building footprint estimates for commercial facilities were estimated from the 2003 Commercial Buildings Energy Consumption Survey [51]. Floorspace coupled with data on the number of floors enabled an approximation of building footprint by industry. However, building footprint does not include parking and other ancillary areas, e.g., staging areas. The value for 3-digit NAICS was assigned to 6-digit sectors when more detailed data was not available. Note that "number of floors" is not included in the MECS survey and it was assumed that all buildings included in the facility have only one floor, resulting in an overestimate of land use. MECS surveys the facility as a whole and includes all buildings onsite. This assumption is likely to be reasonable for the manufacturing buildings; however, this may introduce error when including other office-type structures included as part of the "facility" surveyed. Calculated building footprint was determined to be the most appropriate allocation proxy as it was the only value directly related to area. A plot of the three allocation methods and a summary of all areas allocated to the 434 sectors can be found in Appendix A.

Construction sectors were not assigned area values because these sectors are not included in the DOE surveys used to disaggregate developed land. There is likely a small portion of developed land associated with offices and storage structures. However, given the magnitude of the values associated with developed land this will not affect the results of this analysis.

A considerable amount of land area, approximately 200 Mha, is not directly used for economic activity and thus is not included in the inventory or EIO-LCA model. Much of this land area, however, is "consumed" by humans in the sense that it is directly occupied by humans e.g., residential land or is set aside for human enjoyment e.g., recreational land or protected areas. However, these areas may be impacted by activities carried out on adjacent land. Residential areas are added to land consumption categories directly without IOA. Recreational areas and barren lands, particularly those protected by the government, are excluded in this analysis.

While not included in this model, a considerable amount of land has been used for military testing. The Nevada Test Site used to test nuclear weapons is approximately 350,000 hectares alone [62] and up to 4 Mha may be contaminated with unexploded ordinances throughout the U.S. [63]. This area is approximately one-third of land used for transportation purposes.

A summary of the production-based inventory organized by aggregate North American Industry Classification System (NAICS) codes, consistent with input-output accounts used in the EE-IOA model is provided in Table 2.6. Table 2.6 also includes the range of calculated, nonzero F values for each aggregate NAICS code. The agricultural sectors account for the largest uses of land, with average values for F in the thousandths Mha/$M. Values for F in all other sectors are two to six orders of magnitude less in value.

Table 2.6. Summary of Production-based Land Use Inventory

NAICS Code	NAICS Code Description	Million hectares (Mha)	Number of Sectors	Number of Sectors with Non-Zero Values	Range in Land Use Multiplier (F) (ha/$M)[3]	Average value of F (ha/$M)[3]
11	Agriculture, Forestry, Fishing and Hunting	650	24	21	58 - 7000	2000
111	Crop Production	140	15	15	65 – 4300	1500
112	Animal Production	310	4	4	58 – 7000	2000
113	Forestry and Logging	200	2	2	-	5700
21	Mining	1	11	9	0.8 – 40	20
22	Utilities	0.3	3	1	-	3
23	Construction	0	7	0	-	-
31-33	Manufacturing	4.1	280	280	0.2 – 970	$1.2e^{-2}$
42	Wholesale Trade	0.3	1	1	-	$9.3e^{-3}$
44-45	Retail Trade	1.7	1	1	-	$4.5e^{-2}$
48-49	Transportation and Warehousing	15	10	9	$2.2e^{-2}$ – 140	30
51	Information	1.4	14	14	$7.3e^{-3}$ – 0.7	0.2
52	Finance and Insurance	0.3	6	6	$1.4e^{-3}$ – $1.1e^{-2}$	$5.3e^{-3}$
53	Real Estate and Rental and Leasing	0.5	6	6	$4.0e^{-3}$ – 0.2	$5.8e^{-2}$
54	Professional, Scientific, and Technical Services	0.1	14	14	$7.2e^{-4}$ – $1.8e^{-2}$	$4.6e^{-3}$
55	Management of Companies and Enterprises	<0.1	1	1	-	$2.1e^{-3}$
56	Administrative Support and Waste Management and Remediation Services	0.2	9	9	$8.4e^{-4}$ – $7.9e^{-2}$	$1.2e^{-2}$
61	Educational Services	1.9	3	3	0.1 – 0.5	0.3
62	Health Care and Social Assistance	1.3	8	8	$1.4e^{-3}$ – 0.4	0.1
71	Arts, Entertainment, and Recreation	0.8	9	9	$2.6e^{-2}$ – 1.2	0.3
72	Accommodation and Food Services	0.3	3	3	$3.4e^{-3}$ – 0.2	$7.2e^{-2}$
81	Other Services (except Public Administration)	0.8	13	13	$5.7e^{-3}$ – 0.5	$8.5e^{-2}$
92	Public Administration	<0.1	11	3	$1.6e^{-2}$ – 2.0	0.7
Residential – Urban		11[1]	-	-	-	-
Residential – Rural		21[1]	-	-	-	-
Total:		710	434	411	-	-

Notes: (1) External model variable in the input-output framework. (2) It was assumed that land associated with building expansion or new construction for individual sectors is negligible in a given year. Note however, that new construction in a given year is largely accounted for by private investments in structures. (3) Only sectors with non-zero values are included in the range and average.

2.4. Results of Input-Output Analysis

IOA was used to determine the values of **f**, Equation 2.2, making up the consumption-based inventory. Agricultural land and timberland are significant in the supply chains of all consumption categories. This is largely because nearly all sectors purchase food products or wood-based products at some point in their supply chain and because, as shown in Table 2.6, the land use multipliers for agricultural sectors are considerably higher than other sectors.

In order to examine whether types of land use vary according to final demand category (Equation 2.1.) the land use required to meet demand categories is determined separately, (Figure 2.1). Final demand from personal expenditures drives the majority of land used for the production of goods and services, accounting for 65% of total land use and 62% of economic expenditure, Figure 2.1. Personal expenditures are responsible for 84% of animal production land, 72% of developed land & mining, 65 % of cropland, and 36% of timberland. This is largely due to food directly purchased and consumed by individuals. Exports account for 18% of total U.S. land use and 8% of domestic final demand. A large portion of domestic cropland, 35%, is exported. Soybeans, corn and wheat are the largest bulk exports by weight and economic value [64]. Cropland is also embodied in exported food and meat products, and to a lesser extent through food and wood products consumed during the production of services and manufactured goods.

A significant portion, 33%, of timberland is associated with demand by Private Investment. The majority of timberland use, 76%, occurs due to large Private Investment demands in construction sectors, NAICS 23, which in turn make large purchases from wood manufacturing and fabrication sectors, e.g., Sawmills and Wood Preservation, Wood Kitchen Cabinet and Countertop Manufacturing, and Wood and Veneer and Plywood Manufacturing.

Demand from the government is the second largest in economic terms, but results in the least land use. The largest economic demands from sectors made by government spending are: General state and local government services (53%), General federal defense

(19%), General non-federal defense (11%), and Other nonresidential structures (10%). Government buildings are included in the developed land value used for the manufacturing and commercial sectors, but data are not available to include government buildings in the allocation. This exception would not change overall results. Also, as mentioned above in the Section 3.3, military testing grounds are not included in the IOA, but are fairly significant.

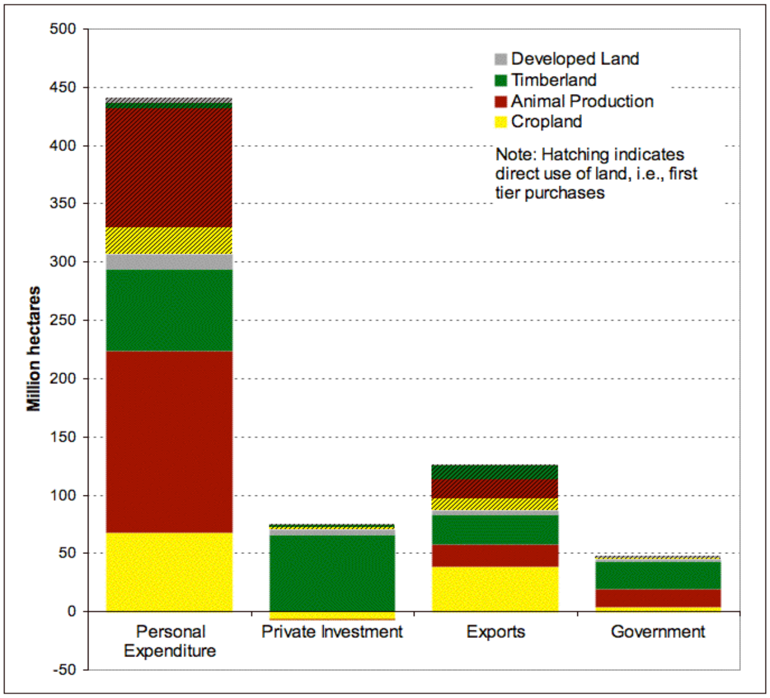

Figure 2.1. Land use associated with categories of final demand. Negative values occur in the Private Investment category due to accounting, i.e., stocks carried over from the previous year are assigned a negative value.

Figure 2.2 indicates the direct and upstream land embodied in consumption groups to meet total domestic final demand, including domestically produced exports. Consumption groups include all 434 sectors and are organized into 13 categories similar to those used in recent work by the community [65]. For example, animal food products include sectors that manufacture animal-based food products (cheese manufacturing, cattle slaughtering and processing) as well as agricultural sectors associated with animal production (hay and pasture farming, cattle ranching and farming). Additional details regarding the sectors included in each consumption group can be found in Appendix A. The most land-intensive commodities demanded in the U.S. are associated with Animal

Food Products, largely due to the area associated with pasturelands. Healthcare and Restaurants/Hotels generate a considerable amount of land in the cropland and animal production sectors due to food purchases. Timberland use is most prevalent in the Construction, Other Manufactured Goods, Communication/Services and Wood Products consumption groups. Land use, through the upstream consumption of agricultural products, e.g., food and paper products, can be significant even in industries that are not typically associated with significant direct land use.

Direct land use generally does not contribute significantly to total land use, average contribution of direct land over all 434 sectors is approximately 27%. Direct land use accounts for 48% of the Animal Food Product consumption group, 38% of Wood Products and 28% of Plant Food Products. This high direct land use occurs due to direct purchases from agricultural and forestry sectors to manufacture output. The least direct land use occurs in Healthcare (1.9%) and Education (2.1%) commodity groups. Healthcare and Education sectors purchase manufactured food and forestry products rather than raw inputs, therefore the bulk of purchases resulting in large land use occur beyond the first-tier of purchases.

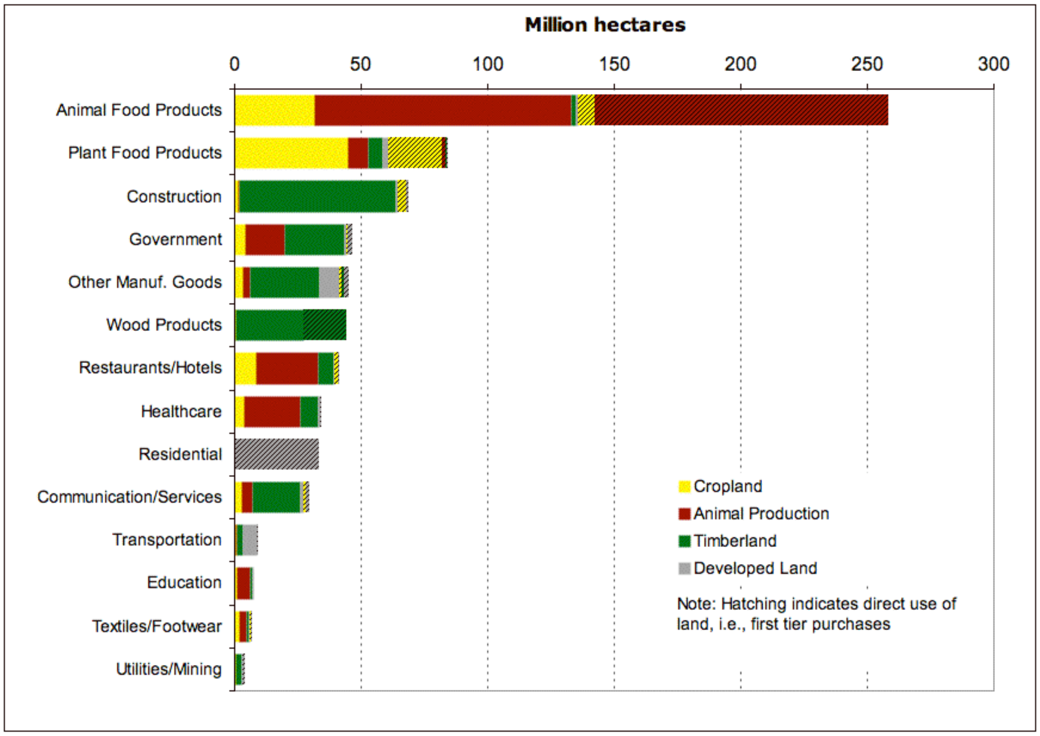

Figure 2.2. Land use required to meet total U.S. demand by consumption group

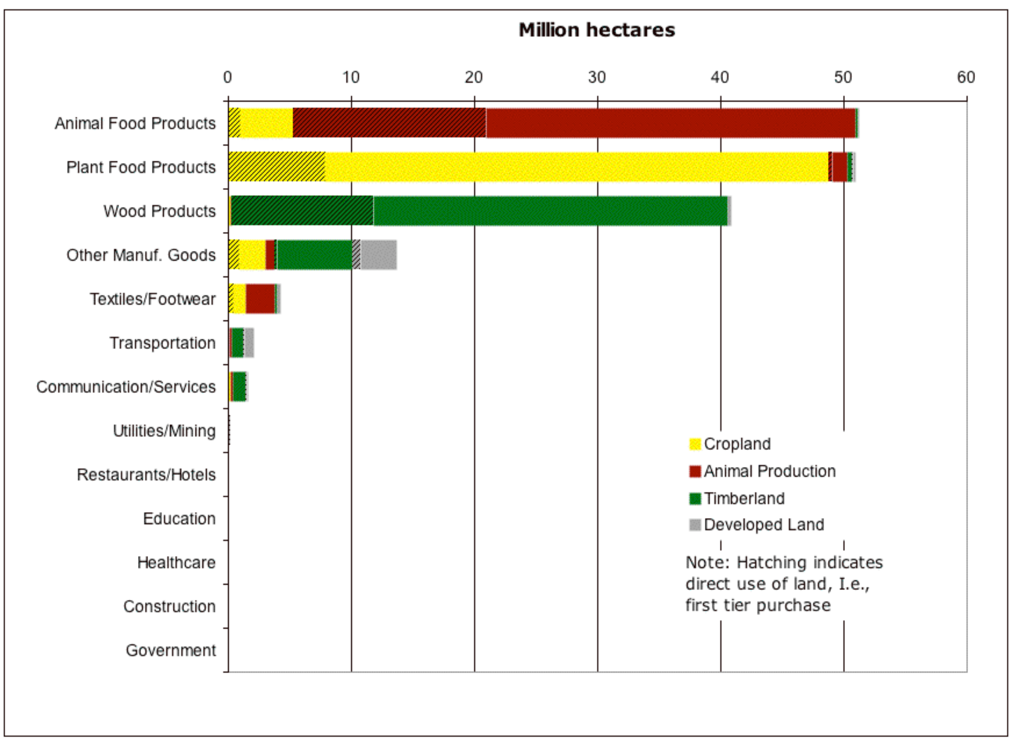

Figure 2.3. U.S. Land exported by consumption group

Total exported land is 165 Mha or 19% of land used for economic production in the U.S., Figure 2.3. Of this 49 Mha is cropland, 35 Mha is land for animal production land, 38 Mha is timberland, and 4.6 is developed land. With few exceptions U.S. crop yields are among the highest in the world. Therefore, if the U.S. were to decrease exports to meet domestic demand then global cultivated land would need to be created, either through increased yields or expansion of land in use.

2.5. Discussion

2.5.1. Uncertainties in Results

There are a number of relevant uncertainties in this analysis. The primary sources of uncertainty in the production-based inventory are allocation methods, data sources that are unavailable or out of date and assumptions about what constitutes 'land use.' For sectors included in the developed land category there is uncertainty regarding the estimation of developed land used to support industry and allocation to individual sectors, and additional discussion is included in Appendix A. However, given that the land areas associated with manufacturing, commercial and service sectors are in total an order of magnitude less than the area associated with cropland, the uncertainty does not have a large impact on the overall findings of this study.

The most recently available mining data (1992) [55] includes only surface disturbances due to mining operations, similar to Lenzen and Murray [8]. Sole consideration of surface activities is consistent with the goals of this analysis. However, inclusion of the subsurface may be very important when comparing LU between fossil fuels and biofuels. A more comprehensive dataset and potentially a separate subsurface metric to include underground mining and groundwater extraction for irrigation would benefit analyses that seek to compare LU between bio-based and fossil-based energy systems.

In some cases temporal and spatial issues introduce considerable uncertainty to the assignment of LU to a sector. These issues are particularly relevant for timberland and pastureland. The degree of use for an acre of timber- or pastureland can vary year to year, i.e., the same hectare of forest cannot be harvested annually. This paper took a conservative approach by including all land classified as useable for timberland and pastureland. This assumption implies that all acres are treated equally despite varying production potential. While in reality, location-specific variables such as soil quality and climate influence the productivity of land. As an illustrative example, in 2002 there were approximately 200 Mha of land classified as timberland in the U.S. [3]. The average area harvested over the years 2001-2005 was approximately 4.4 Mha, with 1.7 Mha clear cut and 2.7 Mha partial cut [46]. If one assigns only the area harvested to the sectors Logging - 113300 and Forest nurseries, forest products and timber tracts –1133A0 then the area required to sustain annual harvest is not accounted for. Alternately, if one assigns the total area designated as timberland then one might overestimate area required to sustain these sectors and implicitly treats all acres, i.e., those harvested in the study year and those harvested 20 years prior to the study year, as equivalent. A more accurate approximation of area would include area required to support annual harvest rates and would include detailed area, tree species and associated re-growth rate data. Similar issues exist for pastureland, e.g., not all areas are grazed with the same intensity and the potential for grazing varies based on land characteristics.

Marginal land and crop rotation present temporal and spatial issues for cropland. Marginal land, generally of less quality than cropland, may be used for cultivation when crop prices are high. The environmental impacts of using this lesser quality land are likely to be different than when cropland is used. Inclusion of a separate category for marginal land use could be useful here; however, it is not clear that these data are available. Crop rotation leads to the potential for land in one year to be used for a different crop in the following year. The corn-corn-soy rotation is well known as a common practice to restore nitrogen to soils through nitrogen-fixing soy following the cultivation of nitrogen-hungry corn. This reduces the amount of nitrogen fertilizer applied in the corn cultivation years. The quality of soil in any given year is a function of the cultivation that has taken place in previous years and could affect yields and thus land use associated with a particular crop. Given that this model was constructed by using actual land used and corresponding yields in 2002 this issue is not problematic in this analysis; however, it may be worth considering if one wished to use the model for future years or was interested in tracking land use impacts for a specified area.

2.5.2. Relevance of Results

Land has been used as a metric to educate the public about the connection between consumption and natural systems, i.e., ecological footprinting. However, such educational tools are of limited use in research efforts aimed at understanding the importance of land in relation to the production of goods or the associated environmental impacts. Further, understanding how land is actually used at a national scale allows for deeper understanding of the limited availability of land as a resource to meet consumption demands. This analysis demonstrates the importance of considering the entire supply chain when assessing land use in the production of any commodity.

Data quality and acquisition, spatial variation in land quality and temporal issues complicate the development of consistent qualitative or quantitative metrics for LU and associated impacts for LCA and sustainability research. Variability in climate and physical properties associated with the location of the land in use make it difficult to develop consistent impact metrics for even the same activity across different locations [66]. This question has become increasingly relevant to the question of biofuels and energy production in general. It is not clear that a generic LU impact metric could be developed to compare biofuel or other renewable and nonrenewable technologies as these activities are anticipated to occur in vastly different ecosystems, e.g., cropland versus mountains, and have very different impacts, e.g., eutrophication of waterbodies or decimation of mountain ecosystems.

Some authors have suggested weighting schemes for LU in an effort to compare scenarios [8, 12]. In general developed land is weighted more heavily than cropland and undisturbed land, e.g., forests, are not weighted at all [8, 12]. For this study no weights were assigned. Weighting schemes provide some insight to the degree of use and implied environmental burdens, however, they do not provide a good sense of how much land is currently dedicated to a particular purpose and may oversimplify actual impact. Alternatively, it might be most useful to organize land in terms of production potential or according to agro-ecological zones [24]. These differentiations would allow one to make assumptions about the potential for increased output from land currently in use versus expansion of land for a specific purpose, e.g., cropland. Since impact assessment metrics are often associated with area, therefore un-weighted areas may be coupled with existing impact metrics.

Connecting total land area to consumption allows one to assess how much land or how much intensification of current LU may be required to meet future consumption expectations. This work provides researchers insight to the type and quantity of land required to meet consumption demands, including upstream use of agricultural lands that may not be considered otherwise. At the large scale this work helps to understand the links between different types of land use activities. The model can be useful for initial scoping to identify land areas of interest for more narrowly focused or qualitative analyses.

At this point in human development, all land is valuable and should be considered a limited resource. All land has a use, and the environmental impacts are a function of the activities and the geography in which the impacts occur. At the global scale the goal should be to minimize land use change and corresponding environmental impacts like eutrophication, soil erosion, and loss of biodiversity. Decisions about LU to meet future energy and food needs should be made on a case-by-case basis with the intention of minimizing disturbance both in terms of quantity and quality. The approach taken in this thesis allows for an understanding of the quantity of land currently assigned to a particular use and thus can offer insight to the quantities of land anticipated to be necessary to achieve various goals. For example, this approach can be used to estimate land area required to meet biofuel production goals mandated by the Energy Independence and Security Act of 2007 [67] or food demand associated with population growth and dietary shifts. Increases in LU for a particular use, e.g., cropland, will come from land currently engaged in another use, whether it is abandoned cropland, forest, or pasture.

3. Chapter 3: Keeping Track of Land Crossing Borders: Land Use in Multi-Regional Input Output Analysis

The previous chapter showed how U.S. land is used to meet domestic and exported demand. The U.S. also imports goods and services produced on land elsewhere in the world. This chapter uses multi-regional input-output (MRIO) methods to quantify the land embodied in imported goods.

The globalization of the economy has created links between resources in one country and consumption in another. A growing effort is being made to quantify the amount and origin of environmental impact associated with traded goods and services. For example, the term "virtual" has been applied to describe the import and export of land [20] and water [28] among countries through traded agricultural products. Virtual land is defined by Wurtenberger as "productive areas hidden in imported or exported agricultural goods" [20]. In 2002 the United States imported over one million metric tons of raw coffee beans, which based on country-specific yield data equates to approximately 1.3 Mha of imported or 'virtual' land to the U.S. [68]. The U.S. imported $1.39 trillion worth of goods and services in 2002 [69], agricultural products accounted for $41.9 billion of these imports [70]. The U.S. exported $682 billion worth of goods and services [69] and $53 billion in agricultural exports [70]. The goal of this chapter is to evaluate the land associated with U.S. trade without directly calculating the land associated with each individual import, including the land associated with non-agricultural imports. Frequently, land associated with non-agricultural imports is not included in the analysis of "virtually" traded land, however, this land use may be significant, given the large upstream land use found in Chapter 2 for many goods and services.

The land embodied in imported goods will be estimated by expanding the IO model described in Chapter 2 to include a region to represent the rest of the world (ROW). A ROW land use multiplier is created using U.S. agricultural commodity import data and yield data for 175 crops in 226 countries [71]. Note that this model does not estimate land use change as a result of increased demand in one country resulting in increased production on marginal or newly cultivated lands, commonly referred to as indirect land use [4, 5].

3.1. Background on Modeling the Environmental Impact of Trade

Many of the modeling constructs and concepts for quantifying the environmental impact of trade were mentioned in Chapter 2, e.g., ecological footprinting, "virtual" land use, MRIO, and economic-based general and partial equilibrium models all attempt to quantify and track emissions through the production of goods and services. These models also allow one to consider the land use associated with each country or region included in the respective models for comparative purposes. In addition to the background information included in Chapter 2, this Chapter includes an overview of producer versus consumer responsibility and a brief discussion of Materials Flow Analysis. These topics provide relevant concepts useful for the discussion of land use and trade. This work uses an MRIO approach and while no particular stance is taken on producer versus consumer responsibility the discussion is important for understanding the significance of the results.

The determination of which country, i.e., the producing or consuming country, is responsible for the environmental impacts associated with the consumption of goods and services is an active area of research most commonly associated with global GHG policy [72, 73], though the issues raised can be extended to all environmental impacts. Land is a unique subject because environmental impacts of LU are typically localized [74], with the exception of carbon emissions associated with land use change [4, 5]. GHGs have global environmental impact and thus all producers and consumers bear the consequences of emissions, while the use and often degradation of land tends to result in localized impacts [74]. The local nature of LU impacts essentially makes the impacts invisible to far away consumers and also results in lack of motivation for tracking and regulating land use. Currently GHG policy is designed to place responsibility on the producer [27, 72]. Weber et al. found that in 2005 up to one-third of Chinese CO_2 emissions were due to the production of exports, likely driven by consumption in developed countries [75].

The producer versus consumer question in essence is, who should be responsible for emissions, the producing country and the country experiencing economic gain or the consuming country, presumably the country creating the demand, which drives the production. These works are mentioned because there are analogous issues to consider in the discussion of land use. This is particularly true as efforts to understand how increased demand for agricultural products may increase land use in foreign countries and as this land use may also result in carbon emissions due to land clearing [4, 5]. While it is not in the scope of this paper to explicitly address these questions, the results will be presented so as to consider both the LU associated with U.S. production and consumption.

Materials Flow Analysis (MFA) is another concept that lends relevance to this discussion. MFA seeks to track the movements of physical materials through economies and uses. MFA has been combined with IOA to track materials through economies and trade [76, 77]. Nutrients and minerals in soils, both applied and naturally occurring, are taken up by crops and animals and transported locally, regionally, and globally in food and feed products [78, 79]. More abstractly, we can think of land required for production being embodied in products and subsequently consumed elsewhere. In fact, Wurtenberger used the principles of MFA to calculate the land associated with agricultural imports, no efforts were made to determine LU for non-agricultural imports [20].

A few authors have used MRIO methods to approximate land associated with trade to and from a particular country [27, 80]. Multiregional input-output analysis (MRIO) is a well-developed method for considering the economic relationships between economies [38]. MRIO models have the ability to distinguish between different production patterns, energy usages, and emissions factors in different locations of global production chains [81]. This ability to differentiate can allow one to better quantify the domestic as well as non-domestic land required to produce a particular good or service. MRIO has been used in numerous studies aimed at tracking embodied emissions and materials through trade [9, 44, 72, 82].

MRIO models have some specific challenges, largely stemming from the difficulty of data acquisition, both for constructing multipliers and for representing the technology matrices of individual countries with the same resolution. There are two major contributors to this challenge. One is developing a technology matrix to represent the other regions (the biggest tradeoff is sector detail versus using country specific technology mixes). The other is gathering data to accurately represent environmental impact per sector. Some have suggested using country-specific yields to assess land used by a particular country to accurately estimate the amount of land embodied in imported goods and services, but simultaneously note the data challenges [83]. Others have used global average hectares or made the assumption that the land associated with imports is the same as the land required in the domestic country of study [80]. Erb et al. conducted an analysis for Austria using global average hectares (as is done in Ecological Footprinting) and a detailed assessment of land embodied in imports using Austria-specific import data and corresponding country-specific yields obtained through the UN Food and Agricultural Organization (FAO) [83]. They found that results differed considerably, actual Austrian land use was less than that approximated with global averages [83]. This points to the importance of using country-specific data to reflect varying yields. Wilting and Vringer use MRIO to assess the GHG emissions and LU for 12 world regions, sector aggregation is more coarse in this study than in the one conducted herein [27]. Results were similar to other studies comparing producer and consumer approaches, i.e., North America, OECD European countries, and the Japan and New Industrializing Economies (Hong Kong, Japan, Korea, Taiwan, and Singapore) have higher GHG emissions and LU in the consumer approach than the producer approach [27]. This general finding of trade and associated impacts flowing from non-Annex I (mostly developed countries) to Annex I (mostly developing countries) countries is consistent with the findings of Peters and Hertwich regarding GHG emissions [72, 75].

In this MRIO analysis the world is split into two regions, the U.S. and the ROW. Land use data for the U.S. are fairly abundant and can be easily updated as new surveys and inventories are made available. Land associated with imports was captured by considering country-specific yield values for agricultural commodity imports. Land use values for non-agricultural commodities were assumed to be equivalent to LU in the U.S.

3.2. Multiregional input-output analysis

The MRIO constructed in this chapter builds on the IO model presented in Chapter 2. The basic principles are the same, except that there are two regions, the U.S. and the rest-of-world (ROW). The 2002 U.S. IO tables developed by the BEA form the foundation of the model and are decomposed into domestic and imported components in order to estimate:

- Domestic and imported land embodied in domestically produced final products,
- U.S. land in exports to the ROW including the amount of land imported to U.S. industry and then exported, and
- Virtual or embodied land in imports to the U.S.

3.2.1. Theoretical background

The Leontief inverse, discussed in Chapter 2, can be generalized for an open economy, where only output related to country 1 is considered [84]:

Equation. 3.1. $x = \left(A_{11} + \sum_{j \neq 1} A_{j1}\right)x + y_{11} + \sum_{j \neq 1} y_{1j} - \sum_{j \neq 1} y_{j1}$

where $\mathbf{A_{11}}$ is the domestic portion of the direct requirements matrix (domestic inter-industry demand on domestic goods), $\mathbf{A^m} = \sum A_{j1}$ is the import matrix (domestic use of imports to make domestic output), and $\mathbf{y_{11}}$, $\mathbf{y^m} = \sum y_{j1}$, and $\mathbf{y^{ex}} = \sum y_{1j}$ represent domestic final demand on domestic production, imports from all countries to final demand in country 1, and exports from country 1 to final demand in all other countries, respectively [85].

This equation can be expressed in matrix form for the m-region multiregional case, where each of m countries imports from every other country, to both inter-industry demand as well as final demand:

Equation 3.2. $\begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & \cdots & A_{1m} \\ A_{21} & A_{22} & \cdots & A_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \cdots & A_{mm} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{pmatrix} + \begin{pmatrix} y_{11} + \sum_{j \neq 1} y_{1j} \\ y_{21} + \sum_{j \neq 2} y_{2j} \\ \vdots \\ y_{m1} + \sum_{j \neq m} y_{mj} \end{pmatrix}$

which shows the relation between total production in each country, x_j, and final demand in each country, both from domestic production ($\mathbf{y}_{mm}$) and from imports ($\sum_{j \neq m} y_{mj}$). Each country $\mathbf{y}_{j1}$ represents imports from country j to final demand in country 1 and $\mathbf{y}_{1j}$ represents country 1's exports to final demand in all other countries [85].

There are two main approaches to evaluating the environmental impact embodied in trade, one considers the total bilateral trade between two regions also referred to as emissions embodied in trade (EEBT), Equation 3.3 and the other is MRIO, which differentiates imports into imports to industry and imports to final demand [72]. The MRIO approach allows for consideration of a specific domestic technology matrix, $\mathbf{A^d}$, the technology mix associated with imported goods to domestic industry, $\mathbf{A^m}$, and imports to final demand are evaluated separately assuming that the technology for goods and services imported to final demand is equivalent to that of the U.S., $\mathbf{A^{ROW}}$. That is to say that the MRIO model distinguishes between trade that goes into intermediate and final consumption [72]. In some cases, the difference in results, specific to GHG emissions, from EEBT and MRIO can differ by 20% or more depending on their trade structures [32, 72].

Equation 3.3. $f^{rs} = F^r \times (I - A^{rr})^{-1} \times e^{rs}$

Equation 3.4. $\left(\frac{X^d}{X^m}\right) = \begin{pmatrix} A^d & 0 \\ A^m & A^{ROW} \end{pmatrix} \times \left(\frac{X^d}{X^m}\right) + \left(\frac{Y^d}{Y^m}\right)$

Equation 3.3. represents the EEBT method of approximating land use, f^{ROW}, associated with final demand for imports. $\mathbf{A^d}$ represents direct domestic, i.e., U.S., inter-industry requirements of production. $\mathbf{A^m}$ represents direct use of imports by U.S. sectors. $\mathbf{A^d}$ and $\mathbf{A^m}$ were derived from the 2002 make, use, and import tables [40]. $\mathbf{A^{ROW\text{-}ROW}}$ is assumed to be equal to that of the U.S. total ($\mathbf{A^d}$ + $\mathbf{A^m}$) direct requirements matrix to keep sectoral consistency with the domestic portion of the model [86]. While ROW production practices may vary the U.S. economy is especially diverse and thus a reasonable selection for this purpose. Use of the most readily available technology matrix, typically that which best matches the other selected matrices is fairly common in these types of analyses [81, 87]. The representativeness of U.S. agricultural practices to the rest of world is discussed below in the uncertainty section. $\mathbf{Y^d}$ represents final demand for goods produced domestically, including intermediate imports, i.e., goods imported to domestic production rather than directly to final demand, and $\mathbf{Y^m}$ represents domestic demand for goods produced in ROW, i.e. imports. This decomposition allows results to be presented in terms of these different demand categories.

Equations 3.5 and 3.6 were used to estimate land use associated with the following: domestically produced and consumed goods and services, U.S. exports, imports to the U.S., and imports to the U.S. that were then re-exported to the ROW.

Equation 3.5. $L^* = \begin{pmatrix} L^d & 0 \\ L^m & L^{ROW} \end{pmatrix} = \left(1 - \begin{pmatrix} A^d & 0 \\ A^m & A^{ROW} \end{pmatrix}\right)^{-1}$

Equation 3.6. $f = F \times \left(\hat{L^*} \times y\right)$

where: $F = \dfrac{F^{US}}{F^{ROW}}, y = \dfrac{y^d}{y^m}$

Where $\mathbf{L^*}$ represents the total requirements matrix or the total supply chain requirements, which represents the interactions between the two regions modeled and **f** represents the land use (Mha) associated with demand, **Y**, million U.S. dollars ($M US) [39]. Demand is separated into demand for domestic, $\mathbf{Y^d}$, and imported, $\mathbf{Y^m}$, goods and services. Both $\mathbf{Y^d}$ and $\mathbf{Y^m}$ are separated into three categories: personal, private, and government expenditures. $\mathbf{Y^d}$ also includes demand for exports. **F** represents the land use multiplier (Mha/$M US) associated with the U.S., $\mathbf{F^{US}}$, and ROW, $\mathbf{F^{ROW}}$. As in Chapter 2, **A** represents direct inter-industry requirements of sectors to produce goods and services.

There are a number of assumptions often associated with IOA models and in addition some specific assumptions were made for this analysis. In general, IOA models make the following assumptions: fixed and linear coefficients, inputs are used in fixed proportions, and price homogeneity [38, 86]. Similar to Peters and Hertwich [86] and Lenzen et al.

[87], it was assumed that multidirectional trade was negligible, that is, the U.S is able to import from and export to the ROW, but U.S. exports are never re-embodied in ROW exports to the U.S. This assumption was made to reduce data requirements and to retain the greater sector detail offered by the U.S. IO tables. Obtaining detailed trade tables between all nations is difficult and requires a great deal of sector aggregation to match trade tables.

3.2.2. ROW Land Use Multiplier

A land use multiplier for the ROW was required to assess the amount of land embodied in goods imported to the U.S. In Chapter 2, agricultural sectors were determined to be the most significant sectors with respect to land use, at an order of magnitude, or more, greater than commercial or service sectors. For example, the majority of land associated with demand, both domestic and imported, for breakfast cereal manufacturing is associated with grain production, 2.1 Mha, and only a small portion is associated with the manufacturing facility processing the grain, 0.04 Mha. Therefore, it was decided that only the 15 crop production agricultural sectors in the land use multiplier would be adjusted to represent ROW land use, while the remaining 419 sectors have the same LU multiplier values as found for the U.S.

First, some information regarding quantity and origin of agricultural imports to the U.S. The U.S. imports a wide variety of crops and produce from nearly every country in the world. The largest quantities of agricultural commodities are imported from Canada and Mexico, both in terms of economic value and weight, Tables 3.1 and 3.2. In general the U.S. imports produce primarily from Mexico and grains from Canada where yields are often comparable to those in the U.S.

Table 3.1. Top 5 countries from which the U.S. imports by weight

Country	metric tons	% of total in USDA data
Canada	4,920,152	23.5%
Mexico	3,541,952	16.9%
Costa Rica	1,539,664	7.4%
Guatemala	1,426,945	6.8%
Ecuador	1,167,614	5.6%

Table 3.2. Top 5 countries from which the U.S. imports by economic value

Country	$1000	% of total USDA data
Mexico	2,516,038	22.3%
Canada	1,270,729	11.3%
Chile	757,242	6.7%
Indonesia	634,426	5.6%
Costa Rica	592,920	5.3%

In order to approximate the land use per dollar of imported demand to create $\mathbf{F}^{\mathbf{ROW}}$ agricultural sectors in the U.S. LU multiplier were adjusted using import data for agricultural commodities and country- and crop-specific yield data [71]. This approach avoids the need to obtain sector-specific data for all countries in the world. This approach also ensured that yields associated with actual imports were used thereby avoiding the inclusion of yields from countries that that U.S. does not import from. The Center for Sustainability and the Global Environment (SAGE) has developed a dataset consisting of production in metric tons and area utilized per crop, per country for 175 crops, in 226 countries, circa the year 2000. The data focus on agricultural land and use two satellite imagery datasets and inventory data from individual countries, often as compiled by the United Nations Food and Agriculture Organization [71]. The following equations describe how $\mathbf{F}^{\mathbf{ROW}}$ for agricultural sectors was created.

Equation 3.7. $F_i^{ROW} = F_i^{US} \times (Y_{US}/Y_{ROW})$, i = 1:15

Equation 3.8. $Y_{US} = \frac{\sum_I Y_{kUS}^{US}}{n}$, where i = 1:15, k = 1:175

Equation 3.9. $Y_{ROW} = \frac{\sum_i m_{k,j}}{\sum_i A_{k,j}}$, where i = 1:15, j = 1:226, k = 1:175

Equation 3.10. $A_{i,j} = \frac{m_{k,j}}{y_{k,j}^{im}}$, where i = 1:15, j = 1:226, k = 1:175

Where $\mathbf{Y}_{US}$ represents the average yield for U.S. crops included in each agricultural sector 1 through 15. Each crop, k, was mapped to an agricultural sector, Table 3.3 notes the crops included in each sector. Generating a sector average for the ROW multiplier required some additional steps. The U.S. imports differing quantities of crops from many different countries. First, agricultural commodity import data were collected from the USDA Foreign Agricultural Service to determine specific crop and origin country data [64]. These data report the agricultural commodities imported to the U.S. from each trade partner in units of physical weight and economic value. Approximately 1700 agricultural commodity entries were collected from the USDA database. Second, a land area was calculated for each imported commodity using the country-specific yield value calculated from the corresponding SAGE data. Thirdly, each crop's weight ($m_{k,j}$) and area ($A_{k,j}$) were summed according to sector, Table 3.3, Equation 3.7, to generate $\mathbf{Y}^{\mathbf{ROW}}$. This weighted average for each sector accounts for the quantity of imports specific to each country to better represent land use from the ROW associated specifically with U.S. demand. Finally, a ratio of $\mathbf{Y}_{\mathbf{US}}$ to $\mathbf{Y}_{\mathbf{ROW}}$, Equation 3.7, was used to estimate the quantity of ROW land required to meet equivalent US demand. For example, yields for soy production are 2530 kg/ha in the U.S. and 2360 kg/ha in the ROW (specific to U.S. imports), thus for each hectare of land required to meet U.S. demand 1.07 hectares are required from the ROW, resulting in F_{ROW} of 0.00238 Mha/$M, Table 3.4. This is in itself an assumption because there are discrepancies in valuation of commodities across countries. In general, the agricultural commodities imported to the U.S. are valued at the location of import and can be though of as producer prices. The uncertainty introduced by assuming economic equivalency is discussed below in the Uncertainty section, Section 3.5.1.

Table 3.3. Crops Included in Economic Sector Groups

Sector	SAGE crops
Soybean farming	soybeans
Other oilseed farming	*castor beans*, coconuts, mustard seed, oil palm fruit, oilseeds (other), poppy seed, rapeseed, safflower seed, sesame seed, sunflower seed, *tung nuts*
Corn farming	corn, *pop corn*, *green corn*
Wheat farming	wheat
Rice farming	paddy rice
Other grain farming	Barley, buckwheat, canary seed, cereals (other), *fonio*, millet, *mixed grain*, oats, *quinoa*, rye, sorghum, *triticale*, beans (dry), broad beans (dry), chick peas, *cow peas (dry)*, lentils, *lupins*, *pigeon peas*, pulses (other), *vetches*, *cassava*
Vegetable and melon farming	Pimento, potatoes, *roots and tubers (other)*, *sweet potatoes*, *taro*, *yams*, *yautia*, artichokes, asparagus, green beans, *green broad beans*, cabbages, cantaloupes and other melons, carrots, cauliflower, *green chilies and peppers*, cucumbers and gherkins, *eggplant*, garlic, lettuce, mushrooms, *okra*, *onions (dry)*, green onions and shallots, green peas, *pumpkins/squash/gourds*, spinach, *string beans*, tomatoes, fresh vegetables (other), watermelons
Tree nut farming	*olives*, almonds, brazil nuts, cashew nuts, chestnuts, hazelnuts, *nuts (other)*, pistachios, walnuts
Fruit farming	apples, apricots, avocados, bananas, *berries (other)*, *blueberries*, *carobs*, *cashew apple*, cherries, citrus fruit (other), cranberries, currants, dates, figs, fresh fruit (other), *fresh tropical fruit (other)*, *gooseberries*, grapefruit and pomelos, grapes, kiwi fruit, lemons and limes, mangoes, oranges, papayas, peaches and nectarines, pears, *persimmons*, pineapples, plantains, plums, *quinces*, raspberries, *sour cherries*, *stone fruit (other)*, strawberries, *tangerine/mandarin/Clementine*
Greenhouse and nursery production	No data.
Tobacco farming	tobacco
Cotton farming	seed cotton
Sugarcane and sugar beet farming	sugar beets, sugar cane, *sugar crops (other)*
Hay and pasture farming[1]	fodder: *beets*, *cabbage*, *carrots*, *green oilseeds*, *swedes*, *turnips*, *vegetables and roots*. forage and silage: *alfalfa*, *clover*, *forage products (other)*, *forage and silage grasses(other)*, *leguminous (other)*, *maize*, *mixed*, *rye grass*, *sorghum*
All other crop farming	Abaca (manila hemp), agave fibers (other), *coir*, fiber crops (other), *flax (fiber and tow)*, *hemp (fiber and tow)*, *jute*, *jute-like fibers*, *kapok fiber*, *kapokseed in shell*, *ramie*, sisal, groundnuts in shell, *hempseed*, *karite nuts (sheanuts)*, linseed, *melonseed*, *anise/badian/fennel*, *areca nuts (betel)*, chicory root, *cinnamon*, *cloves*, cocoa beans, green coffee, *ginger*, *hops*, *kolanuts*, *mate*, natural gums, natural rubber, *nutmet/mace/cardamom*, *pepper*, *peppermint*, *pyrethrum (dried flower)*, *spices (other)*, tea, *vanilla*, *bambara beans*

Note: Crops in italics are included in the SAGE dataset, but were not found as imports to the U.S. in the USDA GATS database. (1) Imported crop residues were not included as this could lead to double-counting of land areas. For example, various grain “sharps” are imported to the U.S., if assigned the yield for the corresponding grain then the area would be counted potentially twice, once for grain and once for the residue.

Table 3.4. Summary of LU multipliers and sector yields for agricultural sectors

Sector Name	US sector yield	ROW sector yield	U.S. multiplier, F^{US}	ROW multiplier, F^{ROW}	Percent Difference in multiplier
Soy farming	2,526	2,360	2.225E-03	2.382E-03	-7.0%
Other oilseed farming	1,412	966	2.008E-03	2.934E-03	-46.1%
Corn farming	8,421	6,843	1.850E-03	2.276E-03	-23.1%
Wheat farming	2,754	2,307	4.460E-03	5.324E-03	-19.4%
Rice farming	6,930	2,952	1.719E-03	4.035E-03	-134.8%
Other grain farming	2,078	2,399	3.874E-03	3.354E-03	13.4%
Vegetable and melon farming	21,533	16,316	1.977E-04	2.610E-04	-32.0%
Tree nut farming	3,173	519	1.604E-04	9.808E-04	-511.5%
Fruit farming	16,608	20,705	2.233E-04	1.791E-04	19.8%
Greenhouse and nursery production	NA	NA	6.472E-05	6.472E-05	0.0%
Tobacco farming	2,357	1,373	1.232E-03	2.116E-03	-71.7%
Cotton farming	1,877	3,805	1.861E-03	9.178E-04	50.7%
Sugarcane and sugar beet farming	63,434	61,824	4.788E-04	4.913E-04	-2.6%
Hay and pasture farming	25,011	NA	1.462E-03	1.462E-03	0.0%
All other crop farming	1,677	826	1.015E-03	2.062E-03	-103.1%

As can be seen in Table 3.3, the number and variation in crops included in each sector is considerable, with the exception of single crop sectors Soy, Corn, Wheat, Rice, Tobacco, and Cotton. Though even single-crop sector yields represent a weighted average based on imports from multiple countries with differing yield values, Table 3.4. For sectors with many contributing commodities the sector yield is representative of vastly differing commodities from many countries resulting in two sources of aggregation error. In some cases, the U.S. imports a number of commodities that are not grown at all in the U.S., or at least grown in very small quantities compared to imported quantities. For example, the U.S. produced only 9,070 mt of bananas while imports were approximately 3.91 million mt from 13 different countries. For these reasons, caution should be taken when interpreting the difference between U.S. and ROW land use multipliers.

3.3. Results

Figure 3.1 indicates domestic and imported land use required to meet the demands associated with the four final demand categories, personal, private and government expenditures and exports. The columns show the type (cropland, animal land, i.e., pastureland and grazed land, timberland, and developed land) and origin (domestic or imported from ROW, imports are noted with hatching) of land required to support domestic demand. Personal expenditures result in 570 Mha of land, by far the largest cause for land use in the U.S., of this 23% is imported from the ROW. The majority of domestic and imported land required to meet demand for personal needs is agricultural. Exports are the second largest demand on U.S. land, also note that 14 Mha of imports to industries are re-exported. Agricultural lands makes up the majority, 96%, of exports. Similar to the results in Chapter 2, Private and Government demand require the least LU to meet demand.

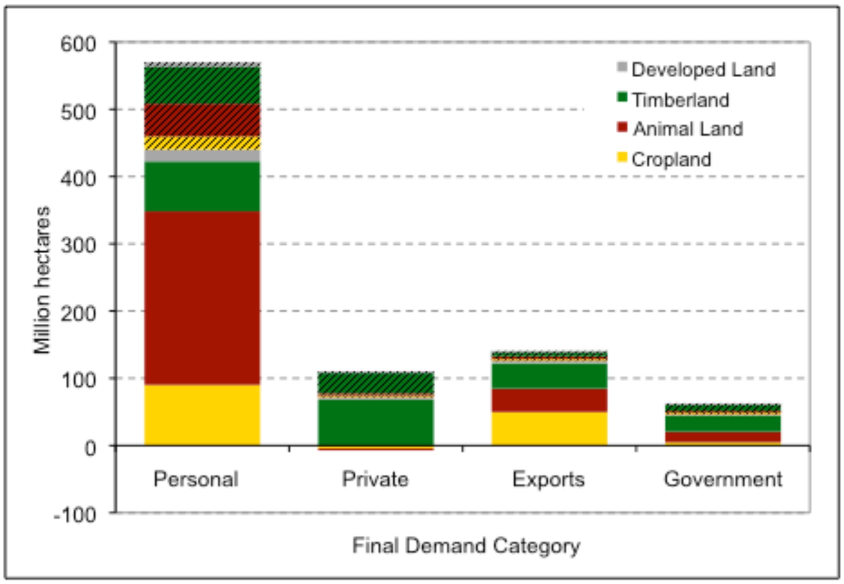

Figure 3.1. Land Area Required to Meet Final Demand Category, hatching indicates imported land from the ROW to meet domestic demand.

Figure 3.2 presents the land required to meet domestic demand and exports, represented by the line, as organized by consumption category. As is the case in Figure 3.1, the columns represent land required to meet U.S. consumption, the hatched portions of the column represent the land imported from the ROW. The consumption categories are the same as those found in Chapter 2 and described in detail in Appendix A. The 'uncertainty' bars indicate the range in cropland estimated using the lowest and highest yields within the range for imported agricultural commodities used to generate weighted-averages for sectors. That is, if all commodities were imported from the country with the lowest yield, cropland would be estimated as the value represented by the 'top' of the uncertainty bar and vice versa. In some cases this range is fairly large, e.g., Plant food products, but overall this would not change results. Recall that in some cases, e.g., Vegetable and melon farming, the range in yields is large due to variation in crops and associated yields. It is likely that this range in estimated land use would decrease if these sectors were further disaggregated.

Figure 3.2 shows findings similar to those found in Chapter 2, land use associated with demand for Plant and Animal products dominates land use, followed by the Construction category. The line overlaying the columns on Figure 3.2 represents the quantity of U.S. land embodied in exports to the ROW in each consumption category. Table 3.5 summarizes domestic and imported LU associated with U.S. domestic consumption. The result of including imported goods and services and the associated 'virtual' land imported increase land associated with U.S. consumption considerably. Figure 3.2 and Table 3.5 show that 182 Mha of land are virtually imported to meet U.S. consumption, not including the 14 Mha re-exported.

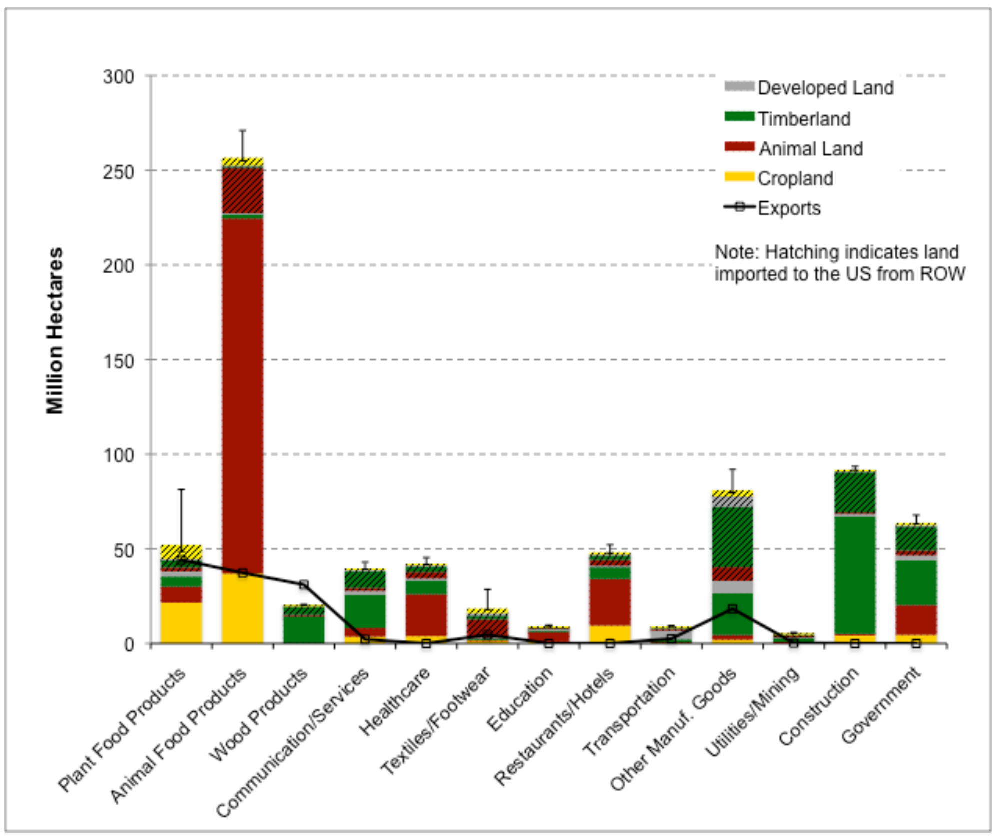

Figure 3.2. US Land Consumption by Type and Origin, Including Exports (2002)

Table 3.5. Domestic and imported land used to meet demand in each consumption category

Consumption Category	Demand met by Imported LU (%)	Domestic Land (Mha)	Imported Land for Domestic Use (Mha)
Textiles/Footwear	83%	3	15
Other Manuf. Goods	59%	33	48
Communication/Services	30%	28	12
Utilities/Mining	27%	4	1.5
Government	27%	47	17
Plant Food Products	27%	38	14
Wood Products	26%	15	5.2
Construction	25%	69	23
Healthcare	18%	34	7.7
Education	17%	8	1.5
Transportation	16%	8	1.5
Restaurants/Hotels	15%	41	7.0
Animal Food Products	11%	227	29
Total	25%	555	182

There are some interesting observations to be made regarding sectors and consumption categories that have high import to domestic ratios. In total approximately 25% of all land required to meet U.S. consumption is imported. The percent of imported land varies considerably with regard to consumption category. Demand for Animal Food Products is largely met my domestic lands, 89%, however imports to this category rank second by quantity. This is largely because LU associated with cattle production is very large. U.S. demand in the Textiles/Footwear category is met largely with land outside of U.S. borders. The Other Manufactured Goods category is the second largest category met by imported land. This category includes 204.5 (some sectors were split across categories) sectors and is associated with 81 Mha of land, 59% of which is from the ROW. Table 3.6 presents data for the sectors in the Other Manufactured Goods consumption category with more than 1 Mha of total imported LU, they are included here to provide insight to the type of data generated for each sector. Aside from land use associated with animal production in vehicle manufacturing, i.e., leather used for interiors, timberland is largest land use type associated with these imported goods, largely associated with packaging.

This closer look at the type of land use associated with the Other Manufactured Goods consumption category reflects the importance of including all sectors in land use analyses. In general, LU is not thought to be very large for non-agricultural imports and thus they have often been neglected in similar analysis [20, 83]. Omission of these non-agricultural goods and services would result in a significant oversight of approximately 134 Mha, of these 85 Mha are timberland, 29 Mha are animal production land, 11 Mha are cropland, and 9 Mha are associated with developed land. This result highlights the benefit of assessing LU using an IOA method. Input-Output analysis allows the upstream and often more land intensive inter-industry purchases and associated LU to be quantified for products that are generally not considered to be land-intensive. Further, the importance of agricultural land use in non-agricultural goods and services becomes apparent.

Table 3.6. Sectors with more than 1Mha of virtually imported land in the Other Manufactured Goods consumption category

Sector Number	Sector Name	Total Imported Land (Mha)	Cropland (Mha)	Animal Land (Mha)	Timber -land (Mha)	Developed Land (Mha)
336112	Light Truck and Utility Vehicle Manufacturing	7.7	0.5	2.7	3.4	1.1
337122	Nonupholstered wood household furniture manufacturing	6.4	0.1	0.0	6.3	0.1
336111	Automobile Manufacturing	6.4	0.4	2.5	2.4	1.1
325412	Pharmaceutical preparation manufacturing	1.8	0.5	0.7	0.5	0.1
339930	Doll, toy, and game manufacturing	1.7	0.1	0.0	1.5	0.1
334300	Audio and video equipment manufacturing	1.7	0.1	0.3	1.0	0.3
326210	Tire manufacturing	1.6	0.1	0.0	1.5	0.0
337121	Upholstered household furniture manufacturing	1.3	0.1	0.0	1.2	0.0
337212	Custom architectural woodwork and millwork	1.2	0.0	0.0	1.1	0.0
33999A	All other miscellaneous manufacturing	1.0	0.0	0.0	1.0	0.0
339920	Sporting and athletic goods manufacturing	1.0	0.0	0.0	0.9	0.0
	Sum of Remaining Sectors	15.9	1.4	1.0	11.2	2.4
	Total	47.8	3.2	7.2	31.9	5.4

Note: Some totals may not sum due to rounding.

If trade of materials and resources were balanced and environmental impacts for all extraction and production processes were equivalent then the issue of producer versus consumer responsibility would not be necessary. As alluded to previously in Section 3.1, the flow of materials and resources is not balanced and generally the flow is from developing nations to developed nations. The results of this MRIO analysis allow us to assess the balance of land use with respect to trade for the U.S. Figure 3.3 shows the virtual land imported and U.S. land exported by consumption category.

Of the 682 Mha of land associated with economic output in the US, 555 Mha are used to meet domestic final demands and the remaining 127 Mha are exported to the ROW. In total 196 Mha of land are imported to the US, of which 121Mha are used in domestic sectors to produce goods, 62 Mha are imported directly to final demand, and the remaining 14 Mha are re-exported to the ROW. So in summary, the U.S. trade balance is negative, with approximately 55 Mha more land virtually imported through goods and services than exported.

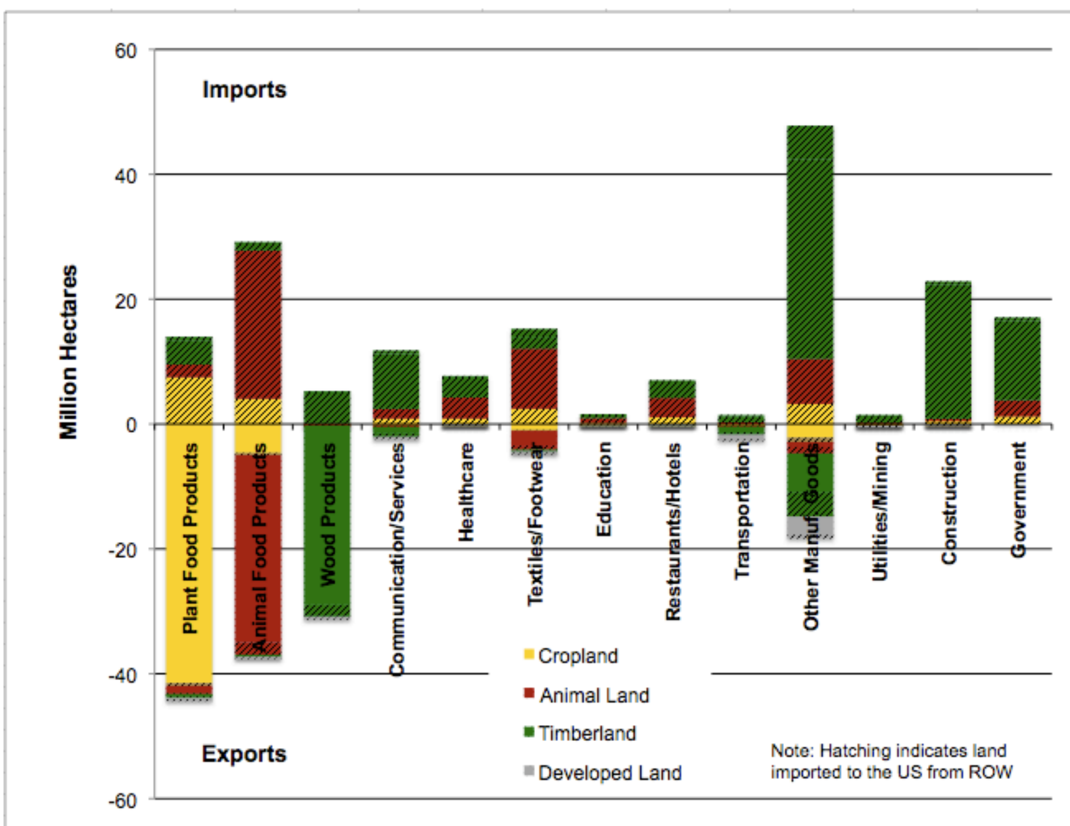

Figure 3.3. Land Imported to and Exported from the US by Type and Origin

3.3.1. EEBT versus MRIO

Comparison of the EEBT method to the MRIO method demonstrates the value of using an MRIO model. The benefit of using MRIO over EEBT can be seen when comparing the individual consumption categories, Figure 3.4, MRIO provides more detail from the consumption perspective. These differences arise because of how demand for imports is modeled in the two approaches, in EEBT the imports to final demand are modeled. In MRIO, the demand is separated into demand for industry and final demand for consumption. In general, this results in the EEBT method assigning higher land use for final goods and MRIO to have higher land use associated with commodities. Figure 3.4 shows that EEBT LU results for the service-oriented sectors, Communication/Services, Healthcare, Government, Construction, Restaurants/Hotels, Education and Transportation have near zero values because direct imports to final demand in these categories are zero or very small. The MRIO approach models imports to these industries and thus land use is associated with these categories when this method is used. As can be seen in Table 3.7, the total difference in land use associated with imports is small, only 7%, and the quantity of the types of land used are very similar.

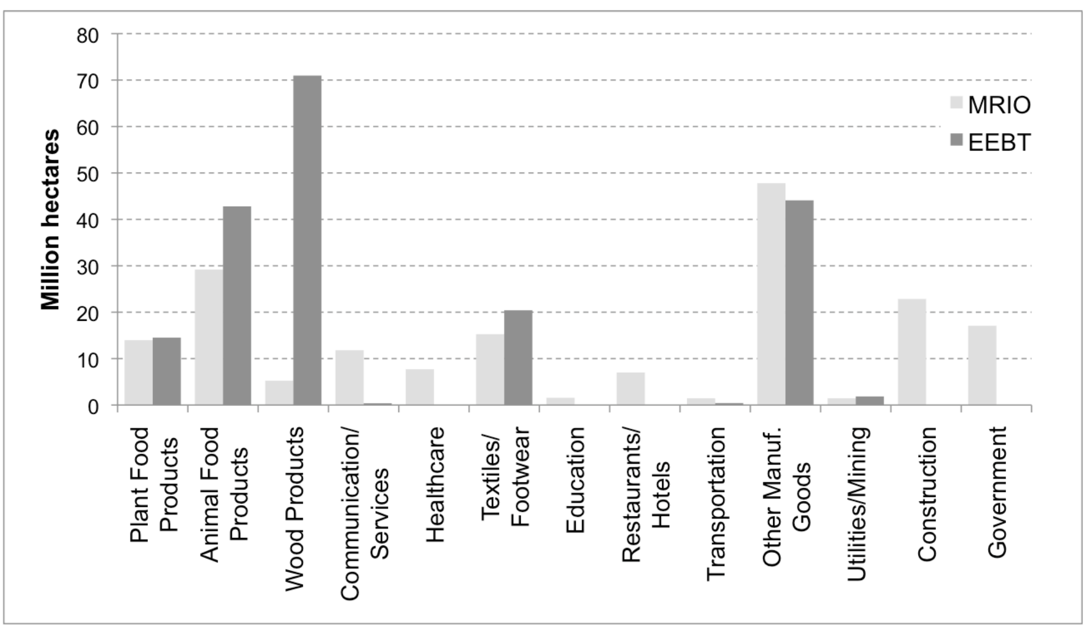

Figure 3.4. Comparison of EEBT and MRIO methods

Table 3.7. Land Use by Type, MRIO vs. EEBT

Model	Cropland (Mha)	Animal Land (Mha)	Timberland (Mha)	Developed Land (Mha)	Total LU (Mha)
EEBT	23.9	58.6	102.5	10.6	196
MRIO	22.3	54.6	95.6	9.9	182

3.4. Scenarios

Biofuels are a major concern for future land use, the U.S. has established a goal of producing 35 Bgal of biofuels by 2022,with 15 Bgal of ethanol slated to come from corn and 1 Bgal of biodiesel to come from soybeans [67]. There are a number of possibilities for meeting these goals and a great deal of uncertainty regarding which is most likely to occur. The U.S. could expand domestic land in cultivation to meet demand domestically or the U.S. could import feedstocks or, more likely, ethanol from other countries. If the U.S. expands into land within its own borders it may come from remaining cropland, land in the Conservation Reserve Program or other marginal lands, undisturbed forests or pastureland may be converted (if soil qualities are appropriate). Land could potentially be made available by reducing exports, increasing yields or possibly through shifts in diet.

First, scenarios were created to explore the land use associated with meeting ethanol goals set by EISA. The LU associate with demand for corn and soy was determined under two extreme scenarios, (1) that all corn and soy are produced within the U.S., (2) that all corn and soy are produced and imported from the current mix of countries that the U.S. imports from, (3) similar to scenario 2 sugarcane production in the ROW is increased to meet ethanol goals, and (4) all mandated ethanol for 2015 is produced domestically from cellulosic materials. While it is possible to directly approximate the land area required to meet a specific production goal using yield values and biofuel conversion rates, this straightforward approach does not capture the additional land use generated in upstream sectors. In order to make corn and soy, corn and soy are also consumed and this circularity should be accounted for. This is the unique advantage offered by conducting an IOA, which can capture this circularity effect. Further, U.S. final demand is also linked to imports to industry, thus imported land may also be affected.

Ideally demand for ethanol and biodiesel would be modeled, however there are no ethanol or biodiesel production sectors in the model. Therefore, land use estimates for biofuel production were generated by placing demand in the Corn and Soy farming sectors. The required masses of corn and soy were calculated based on conversion rates of 3 gal of ethanol/bushel of corn and 1.3 gal biodiesel/bushel of soy. Based on these assumed conversion rates, 127 billion kg (Bkg) of corn and 21 Bkg of soy are required to produce 15 Bgal of ethanol and 1 Bgal of biodiesel. In 2002, 2.14 Bgal of ethanol and 10.5 million gallons of biodiesel were produced [88].

Input to the MRIO model must be in U.S. dollars and so kg were converted to U.S. 2002 dollars using the multiplier values for corn and soy from **F** (ha/$) and yield values anticipated in 2015 (kg/ha) [89]. This approach crudely accounts for the decrease in land use associated with increased yields. Table 3.8 summarizes this information. A similar approach was taken to approximate the economic demand required to meet corn and soy production from the ROW, Table 3.8. It was assumed that ROW yields would increase at the same rate as in the U.S.

Table 3.8. Domestic and Imported Land Required to Meet U.S. Corn Ethanol and Soy Biodiesel

	U.S.			ROW		
	corn	soy	cellulosic	corn	soy	sugarcane
Ethanol/Biodiesel Production (Bgal)	15.0	1.0	19.5	15.0	1.0	15.0
Production (Mkg)	127,300	20,700	19,500	127,300	20,700	668,000
Yield, 2015 (kg/ha)	10,520	3,020	5,250[a]	9,080	2,830	61,800
LU calculate directly (Mha)	12.1	6.8	37.1	14.0	7.3	10.8
kg/$	19.5	6.7	7.9	20.9	6.8	30.4
Demand, $M	6,500	3,100	24,700	6,100	3,000	22,000
Land Use, Total	14.7	7.7	40.4	15.8	8.2	13.0
Land Use, Cropland	13.7	7.7	39.7	15.5	8.1	11.1

Notes: (a) This is the yield value for hay included in the Hay and pasture farming sector used to approximate switchgrass production. Observed yields for switchgrass range from 5,500 to 21,600 kg/ha [90].

The results indicate that producing corn and soy domestically would use 1.6 Mha less land than if produced by current U.S. trading partners. The majority, 94%, of corn is currently imported from Canada where a yield of 7250 kg/ha is achieved, compared to a U.S. yield of 7920 kg/ha. Similar results can be seen for soy yields, weighted average ROW yield was 2360 kg/ha compared to 2530 kg/ha in 2002. This yield disparity is assumed to remain in 2015. It is uncertain, if not unlikely, that this current import structure will be maintained given such an increase in demand. Further, the linear nature of this model ignores complex, dynamic market interactions.

The Hay and pasture farming sector was used as a proxy to approximate the land required to meet ethanol production goals with cellulosic materials. Switchgrass is currently the most discussed option in the U.S. for the production of ethanol from cellulosic materials. The average yield for hay in 2002, 5,250 kg/ha, was below the lowest observed yield for switchgrass, observed yield range 5,500 to 21,600 kg/ha based on field trials [90]. Direct calculation of land required to produce 19.5 Bgal of ethanol, assuming a conversion rate of 100 gal/mt using this range is 9.0 to 35.5 Mha. Table 3.8 suggests that an additional 8% over directly calculated land area is required due to circularity and upstream land use. If this additional 8% is applied to the direct land use calculated from the switchgrass yields land use would increase to 9.8 Mha and 40.1Mha, respectively.

It is anticipated that fertilizer applications to switchgrass will be higher than current fertilizer application to hay. Therefore, the technological relationship suggested by the **A** matrix for Hay and pasture farming may not apply to the cultivation of switchgrass. To more accurately express the land use and associated environmental impacts of cultivating switchgrass an additional sector should be added to the EIO-LCA model.

It is also possible that the U.S. may import ethanol directly, possibly from Brazil where ethanol is produced from sugarcane. The amount of sugarcane required to produce 15 Bgal of ethanol is 66.8 Bkg based on a conversion rate of 85 liters of ethanol per ton of sugarcane [91]. An approximate economic value was determined using the approach described for corn and soy and added to the demand for sugarcane imports from the ROW, resulting in an increase in virtual imports of 13.0 Mha, Table 3.8. Note that this estimation is based on the yields observed in current imports. The number one source of sugarcane imports is from the Dominican Republic where yields are roughly half of those observed in Brazil.

Along with the demand for ethanol, there is a desire to reduce reliance on imported goods (particularly with regard to energy), pressure to avoid land use change domestically and abroad, and to avoid competition with food products. This is a tall order, which can only be met by drastic technological developments such as large yield increases and perhaps realizing the full potential of cellulosic ethanol production to avoid using food crops for energy. Another possibility may be to free up land used for food production by shifting U.S. dietary choices. Animal food products use large quantities of land as demonstrated in previous results and thus we might expect shifts toward vegetarian diets to free up land. In order to create scenarios within the context of the MRIO model a few assumptions were made: (1) all cellulosic ethanol feedstocks are cultivated on marginal or other grasslands and are not included in these scenarios, (2) a corollary to assumption 1, only corn and soybeans are considered for meeting 15 Bgal of ethanol and 1 Bgal of biodiesel (3) calories are an appropriate nutritional unit for approximating dietary shifts, and (4) 2002 technology is assumed to be appropriate for modeling land use in 2015 when EISA mandated corn ethanol goals are to be met.

Shifts in diet were explored to assess the potential for making sufficient domestic land available to meet ethanol production goals without increasing LU. Based on the previously stated assumptions and results from Table 3.8, in order to avoid an increase in domestic LU dietary shifts would need to free up 22.4 Mha of cropland or the U.S. would need to reduce imports of cropland by 24.0 Mha. Weber and Matthews found that decreasing red meat consumption resulted in large GHG savings across diet choice tradeoffs [92]. This is largely due to methane emissions directly associated with cattle, see Chapter 5. Cattle also require a great deal of land, primarily pastureland, and thus we might expect to observe decreases in LU with a decrease in beef consumption.

Table 3.9 summarizes land use associated with 2002 personal consumption expenditures in various food categories. Restaurants are not included in these categories but result in non-negligible use of land, Figure 3.2. However, food consumption in restaurants is much less than food directly purchased through personal expenditure and is unlikely to change the general observations made with these scenarios. Loss of food due to waste is also not included here but may represent up to 27% of food production by weight [93].

Table 3.9 indicates that eliminating beef consumption entirely will not make enough cropland available to meet corn ethanol and soy biodiesel goals. Further, in order to maintain the current caloric consumption in the U.S. demand for other foods must increase. A number of scenarios were explored to quantify these tradeoffs more specifically. Assumptions about U.S. diet and caloric quantities are adopted from Weber and Matthews [92] and included in Appendix B. Sector to food category allocation assumptions are included in Appendix B.

Table 3.9. Domestic Land Use Due to Personal Expenditures in Food Manufacturing, Fruit and Vegetable Farming Sectors

Food Category	Total LU (Mha)	Cropland	Animal Land	Timberland	Developed land
Cereals/Carbohydrates	13.0	10.3	1.2	1.1	0.4
Beef	147.9	9.9	137.5	0.4	0.1
Fruit/Vegetables	14.6	7.8	5.7	0.9	0.2
Poultry/Eggs	14.1	7.3	6.3	0.4	0.1
Other/Miscellaneous	40.0	6.6	32.6	0.6	0.2
Oils/Sweets/Condiments	8.3	6.0	1.1	0.8	0.4
Dairy	14.4	5.3	8.2	0.6	0.2
Pet Foods	8.2	5.1	2.8	0.2	0.1
Beverages	5.2	2.9	0.3	1.4	0.6
Total	265.6	61.2	195.7	6.3	2.4

Figure 3.5 shows LU for the following scenarios: base case, current personal consumption expenditures on food products (1) substitution of dairy products for grain products, based on results in Table 3.9 Cereal and carbohydrate foods are currently the largest consumers of cropland and Dairy the least (2) substitution of meat food products (beef, chicken, pork and dairy) with grain food products (3) same assumptions as scenario 3, but with half of the calories replaced with grain food products and half replaced with fruit and vegetable food products and (4) replacement of beef with poultry.

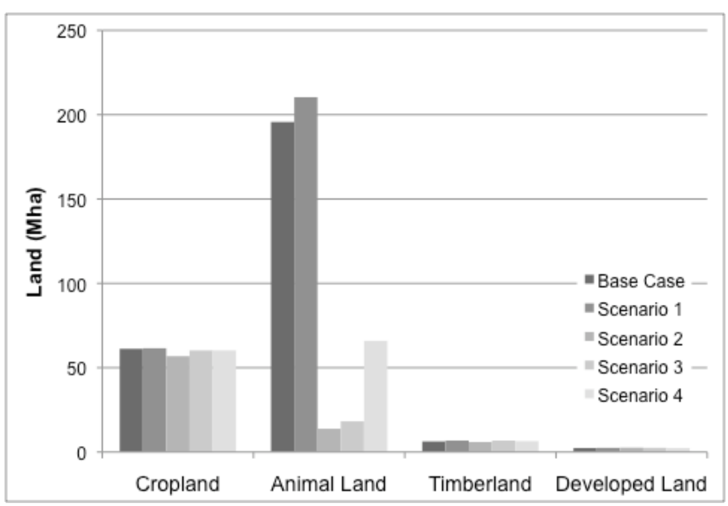

Figure 3.5. Land Use Associated with Select Dietary Shift Scenarios

Not surprisingly replacing dairy products with grain products increased land use across all categories, dairy cows consumed grain in order to produce output and thus there are no gains in cropland. While this result may seem obvious, it was included here to demonstrate that animal food products as currently produced require a large amount of grain. Scenarios 2 and 3 were created to explore the potential for vegan diets to free up cropland, however by substituting grain or fruit and vegetables for meat products cropland is consumed nearly equivalently. Note however, that very large amounts of pasture and grasslands are freed up in these scenarios, which may be useful for cellulosic ethanol feedstock production. Scenario 4 demonstrates that cattle are the primary cause for pasture and grassland use. Again this result may seem obvious, but if the U.S. is interested in making these lands available for cellulosic feedstocks without sacrificing meat as a major food source, poultry and swine products may be helpful.

The overall conclusion here is that dietary shifts are unlikely to make enough cropland available to meet biofuel production goals. However, dietary shifts may improve the outlook for cellulosic feedstock production. Cropland associated with imported food products is estimated at 4.9 Mha by this model, therefore, even if import of food products was ceased there would not be enough land made available for ethanol. Imports to domestic industry do fluctuate in each scenario, but only in very small quantities.

3.5. Conclusions

3.5.1. Uncertainty

All of the sources of uncertainty noted for the domestic only IOA in Chapter 2 apply to this MRIO analysis as well. The use of an MRIO model and associated assumptions introduce new uncertainty concerns, which will be explored in this section. Sources of uncertainty include the data and allocation methods used to create the land use inventory, uncertainty inherent to IOA models, and the assumptions made for the MRIO model. Uncertainty associated with the data and allocation choices for creating the U.S. land use multiplier, **F**, is discussed in Section 2.5.1.

This model assumes unidirectional trade, mathematically expressed by entering zeros in the upper right quadrant of the direct requirements matrix. As explained in Weber 2008 this assumption implies that direct trade (aka first-level trade) dominates overall trade, effectively redirecting the remainder of the supply chain to the current trading partner [81]. Lenzen et al., 2004 showed that the error associated with cutting off such feedback loops in trade supply chains is about 1-2% [87]. It was assumed that the ROW direct requirements matrix is equivalent to that of the U.S. The direct requirements matrix for the ROW was assumed to be equivalent to the total U.S. direct requirement matrix, i.e., the domestic and import, direct requirements matrix for the U.S. This is a common assumption in MRIO modeling. Specific to agricultural activities care should be taken if LU (as implied quantity) associated with fertilizers or pesticide use may be over-represented. Since the land is fairly small this is not a large concern, though note that fertilizer use in ROW is typically less.

There are a number of sources of uncertainty associated with the ROW land use multiplier. Data are from a single year and thus variability in yield is not captured. Aggregation of very different crops and thus yields limits the ability of the model to estimate the land use associated with a single crop, this is particularly relevant to fruit and vegetable farming sectors. In this thesis the total U.S. demand for domestic and imported crops is input to the model to approximate land use. Similarly, the land use multiplier reflects the total area used for all crops in the U.S. Thus the land use estimates for total U.S. domestic and imported demand are as accurate as the USDA and SAGE data. However, uncertainty can arise if land use associated with a particular fruit or vegetable is desired. The total area for all crops included in an aggregate sector would be applied to the individual crop. Land use and economic data are available to disaggregate the fruit and vegetable farming sectors both domestically and internationally. The **A** matrix could be disaggregated with economic data following the steps outlined in Section 2.2. The USDA reports area in production and yield for most fruits and vegetables [48] and SAGE data include fruits and vegetables as noted in Table 3.3.

The modification of $\mathbf{F}^{\mathbf{US}}$ to create $\mathbf{F}^{\mathbf{ROW}}$ assumes that the same quantity of agricultural commodity can be purchased with the same dollar, however U.S. prices may differ from ROW prices. However, this is not quite accurate as imported prices are not equivalent with U.S. domestic prices. Though they are unlikely to vary too significantly as global markets set commodity prices. There are limited options for addressing this uncertainty.

A physical unit MRIO model would be one way to more accurately track land use, though sector aggregation would still be a limitation. Also, obtaining the data necessary to develop this model would be very difficult.

The aggregation of both crops into sectors and across countries generates some uncertainty. Approximation of the land imported via processed foods is based on agricultural commodities from current trade partners. This may lead to misrepresentation of imported processed foods. For example, the U.S. imports wine and the land use associated with grape production for that wine is estimated using the ROW multiplier value for Fruit farming. This results in two sources of uncertainty in the estimation of this land use. First, the previously mentioned aggregation issue as this sector includes many fruits in addition to grapes. And secondly, the grapes used to produce the wine are not accounted for if the U.S. does not also import grapes from the same country. In order to accurately quantify the land imported through these processed goods the model would have to be expanded to include essentially all regions or countries of the world and would further require detailed knowledge of trade relationships between each of these countries. Acquiring this level of detail would be extremely data and time intensive if not impossible and would likely force loss in sectoral detail obtained by using the U.S. IO tables.

Ideally a distinct region would be modeled for each U.S. trade partner. Limitations for doing this are largely concern data availability and aggregation issues. That is, it is difficult, if not impossible to obtain distinct technology matrices for all countries and those that are available are unlikely to consist of the same economic sectors across countries. In this analysis a two-region model was chosen, this choice is acceptable given the questions asked of the model, i.e., how much land is embodied in U.S. imports. Given the relatively narrow range of yields observed in imported agricultural commodities as demonstrated in Figure 3.2. inclusion of additional regions and country-specific land use multipliers would not change the results of this analysis. If, in the future, trade partners shift drastically to include countries with greater yield differences the relevance of this assumption should be re-visited. Similarly, if one is interested in more accurately representing the land associated with a particular commodity or good, e.g., biofuels, it may be worth expanding the model to include additional regions.

The dietary shift scenarios assume that calories are a valid means for substituting food choice, other nutritional metrics may be relevant, e.g., protein content, minerals, and vitamins. Since only final demand in personal expenditures was considered food consumed in restaurants or otherwise not purchased directly is overlooked. While this is a nontrivial amount of food, it is considerably smaller than the food consumption modeled and is unlikely to change the overall result. The original determination of household food consumption generated some uncertainty due to imperfect mapping of the benchmark IO accounts for total economy-wide household expenditure on food and food availability statistics from the USDA for household caloric consumption of food [92]. See Weber and Matthews [92] and Appendix B for additional detail regarding these assumptions.

3.5.2. Discussion

The goal of this Chapter was to quantify the land embodied in U.S. imports. Based on the results we can see that the U.S. relies heavily on land in other countries, with total land associated with imports at 182 Mha of ROW land consumed domestically.

The method presented in this chapter has similarities to the ecological footprint approach but improves upon the method by incorporating actual U.S. LU data, rather than global average hectares. While there have been a number of attempts at incorporating LU into MRIO, this analysis provides the most detailed in terms of number of sectors. Further, the attempt to most accurately quantify the land embodied in U.S. imports offers a novel approach. GTAP may better represent the dynamic economic interactions in more regions (87 regions), however, GTAP has less sectoral detail than the model created here.

According to the Global Footprint Network the per capita ecological footprint for the average American is 9.02 hectare [94]. When area assumed to be used to sequester carbon associated with fossil fuel use and fisheries are subtracted the EF is 2.44 [94]. This analysis estimates U.S. per capita land use to be 2.62, including imports. The estimates are similar, though this analysis allows one to more closely examine how land use is linked to consumption. Similarly, one could use this model framework to compare the land use associated with different types of households consumption patterns.

The scenarios created herein assume static and linear economic relationships. This is very likely an oversimplification of actual demand changes and market dynamics. Searchinger et al. provided one of the early estimates of global LU changes as a result of biofuel demand and used linear relationships to approximate LUC [4]. Searchinger et al. estimated that 10.8 Mha of land would be converted to meet the 15 Bgal of corn-based ethanol demand in the U.S. [4]. These initial estimates of international land use change were recently revised, and significantly reduced, by Hertel et al. who estimate only 3.8 Mha of global land use change [95]. Hertel et al. use GTAP to show that land use change as a result of a specified agricultural demand is nonlinear, rather market-mediated effects occur, such as increased cost of meat to reduce the total land use change [95]. Both of these estimates are considerably lower than those found in this study. This is because market-mediated effects are not considered in this analysis and ROW land use is approximated using current trade relationships, which may not hold under biofuel scenarios. However, an IO model such as the one developed herein can generate useful comparative output more quickly.

Including restaurants and food waste, i.e., total food production, rather than solely household consumption may make the food scenarios more robust. Exploration of alternative food production options such as free-range and grass-fed animals and organic cultivation may also prove useful and may show very different results.

Without much more detailed knowledge about soil quality, topography, distance to market and land rents and various other important variables determining agricultural productivity and profitability it is difficult to approximate where and what types of land will be converted. Walsh et al. have used more detailed information at the U.S. county level to explore the likely location of corn, cellulosic materials, soy and other major bulk grains under varying price assumptions [96]. Also, availability of abandoned cropland may be significant. Field et al. find that there are 386 (+/- 50%) Mha of land available globally that can be defined as marginal, specifically land previously cleared for anthropogenic purposes and currently not utilized for production that may be able to meet ethanol goals [97].

4. Chapter 4: Nitrate and Greenhouse Gas Emissions Associated with Agricultural Land Use[2]

4.1. Introduction

There is growing concern that the use of agricultural products for liquid transportation fuels (biofuels) will result in an unacceptable increase in the negative aspects of agricultural activity. Agriculture is currently responsible for 6% of GHG emissions within the US [10], is a large source of nutrient and pesticide runoff to water bodies [98], is responsible for carbon dioxide (CO_2) emissions from soils when land is disturbed either directly or indirectly [4, 5], and leads to soil erosion and loss of habitat [99]. Nutrient runoff, particularly reactive nitrogen such as nitrate (NO_3^-), can lead to eutrophication and ultimately to hypoxic (dissolved oxygen < 2mg/L) conditions in waterbodies [100-102].

The hypoxic zone in the northern Gulf of Mexico (NGOM) occurs annually due to anthropogenic activities in early spring/summer disrupting the natural functioning of the ecosystem and reducing fish, crab, and shrimp catches within the zone, Figure 4.1 [102, 103]. Evidence of hypoxia was not observed before 1900 [102]. Nitrate loading increased significantly after 1950 due to deforestation, navigation channelization, wetland draining for cropland, loss of riparian zones and large increases in fertilizer application [102]. The Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (MR/GOM WNTF) established a goal to reduce the hypoxic zone size to 5000 km^2 by 2015 as compared to the current five-year running average (2005-2010) of 17,300 km^2, Figure 4.2 [104, 105]. To date there has been little evidence of progress toward this goal and there is concern that increased agricultural production may further hinder achievement of hypoxic zone reduction.

2 Much of the text in the chapter is based on the following published paper: Costello, C. Griffin, W. M., Matthews, H.S., and Landis A. E. Impact of Biofuel Crop Production on the Formation of Hypoxia in the Gulf of Mexico. Environmental Science and Technology. 43(20); 7985-7991.

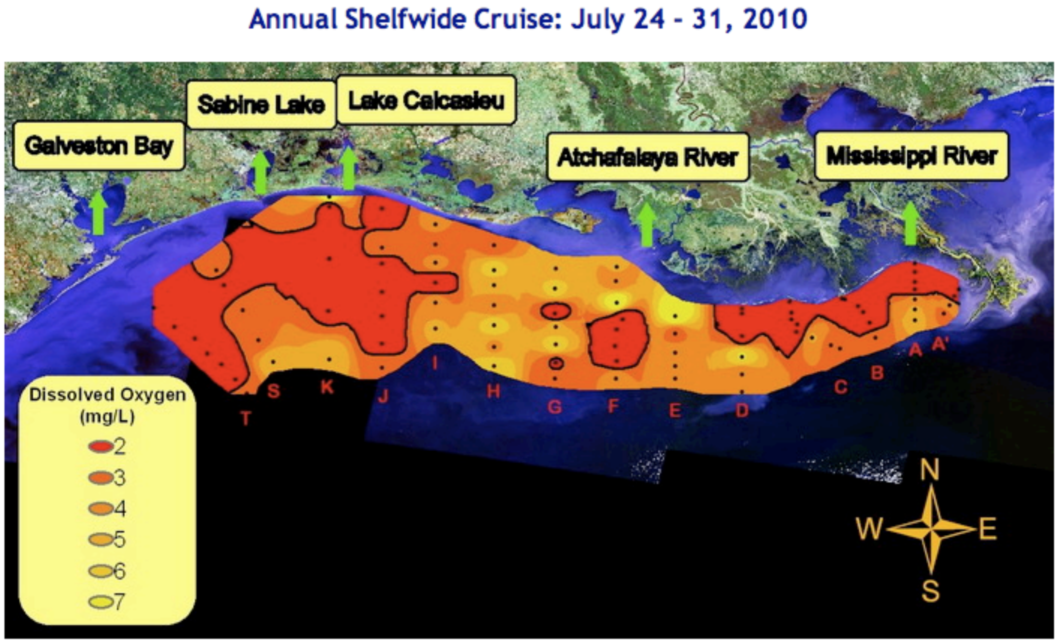

Figure 4.1. Extent of Hypoxic Conditions in the northern Gulf of Mexico 2010[106]

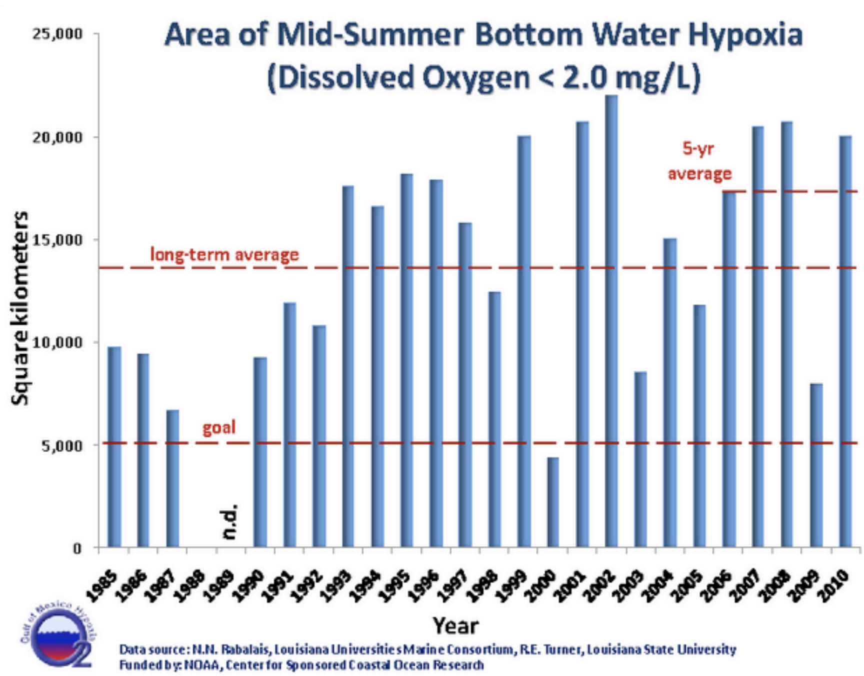

Figure 4.2. Measured Extent of Hypoxia 1985 to 2010 [107]

The formation of the hypoxic zone is dependent on two conditions, stratification of the water column and an abundance of decomposing organic matter [102, 108]. Increased nutrients, specifically nitrogen (N) and phosphorous (P), are associated with increased phytoplankton community productivity leading to increased organic matter which sinks to bottom waters where it is decomposed by aerobic bacteria causing oxygen depletion [102, 108]. Nitrogen, specifically NO_3^-, has been noted as one of the principal causes of increased organic matter and thus the hypoxic zone [108-110]. Disruption of the nitrogen cycle has been steadily increasing for decades, Figure 4.3 [111]. There are a number of environmental consequences associated with the accumulation of reactive nitrogen (Nr) in the environment, specifically [98, 111]:

- Production of tropospheric ozone and aerosols which induce human respiratory illness, cancer and cardiac disease;
- Disruption of natural vegetation systems;
- In conjunction with sulfur Nr results in acidification and loss of biodiversity in lakes and streams;
- Eutrophication, hypoxia, loss of biodiversity and habitat degradation in coastal ecosystems;
- Nr contributes to global climate change and stratospheric ozone depletion.

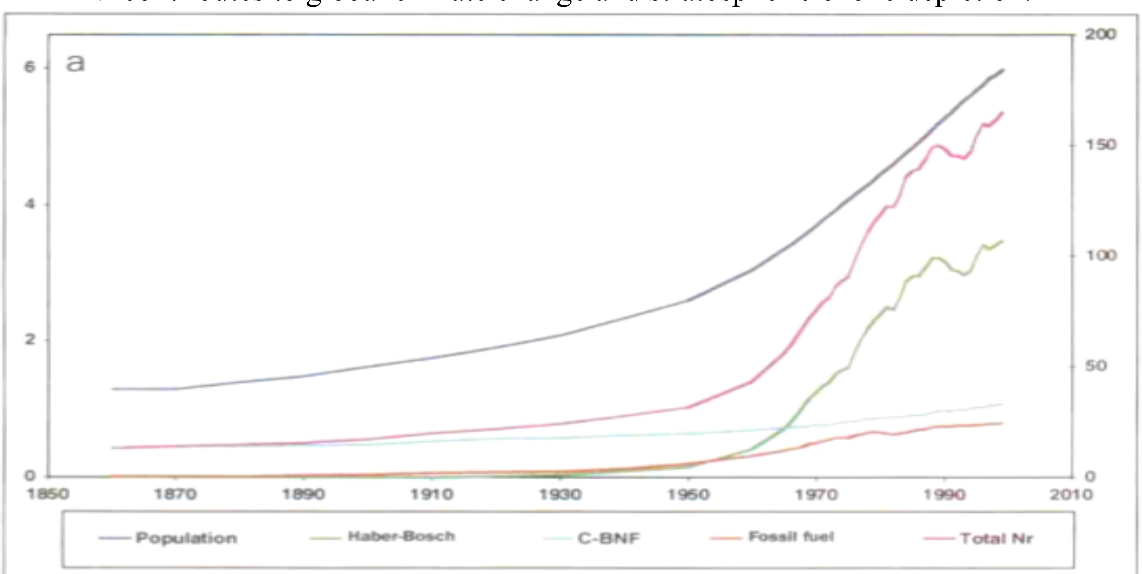

Figure 4.3. Accumulation of reactive nitrogen in the environment. Haber-Bosch: reactive nitrogen (Nr) creation through the Haber-Bosch process including production of ammonia for non-fertilizer purposes. C-BNF: cultivation-induced biological fixation; Nr creation[111]

Phosphorous may play a more significant role in the formation of hypoxia than previously thought [103, 112]. However, it has been suggested that P is only limiting now due to increased nitrogen loads during the 1970s and 1980s [101]. Fertilizers are applied in large quantity within the Mississippi and Atchafalaya River Basin (MARB), and corn cultivation is responsible for the majority of nitrogen fertilizer use in the US [42]. The majority of US corn and soybean production (over 80% by weight) occurs within the MARB [113] and accounts for just over 51% of the total nitrogen (TN) load to the NGOM [112]. Other sources of nitrogen from the Mississippi include: 1) atmospheric deposition (16%); 2) urban and population-related sources, e.g., wastewater treatment plants (9%); 3) production of crops other than corn, soy, wheat and alfalfa (8%); 4) fertilization and animal manure associated with pastureland and range (5%); the remaining sources are forestry, wheat production, alfalfa production, and runoff from shrub and barren lands [112].

Activities that lead to phosphorous runoff to the NGOM differ slightly: (1) animal manure on pasturelands (37%); (2) corn and soybean production (25%); (3) other crops, including alfalfa (18%); (4) urban and population-related sources (12%); the remaining categories include runoff from forestry, shrub and barren lands (8%) [112]. The values from the Atchafalaya differ slightly. Values can be found in Alexander et al. [112]. While phosphorous plays an important role in the formation of hypoxia, this paper focuses solely on characterizing N loadings.

The 2007 Energy Independence and Security Act calls for the production of 36Bgal of biofuels by 2022 of which 15 Bgal is corn ethanol and 21 Bgal is “advanced biofuel” [67]. Advanced biofuels are assumed to be 20 Bgal of ethanol derived from switchgrass or stover and one Bgal of biodiesel derived from soybeans. Achieving these goals may result in a significant increase in demand for agricultural products. Simultaneously as populations increase so will demand for food/feed products. A pressing question to answer is, how will an increase in agricultural activity impact nutrient loading to the NGOM and ultimately the size of the hypoxic zone [110, 114]? Many studies have compared corn-based ethanol to cellulosic ethanol on a per unit basis and have generally concluded that cellulosic ethanol will result in less environmental consequences, including nitrate (NO_3^-) output. A novel approach is to consider system-wide NO_3^- output and the relative areal extent of hypoxia in the NGOM due to the introduction of additional crops for biofuel production.

Grasses, e.g., switchgrass, are a promising potential cellulosic feedstock because they reduce losses of N and P to the environment compared to monocrops, e.g., corn. N and P loss is reduced because the land is not tilled and the grass density slows runoff and increases infiltration [115]. Further, nutrient application for grass production is anticipated to be roughly half that of corn or less [90]. Many authors suggest that replacement of conventional crops with grasses can improve water quality [99, 103, 116, 117]. On a per-unit basis (e.g., per gallon or acre) cellulosic crop cultivation results in less nutrient, pesticide, and sediment runoff compared to corn cultivation [118]. It is unclear whether an overall benefit to water quality will occur when cellulosics are considered within the entire MARB system. Donner and Kucharik examined the impact of meeting EISA mandated ethanol production via corn ethanol on the release of inorganic N and concluded that production of 15 Bgal of corn ethanol would reduce the likelihood of reaching the target set for hypoxia reduction [119]. In this thesis I consider the nitrogen loading to the MARB and the resulting areal extent of the hypoxic zone under various cropping scenarios that more closely follow the EISA mandates, including the use of cellulosic ethanol, as a means to compare the system-wide impact of selecting one crop over another for biofuels production.

4.2. Study Area for Nitrate Analysis

Production values included in Table 4.1 represent production within the MARB only. ArcView 9.3 was used to determine the area of each state within the boundary of the MARB, Figure 4.4. The percentage of each state's area within this area was used to approximate percent of total crop production within the MARB. Using this assumption approximately 82% of total corn is grown within the MARB and 83% of total soy. The quantity of switchgrass assumed to be within the study area, 72%, was determined using the same method but using projected locations for production provided by the US Energy Information Administration (EIA). Projected production values were calculated by EIA using the Policy Analysis System (POLYSYS) model, a national simulation model for the US agriculture sector, with the ability to estimate impacts resulting from changes in policy, economic, resource, or environmental changes [120].

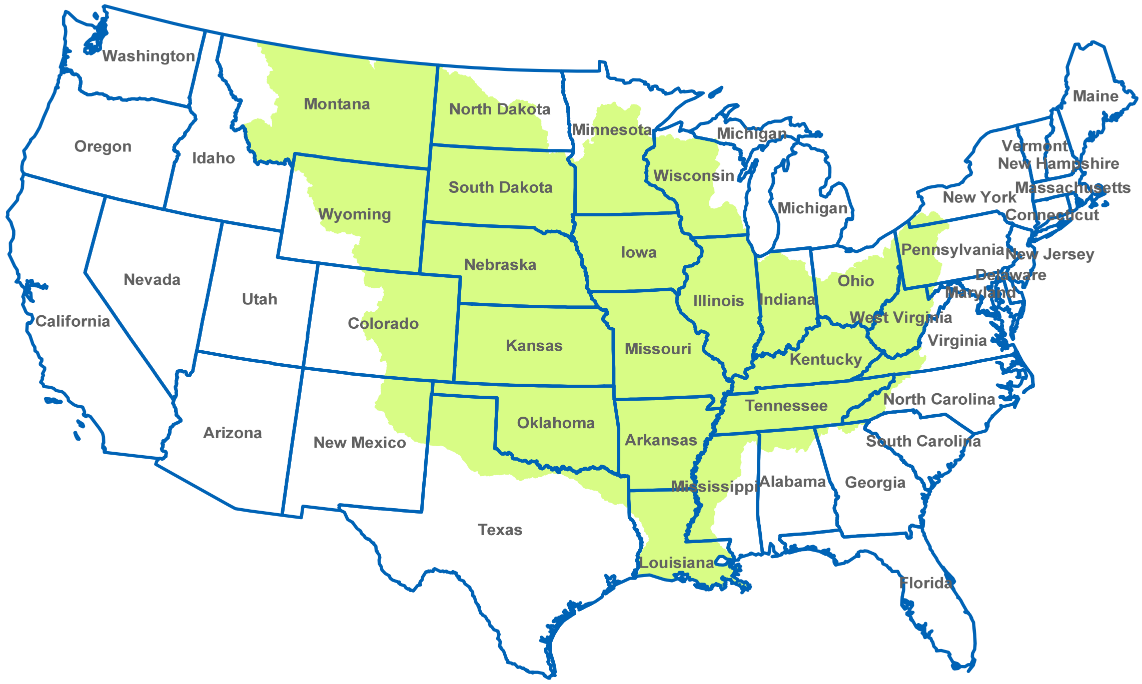

Figure 4.4. Extent of the Mississippi and Atchafalaya River Basin

4.3. Method for Assessing Biofuel Scenarios

4.3.1. Scenario Description

Scenarios were created that consider potential crop mixes to meet EISA goals as well as production required for food, feed and other nonfuel demands, see Table 4.1. NO_3^-output was quantified and the resulting size of the hypoxic zone in the NGOM was estimated for years 2015 and 2022. In 2015 corn-derived ethanol is assumed to reach maximum production of 15 Bgal as outlined in EISA. In 2022 the ethanol production goal of 35 Bgal is assumed to be reached. In addition, each scenario also includes sufficient corn and soy production to meet future non-fuel demands projected by the United States Department of Agriculture [89]. Two scenarios in each year (2015corn/stover, 2015corn/switchgrass, 2022corn/stover, 2022corn/switchgrass) include sufficient corn to produce 15 Bgal of ethanol with the remaining ethanol production, 4.5 and 20 Bgal in 2015 and 2022, respectively, derived from stover and/or switchgrass. Because the majority of corn and soy production currently occurs within the MARB, it was assumed that the majority of additional corn and soy production as well as cellulosic crops such as switchgrass, will also occur within the MARB. Potentially achievable conversion rates of 3 gallons (gal)/bushel corn [121] and 100 gal/metric ton (mt) dry cellulosic material, i.e., switchgrass and stover, were used [122].

Table 4.1. Scenario Summary Table

Scenario	Production in MARB (billion kg[1])				Ethanol (Bgal)			
	corn	soy[2]	stover[3]	swg	corn	stover	swg	total
2015corn/stover	300	76	34 (11%)	-	15	4.5	-	19.5
2015corn/swg			-	30	15	-	4.5	
2015stover/swg	200		96 (49%)	44	-	12.8	6.7	
2015swg			-	128	-	-	19.5	
2015no fuel		59	-	-	-	-	-	-
2022corn/stover	320	81	149 (47%)	-	15	20	-	35
2022corn/swg			-	131	15	-	20	
2022stover/swg	220		105 (49%)	137	-	14.1	21.9	
2022swg			-	229	-	-	35	
2022no fuel		64	-	-	-	-	-	-

Notes: swg – switchgrass. (1) Billion kg of crop including: corn grain, soybeans, dry mass of stover and switchgrass. Production values represent production within the MARB only. The percentage of each state's area within the MARB was used to approximate crop production within the MARB; 82% of corn, 83% of soy, and 72% of switchgrass (Appendix C). (2) Soy production values include soy required to produce 1Bgal of biodiesel. (3) Percent of stover removal is in parenthesis following production value.

Scenarios 2015stover/switchgrass, 2015switchgrass, 2022stover/switchgrass, and 2022switchgrass represent scenarios where no corn is grown to produce biofuels. Scenarios including stover, 2015stover/switchgrass and 2022stover/switchgrass, consider maximum ethanol production from stover based on removal assumptions, with the remaining ethanol production goal met through switchgrass. It is assumed that stover is collected from corn producing acres throughout the MARB. Scenarios 2015switchgrass and 2022switchgrass consider only production of switchgrass to meet ethanol goals. Finally, scenarios 2015no fuel and 2022no fuel consider the scenario where crops are cultivated only for nonfuel purposes. Aside from these production goal scenarios, there are several additional options modeled, as described below.

4.3.2. Stover Removal

Stover, the agricultural residue (i.e., stalks and leaves) left in the field after corn grain harvest, is a cellulosic feedstock. Maximum stover removal rates are an issue of debate. In general, if no-till methods are used stover might be removable at higher rates than under conventional tillage. Sheehan et al. [123] suggest a removal rate of 40% on conventionally tilled fields and 70% removal rate on no-till fields in Iowa and also report that 58% of cornfields practice conventional tillage, 26% practice moderate or mulch tillage, and 16% practice no-till cultivation. These values were used to generate a weighted average removal rate of 49%, the maximum removal modeled in this study. If no-till practices increase in the future stover removal rates could potentially increase. However, there are many issues to consider with regard to appropriate stover removal amounts. A recent publication from Blanco-Canqui and Lal suggests that even under no-till scenarios stover removal can have negative impacts on micro- and macronutrients, soil organic carbon, soil temperature and soil moisture [124]. In order to account for the nitrogen lost to soil due to stover removal it was assumed that the nitrogen content within the stover would be replaced one for one with additions of synthetic fertilizer. This approach is consistent with Sheehan et al. [125] and Hoskinson et al. [123].

4.3.3. Nutrient Management Using Vegetative Buffer Strips

Vegetative buffer strips (VBS) are one management technique shown to reduce nutrient, pesticide, and sediment loads to waterways [126]. Runoff is intercepted by the VBS and nitrate is mitigated through denitrification and nutrient uptake by plants. Limitations to effectiveness of VBS include depth to groundwater, topography, climate, and hydrology, i.e., conditions that reduce the interception and residence time of water above or below ground [127]. Precipitation can drastically influence the effectiveness of VBS. In general, the reduction in NO_3^- concentration due to the VBS is lower when precipitation is high due to reduced retention time within the buffer system [128]. Steep topography can result in rapid water flow through the buffer zone, particularly during high precipitation events [127, 129].

Due to the variety of climates and topography found within the MARB, it is unclear how much runoff within the MARB can be effectively treated with VBS. Tomer et al. [129] found that roughly 50% of the riparian zones suitable for VBS installation in a 49,000-acre Iowan watershed, where 90% of the area was cultivated for corn and soy cultivation. Given the lack of information about the ability to treat all watersheds within the MARB this analysis considered two VBS options: (1) a best case scenario in which all runoff is intercepted by a VBS and subject to reductions in NO_3^- concentration, i.e., 100% Buffer,

Figure 4.6, and (2) a scenario in which 50% of the runoff is intercepted and NO_3^- concentration reduced, i.e., 50% Buffer, Figure 4.6.

4.3.4. Nitrate Model Description

The model developed to approximate NO_3^- output for each scenario builds on the model created by Miller et al. [130], which uses a stochastic approach to generate a probable range of output for nitrogen species in generic watersheds using a linear fractionation of input variables. Only NO_3^- output is considered in this analysis. Monte Carlo Analysis (MCA) was used to generate a range of probable NO_3^-output for each scenario and crop using variable input parameters and the equations found below. MCA is commonly used in risk assessments to quantify the full range of possible outcomes including the most likely as well as extreme scenarios that are unlikely to occur.

Nitrogen inputs were related to nitrogen outputs based on crop-specific data and relationships between nitrogen, crops and the environment. Nitrogen input parameters include fertilizer, nitrogen fixation, and mineralized nitrogen. Other inputs to the model include crop yield and output factors. Input parameters are assigned distributions based on data and values reported in the literature to capture the most likely value as well as the full range of possible values. Additional details and references can be found in Appendix C. Distributions incorporate the inherent variability found in agricultural systems due to regional differences in climate, geology, geography and management practices.

Nitrate output is commonly estimated as a fraction of fertilizer application. Nitrate output varies considerably from 3% to 80% of applied fertilizer depending on soil, climate, and fertilizer application rates [98]. Only a small fraction of soybeans, roughly 25%, are fertilized annually [42]; this was accounted for in the MCA (Appendix C). It was assumed that mineralized nitrogen from soybeans would result in similar output as fertilizer and thus the same fractionation parameter is used (Equations 3 and 4) [130]. A large factor in the variability of NO_3^-output is precipitation, because NO_3^- builds up in soils during droughts and can be released in large quantities during high rain events [114, 131].Therefore, it is not always possible to associate fertilizer application and soil mineralization of nitrogen to output that occurs in the same year.

Mitigation scenarios, via 50% and 100% Buffer, were modeled as vegetative buffer strips, as described above. Seventy field measurements of NO_3^- concentration reductions of water entering versus exiting a buffer were collected for a wide variety of VBS designs implemented across the United States and in Europe [126, 128, 132-135]. The probability distribution function for NO_3^-concentration reduction, *r* from Equation 8, generated from these values is skewed toward the right with a mean value of 75%. In the 50% Buffer scenario 50% of the runoff passes through a VBS, and nitrate concentration is reduced according to the distribution *r* for an overall mass reduction of 35% (+/-14) and 68% (+/-27) in the case of the 100% Buffer scenario.

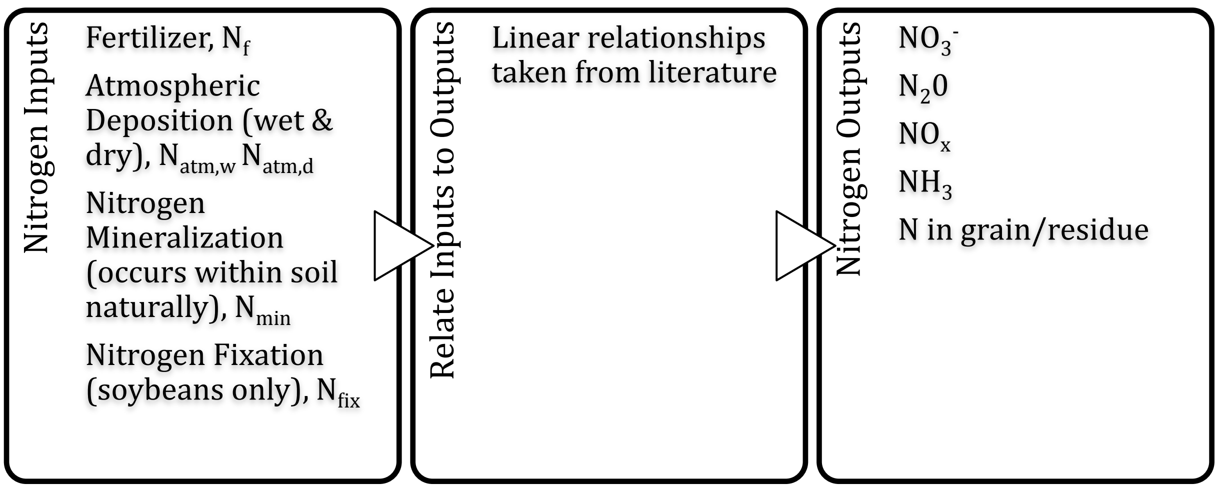

Figure 4.5. Conceptual Overview of Nitrogen Mass Balance Model

Model Equations and Input Parameters:

Equation 4.1. mass N in grain:

$$N_{grain} = \left(H \times f_{grain}\right) \times A$$

Equation 4.2. mass N in residue:

$$N_{residue} = \left(H \times HI \times f_{residue}\right) \times A$$

Equation 4.3. mass N fixed (soy only):

$$N_{fix} = f_{fix} \times \left(N_{grain} + N_{residue}\right)$$

Equation 4.4. mass NO_3^- from fertilizer:

$$N_{NO_3^-,f} = \left(N_f \times f_{NO_3^-}\right) \times A$$

Equation 4.5. mass NO_3^- from mineralization (soy only):

$$N_{NO_3^-,m} = \left(N_{\min} \times f_{NO_3^-}\right) \times A$$

Equation 4.6. mass stover removal:

$$H_{ST} = \left((\%stover\_removal) \times H_{corn} \times HI_{corn}\right) \times A$$

Equation 4.7. additional fertilizer required due to stover removal:

$$N_{f,ST} = \left(H_{ST} \times f_{residue}\right) \times A$$

Equation 4.8. mass NO_3^- reduction from riparian buffer:

$$R_{NO_3^-} = \left(N_{NO_3^-,f} + N_{NO_3^-,m}\right) \times r \times M$$

Equation 4.9. total nitrogen loading to the MARB:

$$N_{tot\_MARB} = \left(N_{NO_3^-,f} + N_{NO_3^-,m} - R_{NO_3^-}\right) \times 0.53 \times 1.33 \times 1.49$$

Where: N_{grain} = nitrogen exported via grain (kg N); H = grain harvested, i.e., yield (kg grain or biomass/ha); f_{grain} = nitrogen fraction of harvested grain (kg N/kg grain or biomass); $N_{residue}$ = nitrogen exported via residue (kg N); HI = harvested index (mass residue/mass grain); $f_{residue}$ = nitrogen fraction of residue (kg N/kg dry residue); N_{fix} = nitrogen fixed via biological nitrogen fixation (kg N/ha); f_{fix} = fraction of total plant nitrogen obtained through biological nitrogen fixation (%); N_{NO3-} = nitrogen runoff as NO_3-, subscript f – from fertilizer, subscript m – from mineralization (kg N); N_f = rate of fertilizer application (kg N/ha); f_{NO3} = fraction of fertilizer to NO_3runoff (%); N_{min} = mineralized nitrogen from soil and crop residue (kg N/ha); A = area cultivated with a particular crop (ha); R_{NO3-} = reduction in nitrate output due to vegetative buffers (%) note this term is zero in base case scenarios; r = percent concentration reduction due to vegetative buffer (%); M = percentage of total area assumed to be managed for nitrate output using vegetative buffers 50 or 100% Buffer; N_{tot_MARB} = total nitrogen load to the NGOM (kg N). Equation 4.9 converts modeled nitrate output within the basin to TN load reaching the NGOM, additional details are provided below. Equations 4.1 through 4.5 are adapted from Miller et al. [130].

4.3.5. Crop Yields

Data from 1997 to 2007 were used in this analysis to ensure that the distributions included observed annual variability. Area, *A*, required to meet production goals was determined by dividing the static production value (entered into the model) by the crop yield distribution, *H*, creating a range of required area. Yields are projected to increase in the future due to increases in management and technology while fertilization rates are expected to remain fairly constant, consistent with observed trends over the past thirty years [136]. Increases in corn and soybean yield, as projected by the USDA and historical state yield data were used to generate yield distributions for 2015 and 2022 [89].

The switchgrass yield distribution is based on 260 yield values collected from field trials over 1992 to 2001 [90, 137-139]. Each collected value was increased annually by 3.2% for eight and 15 years for 2015 and 2022, respectively. New distributions were generated to reflect the higher yields. Projected switchgrass yields were modeled using assumptions provided by the Energy Information Agency as cited in Wakeley et al. [140].

4.3.6. Relationship Between Nitrate Runoff to Areal Extent of the Hypoxic Zone

Forecasting the areal extent of the hypoxic zone is a difficult task as there are many variables to consider, particularly weather-related variables, which are notoriously unpredictable and also contribute considerably to the formation of hypoxia. For example, the 2008 areal extent of hypoxia was anticipated to be the largest on record given increased corn production and flooding [141]. However, Hurricane Dolly caused mixing in the NGOM, aerating portions of the water and reducing the extent to the second largest on record [142]. The intention is not to forecast the exact size of the hypoxic zone, but only to show the relative difference among various cropping scenarios using mean, 10% and 90% confidence interval values for nitrate output with all other factors the same.

The areal extent of the hypoxic zone is estimated using a dissolved oxygen model driven by nitrogen load and a simple parameterization of ocean dynamics developed by Scavia et al. [100, 101]. This model is assumed to be steady state and ignores longitudinal dispersion.

Equation 4.10. $D = [\, a / (b-a) \,]\, B_o \,[e^{-ax/v} - e^{-bx/v}]$

Where: B_o - oxygen demand at the point source (mg/L); a - first-order rate constant for organic matter decomposition (day^{-1}); b - first-order rate constant for oxygen flux (day^{-1}); D - dissolved oxygen deficit (mg/L); x - distance downstream from the point source, i.e., the length of the hypoxic zone (km); and v - net downstream advection of subpycnoclinal waters, i.e., below the layer in which density increases rapidly with depth (km/day). The v term is also used as a calibration term to capture all un-modeled processes and associated uncertainties including the many interactions among buoyant river plume, tidal currents, the Louisiana costal current, northward excursions of the Loop Current and its eddies, wind-driven circulation, and hurricanes [100, 101]. Typical values for v are between 0.5 and 1 km/day with a mean value of 0.56 km/day (+/- 0.20) [100]. Nitrogen load is converted to algal carbon by the Redfield ratio (5.67 C g^{-1} N), which is related to oxygen consumption using a respiratory quotient of 0.77 (3.47 g O_2 g^{-1} C), and an estimate that 50% of surface algal production settles beneath the pycnocline [100]. Areal extent is related to the downstream distance by a linear regression forced through the origin of observed hypoxic area and length: Area = 33.13x [100].

Total nitrogen delivered to the NGOM is required to approximate the size of the hypoxic zone. The MCA estimates the total amount of NO_3^- generated within the MARB, however, only 53% of the NO_3^-outputis transported to the NGOM [143]. Nitrate accounts for approximately 75% of the TN reaching the NGOM [108]. Nitrogen from corn and soy cultivation in the MARB accounts for roughly 51% of the TN load to the NGOM, the remaining 49% is the result of other activities described above [112]. This information was used to approximate TN loading to the NGOM from NO_3^- output (Eq 4.9). Adjustments were made to approximate spring/early summer loading, additional information in Appendix C. To validate this approach, agricultural production of corn and soy from 1986 to 2002 were used to model the NO_3^- output and daily May/June TN load to the NGOM. The TN and May/June results compared well to those reported by the USGS (Appendix C) [144]. The TN load was split between the Mississippi River and the Atchafalaya River assuming a ratio of 2.95:1 and x was determined using Eq. 4.10 for each point source [100].

The oxygen demand, B_o, was determined at two point sources, the Mississippi and Atchafalaya Rivers. Mean annual nitrate output determined by the MCA is converted to annual TN as described by Eq. 4.9. Daily May/June loading is approximated by dividing the total nitrogen loading to the NGOM (Equation 4.9) by 365 (days/year) and scaling up by 44% [144]. The 44% May/June adjustment factor was derived from monthly TN flux to the NGOM over the years 1985 to 2002 [144]. It is assumed that the ratio of Mississippi to Atchafalaya total nitrogen is 2.95:1, the variability is +/-0.34 but is not accounted for in this study [100]. Total nitrogen is converted to oxygen demand as described in the main text. The mean values provided by Scavia for *a*, *b*, and *v,* 0.003, 0.01, and 0.56, respectively, were used to calculate *x* where the dissolved oxygen was 3 mg/L in the subpycnocline. The model simulates the subpycnocline but the observations of hypoxia are measured along the bottom, therefore, vertical oxygen profiles were used to determine that a dissolved oxygen concentration of <3 mg/L in the subpycnocline corresponds to a dissolved oxygen concentration of <2 mg/L in bottom waters [100]. Historically observed total nitrogen output to the NGOM and spring/summer daily loads compared well with modeled values and are included in Appendix C.

4.4. Nitrate Output and Extent of Hypoxia Summary

The nitrate output ranges from the MARB for the scenarios described above are summarized in Table 4.2. The areal extent of the hypoxic zone based on mean NO_3^- output values and mean values for the terms in Eq. 4.10 for the scenarios with No Buffer and 50% Buffer are shown on Figure 4.6. The inputs to the model do not result in the formation of hypoxic conditions for the 2015no fuel, 2022no fuel and 50% Buffer scenario or the 100% Buffer scenarios. However, if the 90% credible interval value for nitrate output is used the model does predict hypoxic conditions. In order for the model, using the assumptions described above, to result in the formation of a hypoxic zone greater than 5000 km^2, the modeled NO_3^- must be approximately 980,000 mt. It is important to note that 100% interception of runoff by buffers from agricultural fields is unlikely and this idealized scenario is included to illustrate the need for aggressive nutrient management within the MARB.

Table 4.2. Summary of Modeled Scenario Nitrate Output

Scenario	No nutrient management				50% Buffer Mitigation				100% Buffer Mitigation			
	Nitrate Outputs (1000 metric tons)											
	mean	std. dev	(10%-	90%)	mean	std. dev	(10%-	90%)	mean	std. dev	(10%-	90%)
2015corn/stover	1,860	700	1,100	2,750	1,220	540	660	1,920	590	590	16	1,410
2015corn/swg	1,830	690	1,080	2,700	1,200	530	650	1,880	580	580	15	1,390
2015stover/swg	1,600	620	960	2,360	1,050	470	570	1,640	510	510	13	1,210
2015swg	1,520	600	900	2,260	1,000	460	540	1,570	480	490	12	1,160
2015no fuel	1,250	500	720	1,890	820	380	440	1,300	400	400	10	960
2022corn/stover	2,010	720	1,220	2,940	1,330	560	740	2,050	640	630	17	1,520
2022corn/swg	1,860	670	1,130	2,730	1,220	520	670	1,900	580	580	15	1,400
2022stover/swg	1,680	610	1,020	2,450	1,100	470	610	1,700	530	530	14	1,250
2022swg	1,560	600	930	2,320	1,030	460	560	1,610	490	500	13	1,180
2022no fuel	1,260	490	740	1,880	830	370	440	1,300	400	400	10	950

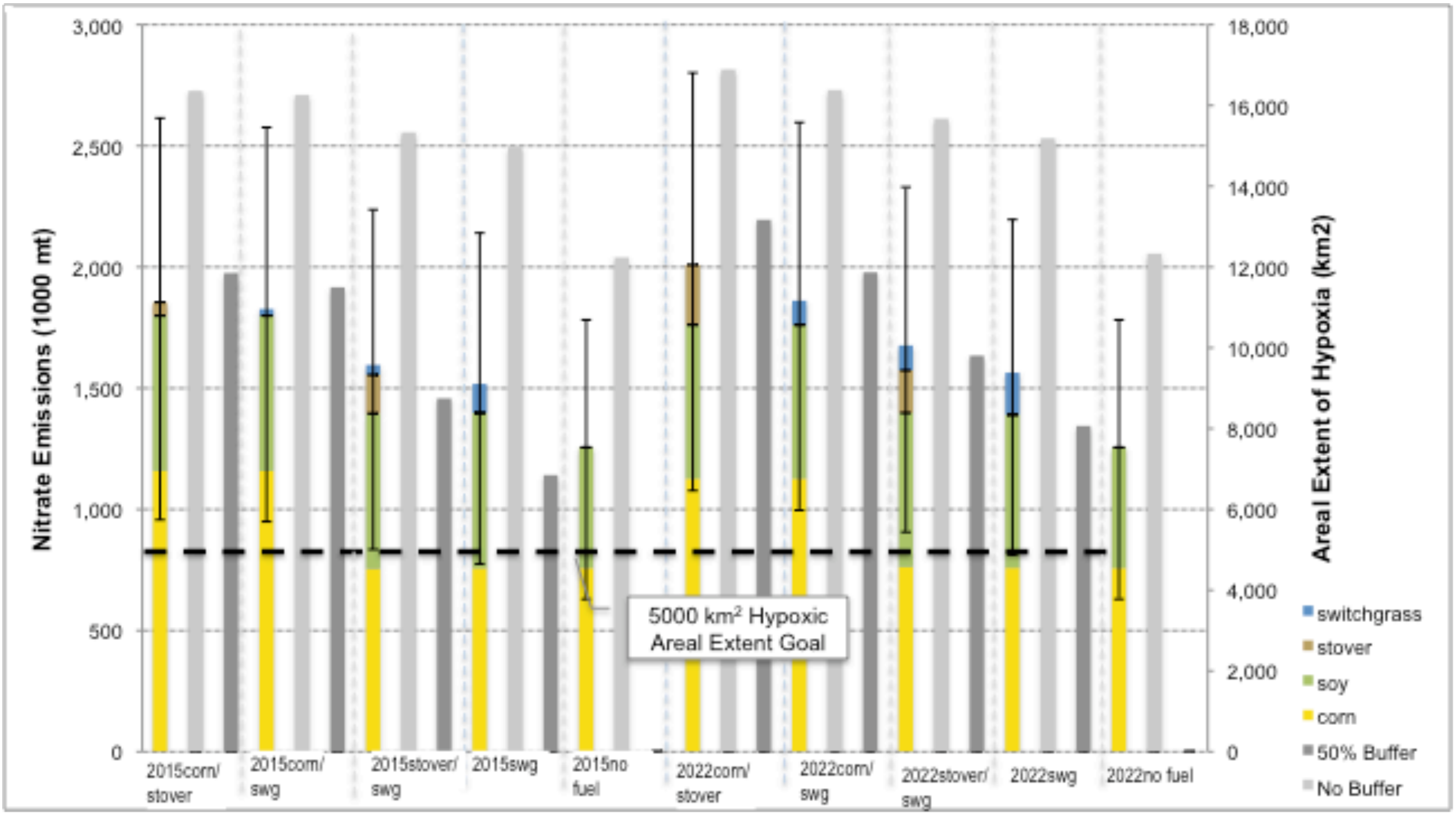

Figure 4.6. Nitrate output within the MARB (colored bars, lefthand y-axis) and mean areal extent of hypoxia in the NGOM with "No Buffer" and "50% Buffer" (grey-scale bars, righthand y-axis). Nitrate output columns represent mean values and the 80% credible intervals from MCA modeling. The horizontal dashed line represents the MR/GOM WNTF 5000km^2 goal set for 2015. Note that nitrate output under the 50% and 100% Buffer scenarios decrease linearly at 35% (+/- 14) and 68% (+/- 27), respectively; these results are depicted in Appendix C.

Consistent with previously published literature the results demonstrate that NO_3^- output for corn-derived ethanol will be higher on average than output for switchgrass- or stover-derived ethanol [99, 103, 117]. There is a decrease in mean NO_3^- output between the scenarios inclusive of corn production for ethanol and those that use only cellulosics for ethanol production (Scenarios 2022corn/stover & 2022corn/switchgrass vs. 2022stover/switchgrass and 2022switchgrass). The 80% credible intervals of the modeled scenarios overlap considerably indicating that nitrate mass reductions due to replacement of cellulosics for corn may not be realized in any specific year. While it is true that cellulosics result in lower NO_3^- output on a per unit basis compared to corn (e.g., one gallon ethanol or one acre), the decrease is insufficient to reduce the hypoxic zone below the EPA's 5000 km^2 target.

The nitrate output in 2015 and 2022 associated with corn and soy are roughly the same because yield gains are expected to keep up with non-fuel demand increases and biofuel demand for these crops does not change between these years. As demand for cellulosic crops increases from 45 billion kg (4.5 Bgal) in 2015 to 200 billion kg (20 Bgal) in 2022, the NO_3^- output does not increase proportionally. This is particularly true for switchgrass because annual yield increases are expected to be almost 2% greater than that of corn. For these reasons the total NO_3^- output for 2022 scenarios increases only 2-8% over the 2015 scenarios despite an additional 15.5 Bgal of ethanol production.

Figure 1 shows that switchgrass has lower nitrate output than stover for an equivalent amount of ethanol production, which may not seem intuitive given that the nitrogen fertilizer required to replace removed nutrients for stover is on average half that required for switchgrass, i.e., 35 kg/ha versus 74 kg/ha mean values, respectively. The NO_3^- output factor, f_{NO3-}, for stover is assumed to be equal to that of corn, and is roughly twice the switchgrass NO_3^- factor based on mean values. In 2015 the mean removable stover rate is 4,800 kg/ha and mean switchgrass yield is 19,000 kg/ha, in 2022 yields are 5,100 kg stover/ha and 23,400 kg switchgrass/ha. Therefore, the mean kg NO_3^- output per kg biomass in 2015 is 1.75×10^{-3} and 5.06×10^{-4} for stover and switchgrass, respectively. Due to yield gains the mean kg NO_3^- per kg biomass in 2022 decreases to 1.67×10^{-3} and 4.1×10^{-4}, or a decrease in NO_3^- intensity of approximately 5% and 23%, for stover and switchgrass, respectively. If the upper limit for stover removal under no-till assumptions, i.e., 70%, were removed from all corn producing acres throughout the MARB the need for switchgrass to meet ethanol goals in Scenarios 2015stover/switchgrass and 2022stover/switchgrass would decrease to 1 Bgal and 14.7 Bgal, respectively. The total nitrate output would increase by approximately 2.5% in both cases. Thus this change would not impact the results significantly.

4.5. Sensitivity Analysis

Sensitivity analyses were conducted using Crystal Ball software for Scenarios 2015corn/stover and 2015corn/swg; results are similar for all other modeled Scenarios. The sensitivity analysis showed that nitrate output for both corn and switchgrass are most sensitive to the NO_3^- fractionation variable, fertilization rates, and yield (in descending order). The nitrate output for soybeans is most sensitive to the mineralized nitrogen variable, the NO_3^- fractionation variable, percent of crop fertilized, and crop yields (in descending order). Mineralized nitrogen is the largest source of NO_3^- output due to soybean cultivation. The nitrate output for stover is most sensitive to the nitrate fractionation variable (same value used for corn) and the residue fraction, and the fertilization rate. This sensitivity is not surprising given the large range of the NO_3^- fractionation variable. Yield is important because this variable determines the area required to produce the specified production amount, *A*, (Table 4.1), which is used to scale up nitrate output to the MARB. Further information and sensitivity charts are provided in Appendix C.

4.6. Discussion

Miscanthus x *giganteus* (Miscanthus), a perennial grass popular in Europe for cellulosic biofuel production, has received attention as potentially preferable to switchgrass [145]. Heaton et al. [146] reported average 3-year post-senescence yields over three locations in the Midwest USA of 29.2 (+/- 1.8) dry mt/ha for *Miscanthus* versus 10.4 dry mt/ha for switchgrass. In the Heaton et al. study nitrogen fertilizer was applied once in the 4-year study at a rate of 25 kg/ha, roughly one-third of the average annual value used for switchgrass in this study. While *Miscanthus* was not modeled because data are currently lacking, the nitrate output would fall between "no fuel" scenarios (i.e., no additional fertilizer application and the assumption that there is no release of nitrate through the process of nitrogen mineralization) and Scenarios 2015swg and 2022swg. *Miscanthus* should be included in future studies as data becomes available regarding the feasibility of production at a commercial scale.

An important consideration with respect to nitrate output associated with various biofuel mixes is the change in areal extent of the hypoxic zone in the NGOM. Our goal is not to precisely predict the size of the hypoxic zone, but rather to show the relative changes under identical conditions. Historical observations of the size of the hypoxic zone over 1985-2002 are generally within the range of modeled hypoxic zone size, details are provided in Appendix C. The mean value for the calibration term, *v*, in Eq. 10 was used to approximate the areal extent of hypoxia for future scenarios. While the calibration term, *v*, in Eq. 4.10 may vary in a given year due to various climatic and hydrologic conditions, the mean values provide a comparable baseline from which to assess the relative extent of hypoxia. The size of the hypoxic zone in 2015 and 2022 decreases by approximately 1200 km^2, based on mean NO_3^- output, if corn-ethanol (represented by scenarios 2015corn/stover and 2015corn/switchgrass) is replaced with cellulosic-ethanol (2015stover/switchgrass and 2015switchgrass). The results are shown in Appendix C. No future scenarios, including those with no crops for biofuels, reach the hypoxic areal extent goal of 5000km^2. In many cases the zone reaches roughly three times that size. Results for all Scenarios and additional discussion are included in Appendix C.

There is uncertainty associated with the model (Eq. 4.9 and 4.10) used to predict the size of the hypoxic zone that is not explicitly included in modeled results. For example, the contribution of corn and soy cultivation to TN delivered to the NGOM ranges from 42.2 to 57.4 % (90% prediction intervals) [112]. The amount of N in the MARB delivered to the NGOM has also been estimated at 65% as opposed to 75% used herein. Inclusion of these sources of variability was not deemed necessary because forecasting the climatic factors in the NGOM is difficult and the range of variability in the other factors is not significant enough to change the overall results (see Appendix C for additional information).

In summary, the results of modeling hypoxic area indicates that meeting the biofuel goals set forth by EISA will likely increase the occurrence of hypoxia in the NGOM, regardless of the selection of crops. This work also suggests that aggressive nutrient management is needed even in the absence of energy crops or stover use. There are a number of options to consider for mitigating nitrogen loading from agricultural activities, including wetland construction, vegetative buffers, tillage management, and precision fertilizer application [127]. In this paper mitigation of nitrate output was modeled using vegetative buffer strips and their associated nitrate concentration reduction rates. The nitrate mitigation potential due to the use of vegetative buffer strips is considerable, though given the various siting limitations even the 50% implementation described here may overestimate their effectiveness. The intent of modeling aggressive mitigation scenarios was not to suggest that vegetative buffers alone could improve water quality in the NGOM, but rather to highlight the need for aggressive and significant management of nutrient runoff within the MARB.

The results presented here suggest that only when all of the nitrogen runoff associated with the production of corn, soy, and switchgrass is reduced will the EPA goal be met. This is an over simplification since the approximation of the areal extent of the hypoxic zone includes unmitigated output from all other N sources within the MARB, i.e., other agricultural crops, wastewater treatment facilities, etc. Any aggressive management strategy aimed at reducing nutrient sources within the MARB likely target these other sources as well.

The EPA Science Advisory Board suggests that a regime shift has occurred in the NGOM [103]. In the event of a regime shift it is possible that a threshold is passed such that incremental nutrient load reductions may not result in similarly sized reductions in the extent of hypoxia. This suggests that nutrient load reductions may have to be reduced to a point below where the regime shift occurred [103]. The potential implication is that the longer nutrient loadings go unreduced, the larger future reduction requirements may be [147].

The results of this study demonstrate that using cellulosic crops for biofuel production will decrease TN loading to the NGOM relative to corn but overall TN loading will still increase as the goals of the EISA are met, adding to the need for aggressive nitrogen mitigation strategies.

5. Linking Land Use to Greenhouse Gas Emissions

Chapter 4 indicated that use of land for the cultivation of crops results in significant changes in nitrate output to the MARB. This chapter attempts to demonstrate the connection between agricultural land use and GHG emissions. Approximately 6% of total U.S. GHG emissions occur due to agricultural activities. Despite this relatively small overall contribution, Agricultural activities contribute 31% of CH_4 and 68% of N_2O emissions [10]. U.S. GHG emissions are summarized in Table 5.1. Emissions of $N_2O$and $CH_4$are closely tied to land management practices. For example, N_2O is produced naturally in soils through nitrification and denitrification.[3] One of the most significant controlling factors in this reaction is the availability of inorganic nitrogen often added for anthropogenic purposes [148]. The connection between U.S. agricultural land use and GHG emissions is explored in this section using an expanded GHG multiplier and the EE-IOA described in Chapter 2.

There are a number of agriculture-specific GHG emissions. Table 5.2 summarizes the type and source of GHG emissions from agriculture. Carbon dioxide emissions occur due to fossil fuel combustion both through direct use, e.g., diesel in trucks and indirect use, e.g., purchased electricity. Soil management activities contribute CH_4 and N_2O, e.g., application of fertilizers and natural processes such as soil mineralization. Animal production and associated activities directly contribute CH_4 and N_2O by way of enteric fermentation, manure management and N_2O emissions occur indirectly when nitrogen contained in manure volatilizes as ammonia (NH_3) and NO_x or as runoff and leaching of nitrogen from manure or soil.

[3] The IPCC defines nitrification as the aerobic microbial oxidation of ammonium to nitrate, and denitrification as the anaerobic microbial reduction of nitrate to nitrogen gas (N2). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere.

Table 5.1. U.S. Sources of GHG Emissions (Tg CO2e)[a]

Gas/Source	2002
CO_2	5,918
Fossil Fuel Combustion	5,555
Electricity Generation	2,273
Transportation	1,822
Industrial	833
Residential	361
Commercial	223
U.S. Territories	44
Other	671
Land Use, Land-Use Change, and Forestry (Sink)	-909
CH_4	577
Enteric Fermentation	136
Landfills	120
Natural Gas Systems	129
Coal Mining	57
Manure Management	41
Petroleum Systems	30
Wastewater Treatment	25
Other	39
N_2O	338
Agricultural Soil Management	215
Mobile Combustion	46
Nitric Acid Production	18
Manure Management	17
Waste Treatment	6
Other	36
HFCs	108
PFCs	9
SF6	18
Total	6,967
Net Emissions (Sources and Sinks)	6,058

Note: (a) The data in this table were adapted from the 2009 EPA GHG Inventory.

Table 5.2. Agricultural Greenhouse Gas Emissions by Source, Tg CO_2e[10]

Source	CO_2[a]	CH_4	N_2O
Fossil Fuel Combustion	62.5	-	-
Enteric Fermentation	-	134	-
Manure Management	-	40.4[b]	14.2[c]
Rice Cultivation	-	6.8	-
Field Burning of Agricultural Residues	-	0.7	0.4
Agricultural Soil Management	-	-	207.6
Direct	-	-	173.1
Cropland	-	-	119.1
Mineral Soils	-	-	116.2
Synthetic Fertilizer	-	-	45.4
Organic Amendment [d]	-	-	9.3
Residue N [e]	-	-	7.5
Mineralization and Asymbiotic Fixation	-	-	54
Organic Soils	-	-	2.9
Grassland	-	-	54.1
Synthetic Fertilizer	-	-	1.1
PRP Manure[f]	-	-	10.8
Managed Manure[g]	-	-	1.0
Sewage Sludge[8]	-	-	0.4
Residue N [e]	-	-	12
Mineralization and Asymbiotic Fixation	-	-	28.7
Indirect (All Land-Use Types)[h]	-	-	*34.5*
Cropland	-	-	23.2
Grassland	-	-	10.5
Forest Land	-	-	0.1
Settlements	-	-	0.6
Total	62.5	182.1	222.2

Notes: (a) The estimate of CO_2 emissions was derived using allocation values based on fuel use in agriculture and the EPA total estimate for CO_2 emissions, additional details are provided in the text. (b) Includes CH_4 emission reductions due to anaerobic digestion. (c) Includes both direct and indirect N_2O emissions. (d) Organic amendment inputs include managed manure amendments and other commercial organic fertilizer (i.e., dried blood, dried manure, tankage, compost, and other). (e) Residue N inputs include unharvested fixed N from legumes as well as crop residue N. (f) PRP stands for pastures, rangelands, and paddocks. (g) Accounts for managed manure that is applied to grassland soils. (h) Indirect emissions of N_2O occur through two pathways: (i) volatilization and subsequent atmospheric deposition of applied N, and (ii) surface runoff and leaching of applied N into groundwater and surface water.

The emissions in Table 5.2 were assigned to NAICS sectors creating a GHG multiplier (with the original 428 sectors) for the online tool, EIO-LCA, created by Carnegie Mellon University's Green Design Institute [149]. The online EIO-LCA tool includes five GHG categories including CO_2 from fossil fuel combustion and process-related emissions, CH_4, N_2O, and HFC/PFCs. In order to explore the relationship between land use and environmental impacts, the multiplier was expanded from five to 12 categories based on the source of emissions summarized in Table 5.3. CO_2 from fossil fuel combustion was separated into those that occur as a result of agriculture from all other sources. Methane emissions were divided into those associated with crop and animal production, waste treatment, and fossil fuel production. Nitrous oxide emissions were divided into crop and animal production, fertilizer manufacture, waste treatment, and fossil fuel combustion/production. This additional detail allows one to consider how GHG emissions due to agricultural activities, and particularly land management and use, relate to the production of various goods and services.

Table 5.3. Overview of Greenhouse Gas Multipliers

GHG	Sectors affected	Source of GHG emissions
CO_2-agricuture (CO_2-Ag)	All agricultural sectors, #11	CO_2 from fossil fuel use, including electricity
CO_2-other (CO_2other)	All non-agricultural sectors	CO_2 from fossil fuel use, including electricity
CO_2-process (CO_2p)	12 sectors. Cement, lime, metal refining, fossil fuel extraction and pipeline transportation.	CO_2 from non-fuel combustion industrial processes.
CH_4crop	4 sectors, Soybean, Corn, Wheat, and Rice farming sectors.	CH_4 due to anaerobic conditions in flooded rice fields and field burning for other sectors.
CH_4-animal production (CH_4anim)	4 sectors, Milk production, Cattle ranching and farming, Poultry and egg production, Animal production, except for cattle ranching and farming	CH_4 associated with enteric fermentation and manure management
CH_4-fossil fuel (CH_4foss)	7 sectors, Extraction, refining, and electricity generation of fossil fuels.	CH_4 fugitive and process related emissions.
CH_4-waste treatment (CH_4wste)	2 sectors, Water, sewage and other systems and Waste management and remediation services	CH_4 due to anaerobic decomposition of organic material.
N_2Ocrop	15 sectors (#111)	N_2O emissions due to synthetic fertilizer application, organic amendments to soils, residual nitrogen and soil mineralization.
N_2O-animal production (N_2Oanim)	4 sectors (#112)	N_2O due to animal production occurs due to manure management (including that deposited on grasslands), grassland cultivation, and soil mineralization in grasslands.
N_2O-fertilizer (N_2Ofert)	Fertilizer manufacturing sector	N_2O is produced during nitric acid production resulting in process emissions.
N_2O-waste treatment (N_2Owaste)	2 sectors, Water, sewage and other systems and Waste management and remediation services	N_2O results from nitrification/denitrification processes.
N_2O-other	4 sectors, Other basic organic chemical manufacturing (325190), Power generation and supply, Forest nurseries, forest products and timber tracts and Logging	N_2O from processes. Forestry emission are very small (~0.1Tg CO2e) due to surface leaching of reactive nitrogen.

5.1. Links between GHG emissions and LU

All GHG emissions take place on land and so in a sense all emissions can be associated with the land on which they occur. However, not all emissions are a function of the land on which they occur, this is unique to agricultural activities. Nitrogen mineralization is the largest source of N_2O emissions and occurs during the decomposition of soil organic matter (SOM) or the asymbiotic 'fixing' of nitrogen found in the atmosphere by certain crops (e.g., soy and alfalfa), Table 5.2 [10]. The second largest source is directly related to fertilization. Fertilization rates are dependent on soil quality, crop and yield goals. The rate at which N_2O forms is based on complex interactions involving soil type and quantity, local climate factors and management of the land.

While nitrogen mineralization of SOM is a naturally occurring process, the rates of mineralization are imbalanced due to anthropogenic activities, i.e., addition of fertilizer and cultivation of nitrogen-fixing crops. Nitrogen fixation is also a naturally occurring process, however, cultivation of monocrops on a large scale create a significant disturbance to the balance of N, resulting in increased reactive nitrogen in ecosystems [111]. Since cultivation of large-scale monocrops are a particular type of land use, the emissions associated with this activity can be thought of as a result of land use, i.e., intensive cultivation.

Not all agricultural GHG emissions are a function of the land on which they occur. For example, cattle emit CH_4 as a function of their digestive system regardless of the land they inhabit. However, emissions due to management of grasslands, i.e., fertilization or seeding pastures with nitrogen-fixing crops are a result of using land to graze animals. Similarly, CH_4 and N_2O emissions also arise due to manure deposits on pasture. This is a natural and unavoidable function of animals, however, it is human demand for these animals that results in the occurrence and thus these land-related emissions are elevated due to human demand and land use.

5.2. Creation of the GHG multiplier for Agricultural Sectors[4]

5.2.1. GHGs from Fossil Fuel Use

Agricultural sectors consume fossil fuels to operate machinery and maintain buildings. GHG emissions associated with fossil fuel consumption were determined by using energy expenditure data reported by the USDA [47]. Expenditures were converted to physical units, then energy content, and finally GHG emissions. Energy expenditures were taken from the 2002 Census of Agriculture (Census) in order to estimate GHG emissions from fossil fuel use in agricultural sectors (sectors whose first 3 digits start with 111 and 112, seen in Appendix A**)** [47]. Electricity expenditures were taken from the Economic Research Service as the 2002 Census does not include this information [150]. The Census reports fuel expenditures by NAICS code; in some cases NAICS sectors were aggregated differently than the codes in the benchmark tables used to construct the IOA model. Sectors were either disaggregated using economic output data or added together, Appendix D describes the aggregation and disaggregation of sectors for consistency.

In the 2002 Census fuel expenditures are aggregated into one category, "gasoline, fuels, and oils" [47]. The 1997 Census included more detailed fuel expenditure information with four categories: gasoline and gasohol, diesel, natural gas, and LPG, fuel oil, kerosene, motor oil, grease, etc. [151]. The 1997 ratio of fuels within each sector was used to disaggregate the 2002 Census "gasoline, fuels, and oils" category. The 1997 fuel grouping "LPG, fuel oil, kerosene, motor oil, grease, etc." was disaggregated into LPG, kerosene and residual oil based on reports of consumption of these fuels in agriculture, it was assumed that the remaining petroleum products do not contribute significantly to GHG emissions.

Expenditures were converted into physical units using values in Table 5.4. Physical units were converted into energy content (BTUs) using the conversion factors shown in Table 5.5 and then to carbon content Table 5.6. Carbon content was converted to CO_2 emissions using a factor of 3.67 gram CO_2 per gram of carbon [148].

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[4] Much of the text in this section was taken from the 2002 EIO-LCA Documentation, of which I contributed the estimates of emissions for Agricultural sectors.

Table 5.4. Energy Prices Assumed for Agricultural Fuel and Electricity Use, 2002[a]

Energy Prices Assumed for Agricultural Fuel and Electricity Use, 2002			
Diesel	0.964	$/gal	[152]
Gasoline, bulk delivery	1.374	$/gal	[152]
LPG, bulk delivery	0.925	$/gal	[152]
Residual Oil	0.561	$/gal	[153]
Kerosene	0.99	$/gal	[154]
Electricity	0.0488	$/kWh	[155]
Natural gas	4.02	$/1000 cu ft	[156]

Notes: (a) This table was adapted from the 2002 EIO-LCA Documentation Report.

Table 5.5. Energy content of fuels

Fuel	Value	Unit
barrel crude petroleum=	5,800,000	BTU
short ton anthracite coal=	25,400,000	BTU
short ton bit & lig=	26,200,000	BTU
1000 cu. Ft. natural gas=	1,035,000	BTU
barrel distillate fuel oil=	5,825,000	BTU
barrel residual fuel oil=	628,7000	BTU
barrel LPG=	4,011,000	BTU
barrel gasoline=	5,248,000	BTU
barrel kerosine=	5,670,000	BTU
barrel natural gasoline=	4,620,000	BTU
BTU=	1055.1	Joules
TBTU=	1,055,100	GJ

Note: 1 barrel = 42 gallons

Table 5.6. Carbon Content of Fuels

Fuel Type	C content coeff (Tg C/ Qbtu)[10]
Natural Gas	14.47
Petroleum	
Distillate	19.95
Kerosene	19.72
Residual Fuel Oil	21.49
Motor gasoline	19.35
Industrial Other Coal	25.63
LPG (energy use)	17.2
LPG (non-E use)	16.82

5.2.2. Non-fuel GHG Emissions in Agriculture

Nonfuel GHG emissions in Agriculture include CH_4 and N_2O. Agricultural emissions for 2002 as included in the 2009 EPA GHG Inventory were allocated to NAICS sectors using a variety of approaches as described below results are show in Table 5.7. The EPA reports methane emissions by animal or crop and thus assigning these emissions is simply a matter of matching each crop or animal to the appropriate sector, e.g., enteric emissions from cattle were assigned to the Cattle Ranching and Farming sector.

Since the EPA does not report N_2O emissions by crop allocating the N_2O emissions was slightly more complex. Total fertilizer-related emissions reported by the EPA were assigned to NAICS sectors by creating ratios for each sector based on fertilizer consumption data from the USDA [42, 47]. Residue N was assigned to NAICS sectors using harvested weight data given that these emissions are driven largely by materials remaining on the soil after harvest which contribute to the nitrification and denitrification process [47].

Emissions associated with manure for each major animal were approximated using the IPCC Tier 1 method for calculating "N in urine and dung deposited by grazing animals on pasture, range and paddock" [148]. Since the EPA uses more complex modeling to determine these emissions, Tier III models, the ratio from the Tier I calculations was used to allocated EPA reported emissions to the appropriate sector. All other N_20 emissions were allocated to NAICS sectors using acreage [47].

Table 5.7. Summary of GHG Allocation to BEA Sectors (Tg CO2 equivalents)

Sector Number	Sector Name	CO_2	CH_4	N_2O
1111A0a	Soybean farming	5.7	0.2	22.6
1111A0b	Other Oilseed farming	0.0	0	0.8
1111B0a	Corn farming	5.8	0.3	49.0
1111B0b	Wheat farming	0.5	0.1	15.8
1111B0c	Rice farming	0.0	6.9	1.2
1111B0d	Other grain farming	0.0	0	3.0
111200	Vegetable and melon farming	3.4	0	5.2
111335	Tree nut farming	0.5	0	0.7
1113A0	Fruit farming	2.3	0	3.7
111400	Greenhouse and nursery production	4.3	0	2.1
111910	Tobacco farming	1.0	0	1.8
111920	Cotton farming	2.1	0	6.5
1119A0	Sugarcane and sugar beet farming	0.5	0	2.3
1119B0a	Hay and pasture farming	3.9	0	19.1
1119B0b	All other crop farming	0.1	0	2.7
112120	Milk Production	0.1	46.6	8.3
1121A0	Cattle ranching and farming	4.7	100.7	64.8
112300	Poultry and egg production	11.4	2.7	1.9
112A00	Animal production, except cattle and poultry and eggs	4.8	24.6	9.9
113300	Logging	5.2	0	0.05
113A00	Forest nurseries, forest products, and timber tracts	1.5	0	0.05
114100	Fishing	0.6	0	0
114200	Hunting and trapping	2.8	0	0
115000	Agriculture and forestry support activities	0.7	0	0
	Total	62.5	182.1	222.2

5.3. Analysis with GHG vector and Discussion

The GHG emissions associated with all U.S. final demand were determined using Equations 2.1 and 2.2, Section 2.2, where **F** is replaced with the GHG vector described in this section. GHG emissions were organized into consumption categories as described in previous chapters. From Figure 5.1 it can be seen that CO_2 generated from fossil fuel combustion dominates each category, with the exception of Plant and Animal Food Products. Agricultural sectors are the only sectors in which CO_2 emissions do not dominate GHG emissions. CO_2 generated from fossil fuel combustion have been removed in Figure 5.2 to allow for a closer examination of the sources of GHGs associated with agriculture and land use. For crop sectors, N_2O emissions make up the bulk of GHG emissions in terms of CO_2e. For animal production sectors, specifically cattle, CH_4 contributes a great deal of GHG emissions. These are almost entirely due to beef and dairy cattle consumption. Other sectors with large non-CO_2 emissions are fertilizer manufacturing (N_2O), natural gas pipelines (CH_4), wastewater treatment (primarily CH_4) and waste management and remediation (CH_4). It is also interesting to note that CH_4 from waste management contributes considerably to non-fossil GHG emissions. If we take the viewpoint that CH4crop, CH4animal, N2Ocrop, N2Oanimal are associated with LU then we can say that 6.4% of current U.S. GHG emissions are associated with LU, or approximately 38% of non-fossil fuel GHG emissions.

The GHG multiplier created in this chapter was used to approximate the GHG emissions associated with the U.S. biofuel scenario and food choice scenarios described in Chapter 3. Table 5.8 summarizes the change in GHG emissions as a result of increased corn and soy production in the U.S. to meet EIS biofuel goals. Total emissions are estimated to increase by 0.4%, the majority of which are N_2O associated with corn and soy cultivation.

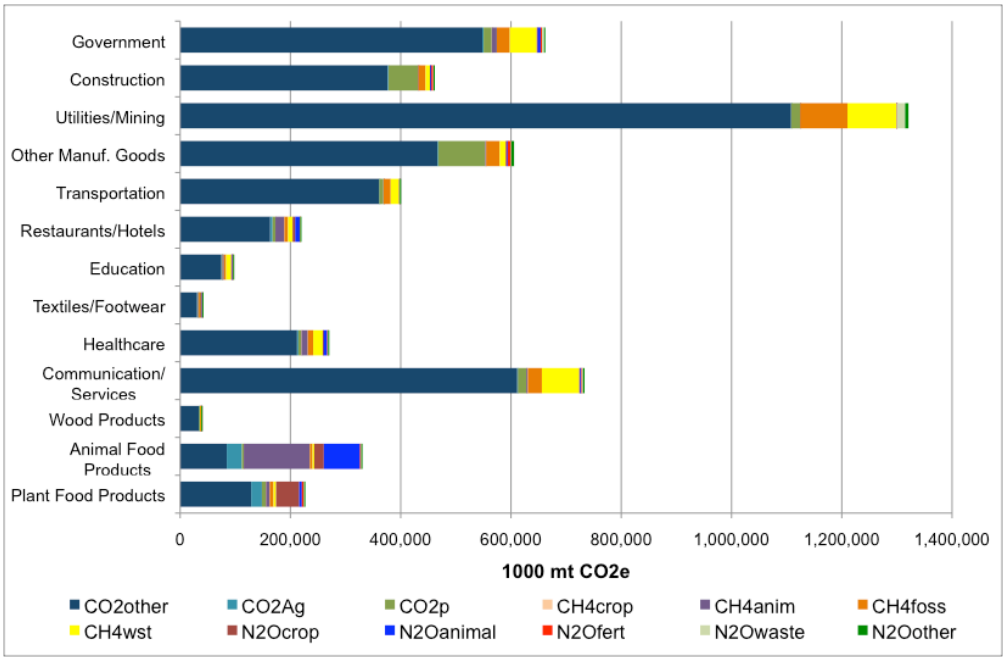

Figure 5.1. GHG emissions organized by consumption categories.

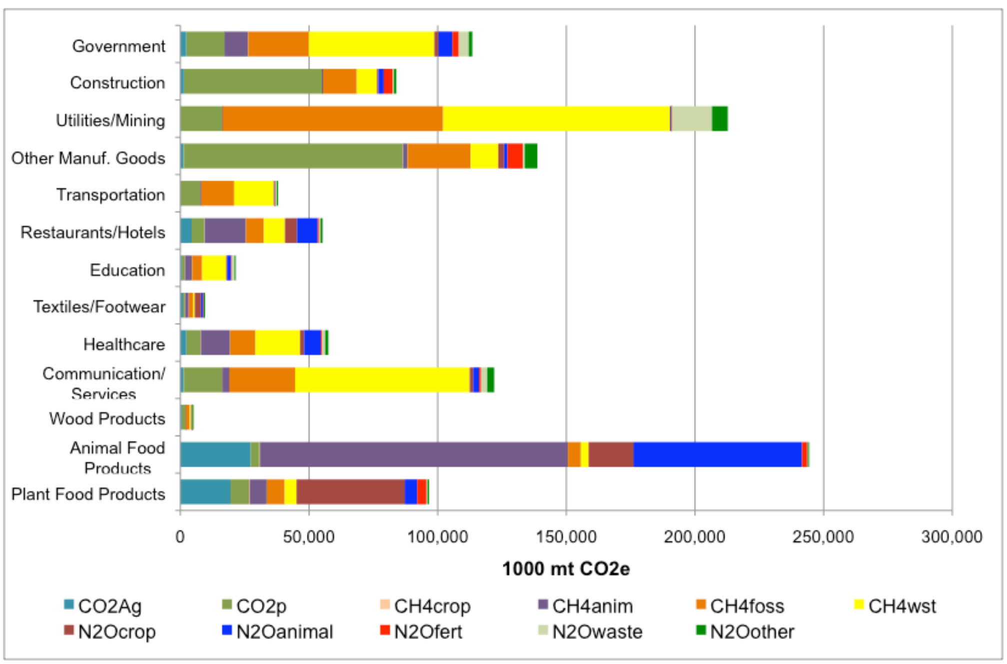

Figure 5.2. GHG emissions, minus carbon dioxide emissions from fossil fuel, organized by consumption sector

Table 5.8. Change in GHG Emissions with Addition of Corn Ethanol (15 Bgal) and Soy Biodiesel (1 Bgal)

GHG Category	Current U.S. Emissions (1000 Tg CO2e)	Increased Biofuel Scenario (1000 Tg CO2e)	Percent Difference
Total GHG	5,452,000	5,472,000	0.4%
CO2Ag	62,000	65,000	4.2%
CO2other	4,201,000	4,204,000	0.1%
CO2p	217,000	218,000	0.3%
CH4crop	1,000	1,000	13.3%
CH4anim	172,000	173,000	0.1%
CH4foss	221,000	221,000	0.1%
CH4wst	283,000	283,000	0.1%
N2Ocrop	75,000	87,000	13.7%
N2Oanimal	98,000	99,000	0.1%
N2Ofert	20,000	21,000	3.1%
N2Owaste	27,000	28,000	0.1%
N2Oother	20,000	20,000	0.1%

GHGs as a result of Scenario 1 (replace cereal/carbohydrate consumption with dairy food products) increased total U.S. GHG emissions by 1.5% due to animal production activities. GHG reductions were observed for all other scenarios. Scenario 2 caused the most significant decrease at 3.6% of total U.S. emissions, Scenario 3 followed with a 2.6% decrease and Scenario 4 decreased emissions by 1.6%. The GHG emissions due to Animal and Plant food product consumption described in Scenario 2 is shown on Figure 5.3, the remaining consumption categories are essentially unchanged and thus not shown here.

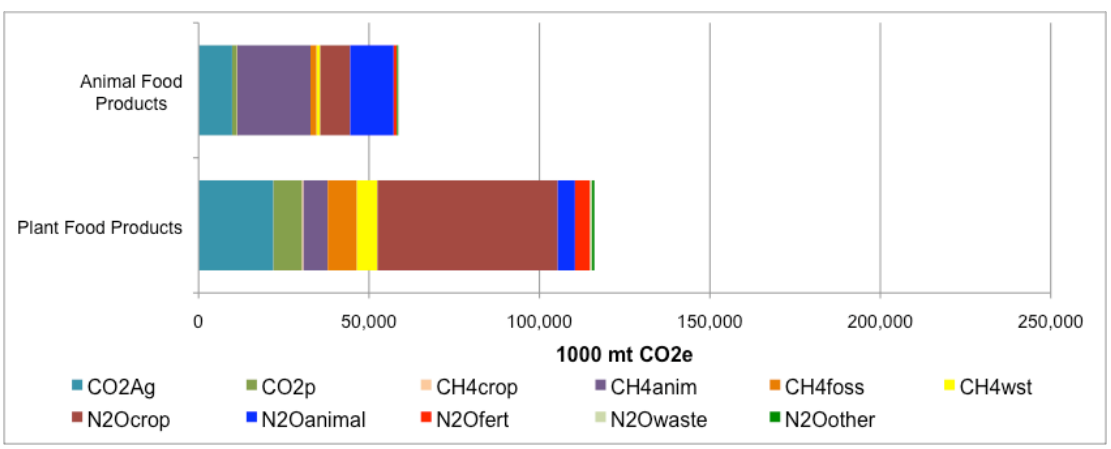

Figure 5.3. Scenario 2 GHG emissions, minus carbon dioxide emissions from fossil fuel

The separation of the GHG vector into category by source of emission provides some insight to the connection between activity and emission, particularly land use activity and GHG emissions. As noted by Weber and Matthews shifts toward vegetarian diets would reduce GHG emissions by a significant amount. If the U.S. pursued a vegan diet as suggested by Scenario 2 GHG reductions of 3.6% of current total would be achieved. This is a fairly considerable amount given that current agricultural emissions are approximately 6%. Shift toward vegetarian diets would also reduce overall U.S. land in use for production, specifically through pasture and grazed land; however, use of cropland would not decrease much.

6. Contribution, General Conclusion, and Future Work

6.1. Conclusions: Research Questions and Contribution Revisited

Each chapter includes a discussion regarding the individual results obtained from the work outlined in the chapter. In this section a few general observations and conclusions are presented.

Research questions were posed in the Introduction chapter of this dissertation and are revisited here for completeness. The first research question sought to determine which economic sectors use the most production land and which consumed goods are the most land intensive. To answer this question an inventory of land use in the U.S. was created. Creation of a land use inventory for all sectors of the U.S. economy is alone a contribution as no such inventory is available to my knowledge. The discussion about allocation of land use data to sectors provides useful instruction for creating subsequent inventories as new IO tables become available. Through creation of the inventory it was found that agricultural land is the most significant land required for production and EE-IOA results indicated that food products are the most land intensive.

Research question 2 was posed to explore the issues with developing metrics for considering land use, particularly metrics appropriate for large-scale analysis. Qualitative and quantitative metric selection when studying land use were discussed in Chapter 2. It is my assertion that quantitative metrics are more relevant for large-scale systems questions, such as integrating biofuels into the U.S. economy or assessing the impacts of major shifts in diet (Chapter 3). Coming to consensus about appropriate qualitative metrics for assessing land use tradeoffs, particularly with respect to biofuels, may simply take too long given a strong desire to make decisions in the relative near term. However, the results of EE-IOA may provide useful insight to the types of qualitative issues that might arise if there are large increases in land use. Particularly since results are associated with particular sectors and organized by land use type. Knowledge about the sector and land use type provides insight to the type of environmental issues likely to arise. For example, crop cultivation is known to increase fertilizer use and specific crops are associated with specific pesticide use.

The primary research question motivating Chapter 3 is: How much land is embodied in U.S. trade? In order to answer this question a novel approach was taken to approximate land embodied in imports. The approach used attempted to combine country-specific crop yields within a two-region model and avoided using global average yields. The results of the model indicate that land virtually imported through goods and services is quite large and is greater than the amount of land virtually exported to the ROW. Scenarios were developed in Chapter 3 to quantify potential increases in land use due to demand for biofuels and diet shift scenarios. Anticipated domestic land use and virtual land use imported from the rest of the world were approximated for select biofuel scenarios. In this chapter it was shown that shifts toward vegetarian diets could free up a large quantity of pasture and grazed land, but is unlikely to result in a decrease in cropland based on results. Total cropland associated with imported food products is only 11.5 Mha and thus even if the U.S. discontinued the import of food products the modeled quantity of land required to meet biofuel goals using land from the ROW is not possible. While not explicitly modeled similar results for imports can be expected given shifts in diet, specifically land for animal grazing may be freed up, but use of cropland will remain steady or increase slightly.

Chapter 4 addresses the question: how will increased demand for biofuels impact nitrate loading to the MARB and the subsequent formation of hypoxia in the NGOM. This analysis also considered the potential for mitigation of runoff to reduce nitrate loading and subsequent hypoxia. Results indicated that unless aggressive nutrient management strategies are implemented the formation of hypoxia is likely to exceed EPA goals under any biofuel production scenarios, even if all 35 Bgal are produced using switchgrass. This result highlights the importance of responsible land use management. The approach taken and results of this study offer a contribution to how we consider the environmental impact of such large-scale systems. Many LCAs have been conducted to compare the nitrate or GHG emissions of various biofuel feedstocks and production methods. However, the per gallon impact results do not provide much insight to the impacts likely to affect the ecosystem as a whole. This type of system-wide analysis is particularly important when the impacted ecosystem is already stressed, as is the case with the NGOM.

Chapter 5 is an extension of the work done in Chapter 2 and further demonstrates the relationship between land use and environmental impact. Many non-fossil generated GHG emissions are a function of processes that occur due to biogeochemical alterations associated with agricultural land use. By separating GHG emissions by source one can observe land use and GHG connections more readily. This chapter confirms that shifts toward vegetarian diets will result in decreased GHG emissions similar to the findings of others [92]. Change in GHG emissions due to increased demand for corn and soy to meet ethanol goals is also presented. As expected, GHG emissions increase with increased crop production for ethanol feedstocks. Note that potential carbon associated with land use change was not evaluated.

6.2. Discussion

The work outlined in this thesis has left me with a great respect for the necessity of considering system-wide impacts as a result of changes to the major systems we currently depend on. This thesis specifically considered land, or more specifically agricultural and food systems; however, exposure to the work of peers demonstrates the importance of using a system-wide, life cycle perspective for all systems, e.g., energy and transportation systems. In order to ensure a more sustainable set of systems to support consumption and quality of life this approach to analysis is critical. Simultaneously, this work has left me with a great interest in capturing variability present at the small scale to better represent impacts at the large scale. Land use provides an excellent example of the importance of considering both scales. Resolving these scales can be difficult. The importance of doing so depends on the research questions being considered. Further, the environmental impacts of using land are themselves dependent on the characteristics of the land.

Another fascinating aspect of studying land use, particularly agricultural land use, is that the use of this land is not optional. One can potentially imagine living in a world with drastically less available energy or material goods. However, no one wants to imagine a world with considerably less food. Further, many would argue that food, or at the very least access to food, is a human right. While energy and material goods contribute to quality of life they are not imperative to survival. Careful use of land and its resources is and will be increasingly important to global societies. In many cases the use of land results in degradation of the land and associated natural systems. Perhaps the most important take away from this research is that there are no easy solutions and all systems are connected if one draws the boundary large enough.

This thesis emphasizes the importance and pervasiveness of agricultural land use in the supply chains of the majority of goods and services. While it is obvious that agricultural land use is imperative for food consumption, the quantity of agricultural land embodied in the supply chains of other goods and services was not so obvious at the start of this research. This finding suggests that land use may be important for evaluating the environmental impact of all goods and services.

It is appropriate to reflect on the methods chosen at the beginning of a research project at the end of analysis. Only through building a model, generating and interpreting results can we really appreciate the chosen approach. From this reflective perspective it is my opinion that the use of EE-IOA is appropriate for asking large-scale questions and particularly for understanding current relationships between land use and consumption. While anticipating possible land use futures with an EE-IOA model is useful for demonstrative and comparative purposes it may not be the most appropriate for research aimed at estimating close to exact values. EE-IOA methods are also valuable because results can be obtained fairly quickly and the sector detail is greater than that found in these other models. The dynamics of land use and land use change are very complex. Even models that include more specific economic relationships fail to capture complex socio-economic realities that drive land use change in developed nations.

6.3. Future Work

This work highlights the value in exploring the connections between how we use and manage land, site-specific variability and large-scale system-wide consequences. The MCA analysis of nitrate output over various biofuel scenarios began to explore these connections by consolidating variability to statistical distributions allowing for estimation of system-wide impacts. Given the size of agricultural land and the limited amount of land available for new use, the identification of land quality characteristics most conducive to large environmental impact is unlikely to result in cessation of their use. There is simply not enough land for such a policy. However, identification of the most significant location-specific variables causing environmental impact would enable researchers to explore the most appropriate management strategies for reducing system-wide impact through location-specific management strategies.

Future work regarding the IOA model should include additional refinement of food scenario tradeoffs. The scenarios created in Chapter 3 only include food purchases by households and do not include food waste. While the general findings are not likely to be altered, i.e., that replacing grain or vegetable foods for meat foods does not free up large quantities of cropland, inclusion of these additional food disappearances would make the results more robust. One could do this by determining total calorie production rather than household consumption of calories. Future work should also include some consideration for other dietary requirements such as protein.

Future work should also include more exploration of the potential impact of increasing global yields. Ideally, this work would be coupled with an effort to identify how increased yields would be obtained (increased fertilizer, genetic modification) and then associated environmental impacts could be approximated. For example, we know that increased fertilizer will not come without additional GHG emissions and nitrate output. There are many other considerations, e.g., increased mechanization may increase soil compaction or soil erosion.

Addition of ethanol sectors to the MRIO model would be useful for better approximating the anticipated LU associated with biofuel goals. It may also be useful to add ethanol production sectors specific to feedstock, e.g., corn, cellulosics, and sugarcane. Expansion to include additional regions may also prove important if the U.S. anticipates importing ethanol from countries with which there is not much existing trade. For example, the U.S. does not currently import the majority of sugarcane imports from Brazil and sugarcane-derived ethanol from Brazil may be important in the future.

As indicated in Chapter 2, areas assigned to pastureland and timberland are fairly conservative. It may be possible to develop more specific estimates of these land uses with better data. For example, if one could acquire specific data about the type of trees and location of harvest, time to re-growth specific to species could be used to approximate area required to ensure sustainable harvest rates. Similarly, in many states pasturelands are assigned animal unit months, a measure of the area required to sustain a 1000 pound cow and a calf for one month [157]. If data could be gathered for all states it may be possible to refine and further categorize the intensity of grazed areas. This data could also enable estimation of the potential for pasture intensification within the U.S.

During the proposal stage of this research I had hoped to integrate soil classification data to further explore the available land potentially useable for crop and grass cultivation. The Natural Resources Conservation Service's Land Capability Classification system categorizes land into eight classes defined according to the land's ability to support cultivation, where Class I is the best and Class VII is incapable of supporting cultivation and Class VIII is land area containing soils and landforms restricted to use as recreation, wildlife, water supply or aesthetic purposes [158]. This was not completed for a number of reasons, one being that it is difficult without spatially explicit data to link land used for production to this soil classification systems. Creating such a link could be helpful for understanding the likely yield, fertilizer input requirements, of available cropland enabling estimation of possible output and potential associated environmental impacts.

Chapters 4 and 5 demonstrate how land use relates to environmental impact. In Chapter 4 the approach was to approximate nitrate output and subsequent formation of hypoxia using statistical and environmental fate models. Chapter 5 related GHG emissions to land use categories using a disaggregated GHG multiplier within an EIO-LCA modeling framework. An interesting study may be found in combining these two approaches to create a nitrate output multiplier. Additional work would include defining nitrate output for all crops. One might also take this to the next step and use the nitrate output estimates to approximate eutrophication potentials. This effort could prove useful for assessing the comparative eutrophication potential for various food choices. Further, animal production, wastewater treatment plants, and household use of fertilizers and excretion of nutrients contribute to eutrophication potential, such a multiplier in the EIO-LCA model could be used to relate these sources to consumption.

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Appendices

Appendix A

1. Primary and Allocation Data Sources Used in the Production based Inventory

The following table describes the data sources used to assign areas to each sector included in the BEA input-output tables.

Table A.1. Summary of Primary and Allocation Data Sources

NAICS code	NAICS Description	Primary Data Source	Allocation Data
1111	Oilseed and Grain Farming	[1]	none
111200	Vegetable and melon farming	[2]	none
111335	Tree nut farming	[1]	none
1113A0	Fruit farming	[2]	none
111400	Greenhouse and nursery production	[2]	none
1119	Other crop farming	[2]	none
1119B0a	Hay and pasture farming	[3]	none
1119B0b	All other crop farming	[2]	[4]
112120	Milk Production	[2]	none
1121A0	Cattle ranching and farming	[3]	none
112300	Poultry and egg production	[2]	none
112A00	Animal production, except cattle and poultry and eggs	[2]	none
113300	Logging	[3]	[4]
113A00	Forest nurseries, forest products, and timber tracts		
114 & 115	Fishing, hunting and trapping & Agriculture and forestry support activities	assumed to be negligible	-
212	Mining (except Oil and Gas)	[5]	evenly allocated
213	Support activities for mining	assumed to be negligible	
221100	Power generation and supply	[3]	[6]
221200	Natural gas distribution	[7]	-
221300	Water, sewage and other systems	not included in the model	-
23	Construction	assumed to be negligible	-
31-33	Manufacturing	[3]	[8, 9]
420000	Wholesale trade	[3]	[8, 9]
481000	Air transportation	[3]	-

482000	Rail transportation	[3]	[7]
483000	Water transportation	not included in the model, there is not sufficient data to approximate associated land-based activities associated with water transportation	-
484000	Truck transportation	[3]	[10]
485000	Transit and ground passenger transportation	[3]	[7, 10]
486000	Pipeline transportation	[7]	
48A000	Scenic and sightseeing transportation and support activities for transportation	[3]	[8, 9]
42	Wholesale Trade	[3]	[8, 9]
44-45	Retail Trade		
48-49	Transportation and Warehousing		
51	Information		
52	Finance and Insurance		
53	Real Estate and Rental and Leasing		
54	Professional, Scientific, and Technical Services		
55	Management of Companies and Enterprises		
56	Administrative and Support and Waste Management and Remediation Services		
61	Educational Services		
62	Health Care and Social Assistance		
71	Arts, Entertainment, and Recreation		
72	Accommodation and Food Services		
81	Other Services (except Public Administration)		
92	Public Administration		

Note: The following sectors also have a value of zero due to lack of data: S00203 – Other state and local government enterprises; S00300 – Noncomparable imports; S00401 – Scrap; S00700 – General state and local government services; S00800 – Owner-occupied dwellings; and S00900 – ROW Adjustment.

1.1. Estimation of area for Transportation Sectors

Modes of transportation included in the model include:

- 481000 – Air transportation
- 482000 – Rail transportation
- 483000 – Water transportation
- 484000 – Truck transportation
- 485000 – Transit and ground passenger transportation, and
- 486000 – Pipeline transportation.

The USDA MULR includes estimates for rural roadways[1] 8.8 Mha, railways 1.3 Mha, and airports 0.97 Mha. The 0.97 Mha area estimated for airports was assigned to sector 481000. Area estimated by the USDA for rail uses were divided between sectors 482000 and 485000 using system mileage data for Class I (freight) rail and commuter/passenger rail [7]. Road area was allocated to two sectors: 484000 and 485000 using USDOT data regarding federal cost associated with damage to roadway usage by vehicle type, i.e., trucks and passenger vehicles [10]. Area was estimated for sector 486000 using linear mileage of pipelines data from the Bureau of Transportation Statistics [7], a buffer of 20 feet was assumed to calculate and area of 1.2 Mha. In many cases, pipelines are underground and/or collocated with roadways, however, as these areas are typically maintained as right-of-ways, the entire area was counted. Water transportation was assumed to be zero. Data for land-based areas associated with water transportation, e.g., ports, administrative offices, were not readily available.

Table A.2. Summary of Areas Assigned to Sectors using Three Allocation Methods

Sector Number	Sector Description	Area - Allocation 1: Building Footprint (Mha)	Area - Allocation 2: Employee Data (Mha)	Area - Allocation 3: Establishment Data (Mha)	Economic Output ($M)
1111A0a	Soybean farming	3.0E+01			13,451
1111A0b	Other oilseed farming	1.4E+00			678
1111B0a	Corn farming	3.2E+01			17,259
1111B0b	Wheat farming	2.4E+01			5,473
1111B0c	Rice farming	1.3E+00			763
1111B0d	Other grain farming	8.5E+00			2,188
111200	Vegetable and melon farming	3.5E+00			17,680
111335	Tree nut farming	3.5E-01			2,172
1113A0	Fruit farming	2.4E+00			10,748

[1] Rural transportation land, as defined by the USDA, includes highways, roads, railroads and rights-of-way outside of urban and built-up areas. Total road area was also estimated using linear mileage and engineering estimates for road width and right-of-way (USDOT, FHA, , Highway Statistics http://www.fhwa.dot.gov/policy/ohim/hs06/index.htm and BTS National Transportation Statistics). The two estimates differed by approximately 100,000 acres. The USDA estimate was used for consistency.

111400	Greenhouse and nursery production	1.0E+00			15,616
111910	Tobacco farming	1.4E+00			1,175
111920	Cotton farming	5.9E+00			3,173
1119A0	Sugarcane and sugar beet farming	9.9E-01			2,071
1119B0a	Hay and pasture farming	2.5E+01			17,165
1119B0b	All other crop farming	3.0E+00			2,920
112120	Milk Production	7.8E+00			20,721
1121A0	Cattle ranching and farming	2.9E+02			41,738
112300	Poultry and egg production	1.2E+00			21,051
112A00	Animal production, except cattle and poultry and eggs	6.4E+00			16,331
113300	Logging	1.4E+02			25,158
113A00	Forest nurseries, forest products, and timber tracts	6.0E+01			10,434
114100	Fishing	0.0E+00			3,177
114200	Hunting and trapping	0.0E+00			2,425
115000	Agriculture and forestry support activities	0.0E+00			16,073
211000	Oil and gas extraction	7.4E-02			89,280
212100	Coal mining	7.4E-02			20,372
212210	Iron ore mining	7.4E-02			1,773
212230	Copper, nickel, lead, and zinc mining	7.4E-02			2,378
2122A0	Gold, silver, and other metal ore mining	7.4E-02			3,863
212310	Stone mining and quarrying	7.4E-02			9,430
212320	Sand, gravel, clay, and refractory mining	7.4E-02			7,281
212390	Other nonmetallic mineral mining	7.4E-02			2,169
213111	Drilling oil and gas wells	7.4E-02			13,239
213112	Support activities for oil and gas operations	0.0E+00			16,713
21311A	Support activities for other mining	0.0E+00			3,570
221100	Power generation and supply	0.0E+00	8.1E-02	2.4E-02	250,159
221200	Natural gas distribution	3.0E-01			93,128
221300	Water, sewage and other systems	0.0E+00	7.2E-03	1.5E-02	43,306
230101	Nonresidential commercial and health care structures	0.0E+00			129,239
230102	Nonresidential manufacturing structures	0.0E+00			23,466
230103	Other nonresidential structures	0.0E+00			292,328
230201	Residential permanent site single- and multi-family structures	0.0E+00			304,951
230202	Other residential structures	0.0E+00			133,484
230301	Nonresidential maintenance and repair	0.0E+00			101,517
230302	Residential maintenance and repair	0.0E+00			47,379
311111	Dog and cat food manufacturing	4.2E-02	2.2E-03	5.7E-04	9,882

311119	Other animal food manufacturing	4.2E-02	5.4E-03	4.0E-03	17,363
311210	Flour milling and malt manufacturing	4.2E-02	2.8E-03	1.2E-03	8,349
311221	Wet corn milling	9.9E-02	1.5E-03	1.5E-04	6,595
311225	Fats and oils refining and blending	4.2E-02	1.2E-03	2.9E-04	8,304
31122A	Soybean and other oilseed processing	4.2E-02	1.3E-03	3.9E-04	12,046
311230	Breakfast cereal manufacturing	4.2E-02	2.1E-03	1.6E-04	7,868
311313	Beet sugar manufacturing	1.7E-01	9.9E-04	1.0E-04	2,255
31131A	Sugar cane mills and refining	1.7E-01	1.3E-03	1.3E-04	4,199
311320	Confectionery manufacturing from cacao beans	4.2E-02	1.5E-03	3.4E-04	2,017
311330	Confectionery manufacturing from purchased chocolate	4.2E-02	5.4E-03	2.2E-03	9,700
311340	Nonchocolate confectionery manufacturing	4.2E-02	3.9E-03	1.6E-03	6,601
311410	Frozen food manufacturing	4.2E-02	1.3E-02	1.7E-03	21,434
311420	Fruit and vegetable canning, pickling and drying	9.9E-02	1.2E-02	2.8E-03	30,155
311513	Cheese manufacturing	4.2E-02	6.1E-03	1.3E-03	20,098
311514	Dry, condensed, and evaporated dairy products	4.2E-02	2.3E-03	5.3E-04	9,886
31151A	Fluid milk and butter manufacturing	4.2E-02	9.4E-03	1.5E-03	23,816
311520	Ice cream and frozen dessert manufacturing	4.2E-02	3.1E-03	1.0E-03	7,851
311615	Poultry processing	4.2E-02	3.8E-02	1.2E-03	37,547
31161Aa	Cattle slaughtering and processing	4.2E-02	3.3E-02	6.8E-03	64,364
31161Ab	Other animal (except poultry) slaughtering and processing	4.2E-02	8.6E-03	1.8E-03	17,686
311700	Seafood product preparation and packaging	4.2E-02	6.3E-03	1.9E-03	8,250
311810	Bread and bakery product manufacturing	4.2E-02	3.6E-02	2.4E-02	36,905
311820	Cookie, cracker and pasta manufacturing	4.2E-02	9.1E-03	2.1E-03	15,819
311830	Tortilla manufacturing	4.2E-02	2.0E-03	7.6E-04	1,397
311910	Snack food manufacturing	4.2E-02	7.4E-03	1.2E-03	18,026
311920	Coffee and tea manufacturing	4.2E-02	1.8E-03	7.6E-04	5,195
311930	Flavoring syrup and concentrate manufacturing	4.2E-02	9.1E-04	4.1E-04	9,386
311940	Seasoning and dressing manufacturing	4.2E-02	4.4E-03	1.5E-03	10,575
311990	All other food manufacturing	4.2E-02	9.7E-03	3.4E-03	16,604
312110	Soft drink and ice manufacturing	5.8E-02	1.2E-02	3.4E-03	32,783
312120	Breweries	5.8E-02	5.0E-03	1.1E-03	21,524
312130	Wineries	5.8E-02	4.3E-03	3.2E-03	9,834
312140	Distilleries	5.8E-02	9.8E-04	2.3E-04	7,949
3122A0	Tobacco product manufacturing	2.3E-01	3.9E-03	3.4E-04	47,464
313100	Fiber, yarn, and thread mills	8.3E-02	9.8E-03	1.5E-03	6,806

313210	Broadwoven fabric mills	8.3E-02	1.4E-02	2.0E-03	7,307
313220	Narrow fabric mills and schiffli embroidery	8.3E-02	2.4E-03	1.0E-03	1,211
313230	Nonwoven fabric mills	8.3E-02	2.9E-03	6.0E-04	4,190
313240	Knit fabric mills	8.3E-02	3.2E-03	9.4E-04	3,202
313310	Textile and fabric finishing mills	8.3E-02	8.6E-03	3.8E-03	12,096
313320	Fabric coating mills	8.3E-02	1.4E-03	5.6E-04	2,247
314110	Carpet and rug mills	4.1E-02	7.2E-03	1.1E-03	12,938
314120	Curtain and linen mills	4.1E-02	9.8E-03	6.3E-03	9,177
314910	Textile bag and canvas mills	4.1E-02	4.3E-03	5.1E-03	2,402
314990	All other miscellaneous textile product mills	4.1E-02	9.5E-03	6.5E-03	7,537
315100	Apparel knitting mills	1.8E-02	9.0E-03	2.3E-03	3,254
315210	Cut and sew apparel contractors	1.8E-02	1.7E-02	1.9E-02	3,990
315220	Men's and boys' cut and sew apparel manufacturing	1.8E-02	1.1E-02	2.4E-03	11,112
315230	Women's and girls' cut and sew apparel manufacturing	1.8E-02	1.2E-02	5.8E-03	16,637
315290	Other cut and sew apparel manufacturing	1.8E-02	2.4E-03	1.5E-03	1,437
315900	Accessories and other apparel manufacturing	1.8E-02	5.5E-03	3.7E-03	2,592
316100	Leather and hide tanning and finishing	1.6E-02	1.5E-03	7.4E-04	2,089
316200	Footwear manufacturing	1.6E-02	3.4E-03	8.7E-04	1,936
316900	Other leather and allied product manufacturing	1.6E-02	2.8E-03	2.4E-03	1,804
321100	Sawmills and wood preservation	2.5E-02	1.9E-02	1.1E-02	29,101
321219	Reconstituted wood product manufacturing	4.3E-02	3.6E-03	7.0E-04	5,789
32121A	Veneer and plywood manufacturing	4.3E-02	7.2E-03	1.2E-03	7,663
32121B	Engineered wood member and truss manufacturing	4.3E-02	7.2E-03	2.8E-03	6,385
321910	Wood windows and doors and millwork	2.4E-02	2.4E-02	1.3E-02	19,368
321920	Wood container and pallet manufacturing	2.4E-02	7.7E-03	7.5E-03	5,173
321991	Manufactured home, mobile home, manufacturing	2.4E-02	8.3E-03	1.0E-03	6,740
321992	Prefabricated wood building manufacturing	2.4E-02	3.9E-03	2.0E-03	3,743
321999	Miscellaneous wood product manufacturing	2.4E-02	5.9E-03	4.8E-03	4,632
322110	Pulp mills	2.0E-01	1.4E-03	1.1E-04	5,266
322120	Paper mills	2.5E-01	1.7E-02	9.1E-04	46,011
322130	Paperboard Mills	1.1E-01	7.9E-03	5.9E-04	19,879
322210	Paperboard container manufacturing	7.4E-02	3.1E-02	6.9E-03	42,160
32222A	Coated and laminated paper, packaging materials, and plastic films manufacturing	7.4E-02	6.9E-03	1.7E-03	11,861

32222B	All other paper bag and coated and treated paper manufacturing	7.4E-02	3.8E-03	7.0E-04	5,045
322230	Stationery product manufacturing	7.4E-02	6.3E-03	1.7E-03	7,600
322291	Sanitary paper product manufacturing	7.4E-02	3.1E-03	3.4E-04	7,740
322299	All other converted paper product manufacturing	7.4E-02	3.2E-03	1.3E-03	4,362
323110	Printing	1.5E-02	1.0E-01	8.6E-02	66,972
323120	Support activities for printing	1.5E-02	9.9E-03	8.8E-03	6,871
324110	Petroleum refineries	2.4E-01	1.0E-02	9.0E-04	191,546
324121	Asphalt paving mixture and block manufacturing	2.4E-02	2.0E-03	3.4E-03	7,460
324122	Asphalt shingle and coating materials manufacturing	2.4E-02	2.1E-03	6.0E-04	5,799
324191	Petroleum lubricating oil and grease manufacturing	2.4E-02	1.6E-03	8.5E-04	7,762
324199	All other petroleum and coal products manufacturing	2.3E-02	4.6E-04	2.1E-04	1,343
325110	Petrochemical manufacturing	4.1E-02	1.7E-03	1.5E-04	22,840
325120	Industrial gas manufacturing	7.4E-03	1.5E-03	1.4E-03	6,052
325130	Synthetic dye and pigment manufacturing	4.6E-02	2.4E-03	5.1E-04	6,256
325181	Alkalies and chlorine manufacturing	1.3E-01	7.3E-04	9.8E-05	3,491
325182	Carbon black manufacturing	9.1E-02	2.8E-04	6.4E-05	1,056
325188	All other basic inorganic chemical manufacturing	3.4E-02	8.1E-03	1.6E-03	17,743
325190	Other basic organic chemical manufacturing	7.6E-02	1.3E-02	2.1E-03	57,261
325211	Plastics material and resin manufacturing	3.6E-02	9.7E-03	1.8E-03	46,422
325212	Synthetic rubber manufacturing	3.6E-02	1.7E-03	4.2E-04	5,790
325220	Artificial and synthetic fibers and filaments manufacturing	2.0E-01	4.3E-03	2.9E-04	12,375
325310	Fertilizer manufacturing	4.6E-02	3.3E-03	1.9E-03	10,291
325320	Pesticide and other agricultural chemical manufacturing	4.6E-02	2.3E-03	6.1E-04	9,570
325411	Medicinal and botanical manufacturing	6.5E-02	3.6E-03	9.1E-04	12,794
325412	Pharmaceutical preparation manufacturing	6.7E-02	2.3E-02	2.3E-03	105,558
325413	In-vitro diagnostic substance manufacturing	6.5E-02	6.8E-03	5.3E-04	9,275
325414	Biological product (except diagnostic) Manufacturing	6.5E-02	4.6E-03	8.5E-04	8,863
325510	Paint and coating manufacturing	6.5E-02	7.7E-03	3.5E-03	19,383
325520	Adhesive manufacturing	6.5E-02	3.4E-03	1.6E-03	7,465
325610	Soap and cleaning compound manufacturing	6.5E-02	8.7E-03	4.0E-03	30,249
325620	Toilet preparation manufacturing	6.5E-02	9.2E-03	2.0E-03	29,920

325910	Printing ink manufacturing	6.5E-02	1.9E-03	1.3E-03	4,098
3259A0	All other chemical product and preparation manufacturing	6.5E-02	1.5E-02	5.9E-03	30,891
326110	Plastics packaging materials, film and sheet	3.9E-02	1.6E-02	3.6E-03	28,524
326121	Unlaminated plastics profile shape manufacturing	3.9E-02	4.1E-03	1.7E-03	5,436
326122	Plastics Pipe and Pipe Fitting Manufacturing	3.9E-02	3.2E-03	1.1E-03	5,315
326130	Laminated plastics plate, sheet, and shapes	3.9E-02	2.1E-03	9.7E-04	2,406
326140	Polystyrene Foam Product Manufacturing	3.9E-02	4.9E-03	1.4E-03	6,119
326150	Urethane and Other Foam Product (except Polystyrene) Manufacturing	3.9E-02	5.4E-03	1.6E-03	6,880
326160	Plastics bottle manufacturing	3.9E-02	5.7E-03	1.2E-03	8,035
32619A	Other plastics product manufacturing	3.9E-02	7.9E-02	2.2E-02	75,893
326210	Tire manufacturing	3.9E-02	1.1E-02	1.8E-03	14,031
326220	Rubber and plastics hose and belting manufacturing	3.9E-02	3.6E-03	6.6E-04	3,919
326290	Other rubber product manufacturing	3.9E-02	1.5E-02	3.8E-03	13,264
32711A	Pottery, ceramics, and plumbing fixture manufacturing	3.1E-02	5.5E-03	2.6E-03	3,004
32712A	Brick, tile, and other structural clay product manufacturing	3.1E-02	3.4E-03	1.2E-03	2,923
32712B	Clay and non-clay refractory manufacturing	3.1E-02	1.7E-03	6.4E-04	2,010
327211	Flat glass manufacturing	2.6E-01	1.6E-03	2.4E-04	1,988
327212	Other pressed and blown glass and glassware manufacturing	6.1E-02	5.0E-03	1.3E-03	9,894
327213	Glass container manufacturing	2.1E-01	2.7E-03	1.8E-04	4,359
327215	Glass Product Manufacturing Made of Purchased Glass	6.1E-02	9.3E-03	3.9E-03	6,210
327310	Cement manufacturing	4.7E-02	2.7E-03	6.5E-04	7,294
327320	Ready-mix concrete manufacturing	4.7E-02	1.5E-02	1.4E-02	20,748
327330	Concrete pipe, brick and block manufacturing	4.7E-02	5.2E-03	3.5E-03	5,848
327390	Other concrete product manufacturing	4.7E-02	9.9E-03	5.9E-03	8,638
3274A0	Lime and gypsum product manufacturing	1.3E-02	2.8E-03	9.7E-04	4,829
327910	Abrasive product manufacturing	3.1E-02	2.6E-03	8.9E-04	3,341
327991	Cut stone and stone product manufacturing	3.1E-02	3.2E-03	3.9E-03	2,319
327992	Ground or treated minerals and earths manufacturing	3.1E-02	1.4E-03	8.9E-04	1,959
327993	Mineral wool manufacturing	5.4E-02	3.2E-03	7.7E-04	4,819

327999	Miscellaneous nonmetallic mineral products	3.1E-02	1.8E-03	1.3E-03	1,874
331110	Iron and steel mills	1.3E-01	2.1E-02	3.2E-03	57,464
331200	Iron, steel pipe and tube manufacturing from purchased steel	7.0E-02	9.5E-03	2.2E-03	8,474
331314	Secondary smelting and alloying of aluminum	1.1E-01	1.4E-03	3.6E-04	116
33131A	Alumina refining and primary aluminum production	3.7E-01	1.7E-03	1.5E-04	9,014
33131B	Aluminum sheet, plate, and foil manufacturing and aluminum rolling and drawing	1.1E-01	8.0E-03	9.9E-04	18,173
331411	Primary smelting and refining of copper	6.0E-02	4.6E-04	3.6E-05	2,780
331419	Primary nonferrous metal, except copper and aluminum	6.0E-02	1.4E-03	3.9E-04	4,034
331420	Copper rolling, drawing, extruding and alloying	6.0E-02	3.5E-03	6.0E-04	8,950
331490	Nonferrous metal (except copper and aluminum) rolling, drawing, extruding and alloying	6.0E-02	5.0E-03	1.4E-03	5,635
331510	Ferrous metal foundaries	7.1E-02	1.6E-02	2.8E-03	14,435
331520	Aluminum foundries	4.0E-02	1.3E-02	3.8E-03	11,170
332114	Custom roll forming	2.0E-02	2.3E-03	9.5E-04	4,089
33211A	All other forging, stamping , and sintering	2.0E-02	6.6E-03	1.6E-03	7,489
33211B	Crown, closure and metal stamping manufacturing	2.0E-02	1.3E-02	5.1E-03	9,859
33221A	Cutlery, utensils, pots, and pans manufacturing	2.0E-02	2.2E-03	5.6E-04	3,217
33221B	Handtool manufacturing	2.0E-02	8.0E-03	3.4E-03	7,073
332310	Plate work and fabricated structural product manufacturing	2.0E-02	2.5E-02	1.4E-02	26,427
332320	Ornamental and architectural metail products manufacturing	2.0E-02	3.8E-02	2.2E-02	30,748
332410	Power boiler and heat exchanger manufacturing	2.0E-02	3.4E-03	9.7E-04	3,358
332420	Metal tank, heavy gauge, manufacturing	2.0E-02	4.7E-03	1.5E-03	4,546
332430	Metal can, box, and other container manufacturing	2.0E-02	5.6E-03	1.6E-03	14,097
332500	Hardware manufacturing	2.0E-02	1.1E-02	2.5E-03	9,898
332600	Spring and wire product manufacturing	2.0E-02	1.0E-02	4.3E-03	4,687
332710	Machine shops	2.0E-02	4.2E-02	5.9E-02	26,120
332720	Turned product and screw, nut, and bolt manufacturing	2.0E-02	1.8E-02	8.4E-03	15,936
332800	Coating, engraving, heat treating and allied activities	2.0E-02	2.2E-02	1.6E-02	19,580
332913	Plumbing Fixture Fitting and Trim Manufacturing	2.0E-02	2.5E-03	4.2E-04	3,091
33291A	Valve and fittings other than	2.0E-02	1.5E-02	3.0E-03	16,846

	plumbing				
332991	Ball and roller bearing manufacturing	2.0E-02	4.8E-03	5.1E-04	5,677
332996	Fabricated pipe and pipe fitting manufacturing	2.0E-02	4.8E-03	2.3E-03	3,707
33299A	Ammunition manufacturing	2.0E-02	2.1E-03	4.2E-04	2,077
33299B	Ordnance and accessories manufacturing	2.0E-02	2.4E-03	6.5E-04	3,115
33299C	Other fabricated metal manufacturing	2.0E-02	1.4E-02	9.2E-03	13,970
333111	Farm machinery and equipment manufacturing	3.0E-02	9.0E-03	3.1E-03	13,814
333112	Lawn and garden equipment manufacturing	3.0E-02	3.8E-03	3.9E-04	6,439
333120	Construction machinery manufacturing	3.0E-02	9.7E-03	2.0E-03	16,550
333130	Mining and oil and gas field machinery manufacturing	3.0E-02	6.1E-03	2.0E-03	7,247
333220	Plastics and rubber industry machinery	3.0E-02	2.7E-03	1.4E-03	2,655
333295	Semiconductor machinery manufacturing	3.0E-02	4.9E-03	6.7E-04	11,276
33329A	Other industrial machinery manufacturing	3.0E-02	1.6E-02	8.8E-03	16,348
333314	Optical instrument and lens manufacturing	3.0E-02	3.4E-03	1.2E-03	2,909
333315	Photographic and photocopying equipment manufacturing	3.0E-02	2.1E-03	8.1E-04	2,000
333319	Other commercial and service industry machinery manufacturing	3.0E-02	8.3E-03	3.3E-03	10,640
33331A	Vending, commerical, industrial, and office machinery manufacturing	3.0E-02	4.3E-03	7.1E-04	4,573
333414	Heating equipment (except warm air furnaces) manufacturing	3.0E-02	3.5E-03	1.1E-03	3,933
333415	Air conditioning, refrigeration, and warm air heating equipment manufacturing	3.0E-02	1.8E-02	2.2E-03	23,348
33341A	Air purification and ventilation equipment manufacturing	3.0E-02	4.0E-03	1.4E-03	3,819
333511	Industrial mold manufacturing	3.0E-02	6.8E-03	5.8E-03	5,931
333514	Special tool, die, jig, and fixture manufacturing	3.0E-02	1.0E-02	1.1E-02	7,928
333515	Cutting tool and machine tool accessory manufacturing	3.0E-02	6.0E-03	4.2E-03	4,696
33351A	Metal cutting and forming machine tool manufacturing	3.0E-02	4.7E-03	2.2E-03	3,838
33351B	Rolling mill and other metalworking machinery manufacturing	3.0E-02	2.7E-03	1.3E-03	3,145
333611	Turbine and turbine generator set units manufacturing	3.0E-02	3.2E-03	3.0E-04	12,718
333612	Speed Changer, Industrial High-Speed Drive, and Gear	3.0E-02	2.1E-03	6.3E-04	1,958

	Manufacturing				
333613	Mechanical Power Transmission Equipment Manufacturing	3.0E-02	2.8E-03	7.2E-04	2,617
333618	Other engine equipment manufacturing	3.0E-02	7.6E-03	7.2E-04	18,478
333911	Pump and pumping equipment manufacturing	3.0E-02	5.7E-03	1.3E-03	7,387
333912	Air and gas compressor manufacturing	3.0E-02	3.2E-03	7.6E-04	4,350
333920	Material handling equipment manufacturing	3.0E-02	1.3E-02	4.4E-03	15,421
333991	Power-driven handtool manufacturing	3.0E-02	2.1E-03	5.6E-04	3,462
333993	Packaging machinery manufacturing	3.0E-02	3.8E-03	1.6E-03	3,947
333994	Industrial process furnace and oven manufacturing	3.0E-02	1.9E-03	9.1E-04	1,562
33399A	Fluid power process machinery	3.0E-02	1.2E-02	5.5E-03	13,437
33399B	Process and oven not fluid power machinery	3.0E-02	5.4E-03	1.2E-03	5,672
334111	Electronic computer manufacturing	4.0E-02	1.0E-02	1.3E-03	41,339
334112	Computer storage device manufacturing	4.0E-02	3.9E-03	4.3E-04	7,877
33411A	Computer terminals and other computer peripheral equipment manufacturing	4.0E-02	1.1E-02	2.4E-03	18,022
334210	Telephone apparatus manufacturing	4.0E-02	1.1E-02	1.2E-03	25,375
334220	Broadcast and wireless communications equipment	4.0E-02	1.9E-02	2.8E-03	31,035
334290	Other communications equipment manufacturing	4.0E-02	3.9E-03	1.2E-03	5,161
334300	Audio and video equipment manufacturing	4.0E-02	4.1E-03	1.6E-03	9,586
334411	Electron tube manufacturing	4.0E-02	2.2E-03	3.1E-04	3,248
334412	Bare printed circuit board manufacturing	4.0E-02	8.8E-03	2.9E-03	6,726
334413	Semiconductor and related device manufacturing	7.3E-02	2.8E-02	2.8E-03	59,986
334417	Electronic connector manufacturing	4.0E-02	5.5E-03	7.9E-04	3,848
334418	Printed circuit assembly (electronic assembly) manufacturing	4.0E-02	1.3E-02	1.9E-03	23,103
334419	Other electronic component manufacturing	4.0E-02	1.2E-02	4.1E-03	10,387
33441A	Electronic capacitor, resistor, coil, transformer, and other inductor manufacturing	4.0E-02	5.2E-03	1.6E-03	3,171
334510	Electromedical apparatus manufacturing	4.0E-02	8.1E-03	1.3E-03	15,180

334511	Search, detection, and navigation instruments	4.0E-02	2.6E-02	1.7E-03	30,705
334512	Automatic environmental control manufacturing	4.0E-02	2.7E-03	8.7E-04	2,525
334513	Industrial process variable instruments	4.0E-02	6.1E-03	2.6E-03	6,969
334514	Totalizing fluid meters and counting devices	4.0E-02	2.0E-03	5.9E-04	5,295
334515	Electricity and signal testing instruments	4.0E-02	9.2E-03	2.0E-03	9,731
334516	Analytical laboratory instrument manufacturing	4.0E-02	5.6E-03	1.5E-03	7,547
334517	Irradiation apparatus manufacturing	4.0E-02	1.9E-03	4.1E-04	4,797
33451A	Watch, clock, and other measuring and controlling device manufacturing	4.0E-02	5.6E-03	2.4E-03	6,011
334613	Magnetic and optical recording media manufacturing	4.0E-02	1.6E-03	5.0E-04	2,568
33461A	Software, audio and video reproduction	4.0E-02	4.4E-03	1.8E-03	5,022
335110	Electric lamp bulb and part manufacturing	5.0E-02	1.9E-03	3.1E-04	2,510
335120	Lighting fixture manufacturing	5.0E-02	8.4E-03	2.9E-03	9,501
335210	Small electrical appliance manufacturing	5.0E-02	3.3E-03	4.9E-04	3,958
335221	Household cooking appliance manufacturing	5.0E-02	2.9E-03	2.8E-04	4,164
335222	Household refrigerator and home freezer manufacturing	5.0E-02	3.9E-03	8.2E-05	5,329
335224	Household laundry equipment manufacturing	5.0E-02	2.7E-03	6.2E-05	4,344
335228	Other major household appliance manufacturing	5.0E-02	2.0E-03	1.1E-04	3,138
335311	Electric power and specialty transformer manufacturing	5.0E-02	3.8E-03	7.4E-04	4,008
335312	Motor and generator manufacturing	5.0E-02	8.8E-03	1.6E-03	9,144
335313	Switchgear and switchboard apparatus manufacturing	5.0E-02	6.4E-03	1.4E-03	7,833
335314	Relay and industrial control manufacturing	5.0E-02	8.2E-03	3.0E-03	8,879
335911	Storage battery manufacturing	5.0E-02	3.0E-03	3.3E-04	3,395
335912	Primary battery manufacturing	5.0E-02	1.3E-03	1.2E-04	2,879
335920	Communication and energy wire and cable manufacturing	5.0E-02	8.0E-03	1.1E-03	10,803
335930	Wiring device manufacturing	5.0E-02	9.5E-03	1.8E-03	8,996
335991	Carbon and graphite product manufacturing	5.0E-02	1.3E-03	3.3E-04	1,652
335999	Miscellaneous electrical equipment manufacturing	5.0E-02	6.0E-03	2.3E-03	7,021
336111	Automobile Manufacturing	1.1E+00	1.8E-02	5.3E-04	86,139
336112	Light Truck and Utility Vehicle Manufacturing	1.1E+00	1.4E-02	2.6E-04	134,989

336120	Heavy duty truck manufacturing	9.2E-02	3.3E-03	2.2E-04	19,083
336211	Motor vehicle body manufacturing	9.2E-02	6.4E-03	1.9E-03	4,846
336212	Truck trailer manufacturing	9.2E-02	3.6E-03	1.0E-03	3,962
336213	Motor home manufacturing	9.2E-02	2.7E-03	1.9E-04	5,409
336214	Travel trailer and camper manufacturing	9.2E-02	5.9E-03	2.0E-03	6,882
336300	Motor vehicle parts manufacturing	9.2E-02	1.1E-01	1.4E-02	197,404
336411	Aircraft manufacturing	9.2E-02	2.5E-02	7.0E-04	61,529
336412	Aircraft engine and engine parts manufacturing	9.2E-02	1.2E-02	1.0E-03	20,416
336413	Other aircraft parts and equipment	9.2E-02	1.7E-02	2.2E-03	20,796
336414	Guided missile and space vehicle manufacturing	9.2E-02	6.8E-03	3.9E-05	11,394
33641A	Other guided missile and space vehicle parts and auxiliary equipment manufacturing	9.2E-02	3.2E-03	1.8E-04	6,082
336500	Railroad rolling stock manufacturing	9.2E-02	4.6E-03	5.1E-04	7,008
336611	Ship building and repairing	9.2E-02	1.4E-02	1.6E-03	12,715
336612	Boat building	9.2E-02	7.3E-03	2.9E-03	7,976
336991	Motorcycle, bicycle, and parts manufacturing	9.2E-02	2.3E-03	9.1E-04	4,235
336992	Military armored vehicles and tank parts manufacturing	9.2E-02	8.7E-04	1.0E-04	1,796
336999	All other transportation equipment manufacturing	9.2E-02	3.2E-03	1.1E-03	7,018
337110	Wood kitchen cabinet and countertop manufacturing	2.5E-02	2.1E-02	2.5E-02	14,329
337121	Upholstered household furniture manufacturing	2.5E-02	1.4E-02	4.2E-03	10,381
337122	Nonupholstered wood household furniture manufacturing	2.5E-02	1.8E-02	1.1E-02	10,739
337127	Institutional furniture manufacturing	2.5E-02	5.5E-03	2.0E-03	4,270
33712A	Metal and other household nonupholsetered furniture	2.5E-02	4.3E-03	2.0E-03	2,677
337212	Custom architectural woodwork and millwork	2.5E-02	3.8E-03	3.2E-03	14,233
337215	Showcases, partitions, shelving, and lockers	2.5E-02	1.0E-02	4.8E-03	8,341
33721A	Office furniture manufacturing	2.5E-02	9.8E-03	2.4E-03	381
337910	Mattress manufacturing	2.5E-02	3.9E-03	1.6E-03	5,046
337920	Blind and shade manufacturing	2.5E-02	3.2E-03	1.2E-03	2,527
339111	Laboratory apparatus and furniture manufacturing	1.6E-02	2.9E-03	9.6E-04	4,729
339112	Surgical and medical instrument manufacturing	1.6E-02	1.7E-02	3.4E-03	20,597
339113	Surgical appliance and supplies manufacturing	1.6E-02	1.4E-02	4.4E-03	22,428

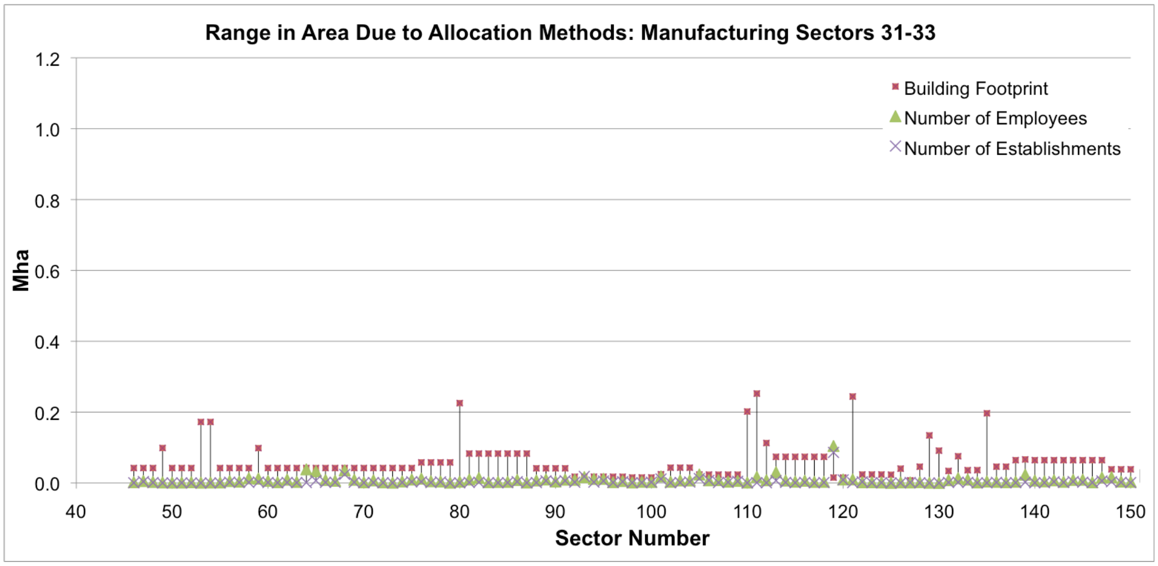
339114	Dental equipment and supplies manufacturing	1.6E-02	2.8E-03	1.9E-03	3,062
339115	Ophthalmic goods manufacturing	1.6E-02	3.9E-03	1.3E-03	4,363
339116	Dental laboratories	1.6E-02	7.2E-03	1.8E-02	3,221
339910	Jewelry and silverware manufacturing	1.6E-02	7.6E-03	7.8E-03	11,359
339920	Sporting and athletic goods manufacturing	1.6E-02	9.8E-03	5.8E-03	11,385
339930	Doll, toy, and game manufacturing	1.6E-02	3.3E-03	2.3E-03	3,805
339940	Office supplies (except paper) manufacturing	1.6E-02	3.5E-03	2.1E-03	3,837
339950	Sign manufacturing	1.6E-02	1.3E-02	1.6E-02	6,846
339991	Gasket, packing, and sealing device manufacturing	1.6E-02	5.7E-03	1.5E-03	5,140
339992	Musical instrument manufacturing	1.6E-02	2.3E-03	1.5E-03	1,779
339994	Broom, brush, and mop manufacturing	1.6E-02	2.4E-03	7.3E-04	2,125
33999A	All other miscellaneous manufacturing	1.6E-02	1.2E-02	8.4E-03	15,172
420000	Wholesale trade	8.1E-03	9.5E-01	1.1E+00	871,529
481000	Air transportation	9.7E-01			102,369
482000	Rail transportation	9.5E-01			42,289
483000	Water transportation	0.0E+00			27,482
484000	Truck transportation	3.6E+00			212,125
485000	Transit and ground passenger transportation	5.6E+00			40,313
486000	Pipeline transportation	1.2E+00			22,316
48A000	Scenic and sightseeing transportation and support activities for transportation	1.2E-02	8.0E-02	6.1E-04	55,907
491000	Postal service	1.4E-03	0.0E+00	0.0E+00	66,501
492000	Couriers and messengers	4.8E-03	9.0E-02	3.4E-02	61,509
493000	Warehousing and storage	3.3E-03	2.4E-02	2.0E-02	42,698
4A0000	Retail trade	4.1E-02	2.4E+00	3.4E+00	908,295
511110	Newspaper publishers	6.7E-04	6.2E-02	2.2E-02	14,745
511120	Periodical publishers	6.7E-04	2.2E-02	1.9E-02	19,700
511130	Book publishers	6.7E-04	1.6E-02	8.3E-03	26,880
5111A0	Directory, mailing list, and other publishers	6.7E-04	1.2E-02	6.5E-03	12,148
511200	Software publishers	6.7E-04	5.1E-02	2.6E-02	91,299
512100	Motion picture and video industries	2.4E-03	4.1E-02	5.1E-02	67,950
512200	Sound recording industries	2.4E-03	4.1E-03	8.7E-03	16,109
515100	Radio and television broadcasting	1.2E-03	4.1E-02	2.3E-02	10,141
515200	Cable and other subscription programming	1.2E-03	1.0E-02	3.3E-03	9,884
516110	Internet publishing and broadcasting	4.8E-03	3.5E-03	2.7E-03	6,673
517000	Telecommunications	6.9E-03	2.2E-01	1.2E-01	410,438
518100	Internet service providers and web search portals	3.4E-03	2.5E-02	2.3E-02	34,318

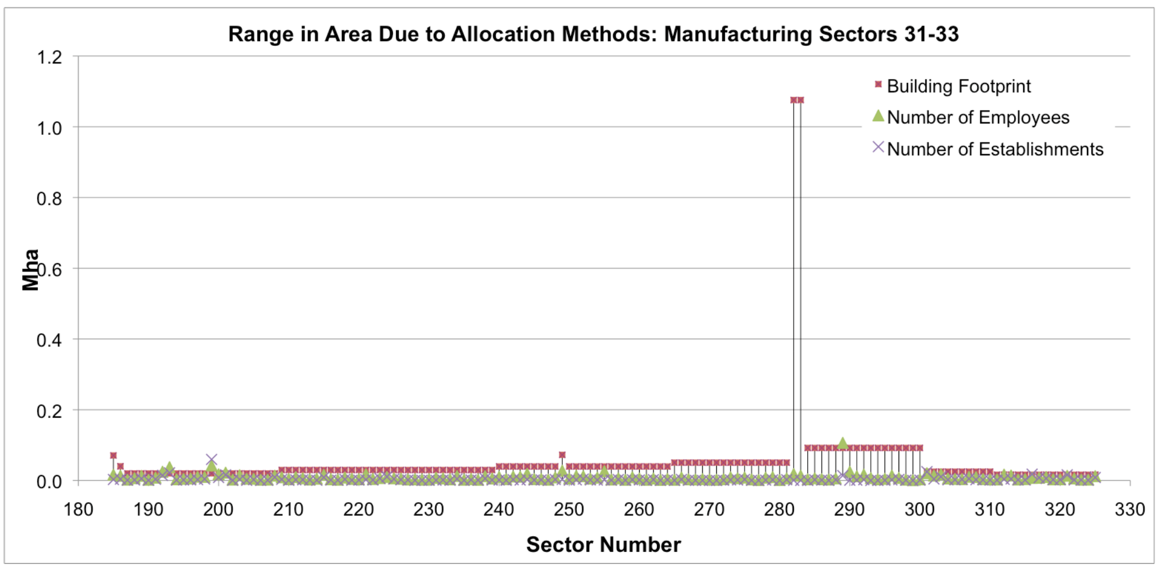
518200	Data processing, hosting, and related services	3.4E-03	5.4E-02	2.9E-02	51,023
519100	Other information services	4.7E-03	7.6E-03	9.4E-03	8,106
522A00	Nondepository credit intermediation and related activities	9.3E-04	1.3E-01	2.1E-01	206,138
523000	Securities, commodity contracts, investments	9.3E-04	1.6E-01	2.1E-01	323,928
524100	Insurance carriers	4.6E-04	2.4E-01	8.1E-02	329,051
524200	Insurance agencies, brokerages, and related	4.6E-04	1.4E-01	3.5E-01	122,859
525000	Funds, trusts, and other financial vehicles	9.3E-04	5.5E-03	9.1E-03	88,019
52A000	Monetary authorities and depository credit intermediation	3.3E-03	3.6E-01	3.0E-01	382,979
531000	Real estate	3.3E-03	2.2E-01	6.6E-01	837,554
532100	Automotive equipment rental and leasing	1.7E-03	2.9E-02	3.1E-02	89,632
532230	Video tape and disc rental	1.7E-03	2.4E-02	4.7E-02	7,998
532400	Commercial and industrial machinery and equipment rental and leasing	1.7E-03	2.7E-02	3.3E-02	52,800
532A00	General and consumer goods rental except video tapes and discs	1.7E-03	2.3E-02	5.2E-02	24,115
533000	Lessors of nonfinancial intangible assets	9.3E-04	3.9E-03	5.6E-03	124,250
541100	Legal services	1.7E-04	1.8E-01	4.6E-01	205,688
541200	Accounting and bookkeeping services	1.7E-04	2.0E-01	2.9E-01	101,089
541300	Architectural and engineering services	1.7E-04	2.0E-01	2.8E-01	176,724
541400	Specialized design services	1.7E-04	2.1E-02	7.9E-02	22,219
541511	Custom computer programming services	1.7E-04	7.4E-02	1.2E-01	146,994
541512	Computer systems design services	1.7E-04	7.5E-02	1.0E-01	45,724
54151A	Other computer related services, including facilities management	1.7E-04	2.6E-02	4.4E-02	74,798
541610	Management consulting services	1.7E-04	1.1E-01	2.4E-01	111,107
5416A0	Environmental and other technical consulting services	1.7E-04	2.2E-02	6.3E-02	18,224
541700	Scientific research and development services	1.7E-04	6.5E-02	3.6E-02	104,808
541800	Advertising and related services	1.7E-04	6.7E-02	9.8E-02	236,302
541920	Photographic services	1.7E-04	1.3E-02	4.7E-02	9,292
541940	Veterinary services	1.7E-04	3.9E-02	6.6E-02	14,779
5419A0	All other miscellaneous professional and technical services	1.7E-04	4.1E-02	7.3E-02	49,844
550000	Management of companies and enterprises	9.3E-04	4.7E-01	1.3E-01	440,898
561100	Office administrative services	1.2E-04	8.0E-02	6.1E-02	35,240

561200	Facilities support services	1.2E-04	2.0E-02	8.8E-03	13,957
561300	Employment services	1.2E-04	6.3E-01	1.1E-01	137,930
561400	Business support services	1.2E-04	1.1E-01	8.7E-02	56,330
561500	Travel arrangement and reservation services	1.2E-04	4.2E-02	7.1E-02	27,997
561600	Investigation and security services	1.2E-04	1.2E-01	5.7E-02	36,484
561700	Services to buildings and dwellings	1.2E-04	2.4E-01	3.9E-01	99,986
561900	Other support services	1.2E-04	5.6E-02	5.4E-02	36,470
562000	Waste management and remediation services	4.8E-03	4.9E-02	4.6E-02	60,528
611100	Elementary and secondary schools	1.6E-02	1.3E-01	5.4E-02	32,225
611A00	Colleges, universities, and junior colleges	1.6E-02	2.4E-01	1.1E-02	123,795
611B00	Other educational services	1.6E-02	6.6E-02	1.2E-01	41,104
621600	Home health care services	1.1E-03	1.3E-01	4.7E-02	47,359
621A00	Offices of physicians, dentists, and other health practitioners	1.1E-03	5.1E-01	1.1E+00	381,001
621B00	Healthcare and social assistance	1.1E-03	1.6E-01	1.1E-01	117,635
622000	Hospitals	6.5E-04	8.3E-01	1.9E-02	471,640
623000	Nursing and residential care facilities	3.3E-03	4.5E-01	1.7E-01	132,154
624200	Community food, housing, and other relief services, incl rehabilitation services	8.7E-03	7.3E-02	5.1E-02	22,888
624400	Child day care services	8.7E-03	1.2E-01	1.8E-01	35,494
624A00	Individual and family services	8.7E-03	1.4E-01	1.3E-01	44,327
711100	Performing arts companies	5.8E-04	2.1E-02	2.4E-02	11,751
711200	Spectator sports	5.8E-04	1.6E-02	1.1E-02	22,577
711500	Independent artists, writers, and performers	5.8E-04	6.4E-03	4.1E-02	18,893
711A00	Promoters of performing arts and sports and agents for public figures	5.8E-04	1.6E-02	2.2E-02	16,887
712000	Museums, historical sites, zoos, and parks	7.5E-03	1.9E-02	1.7E-02	8,188
713940	Fitness and recreational sports centers	2.7E-03	6.8E-02	6.6E-02	14,824
713950	Bowling centers	2.7E-03	1.3E-02	1.3E-02	2,310
713A00	Amusement parks and arcades	2.7E-03	5.5E-02	1.3E-02	66,552
713B00	Other amusement, gambling, and recreation industries	2.7E-03	7.6E-02	7.7E-02	26,449
7211A0	Hotels and motels, including casino hotels	3.1E-03	2.6E-01	1.2E-01	83,734
721A00	Other accommodations	3.1E-03	1.3E-02	3.9E-02	17,930
722000	Food services and drinking places	1.6E-03	1.4E+00	1.3E+00	470,376
811192	Car washes	9.6E-04	2.1E-02	3.5E-02	8,206
8111A0	Automotive repair and maintenance, except car washes	9.6E-04	1.2E-01	3.9E-01	168,170

811200	Electronic equipment repair and maintenance	9.6E-04	2.2E-02	3.6E-02	32,044
811300	Commercial machinery repair and maintenance	9.6E-04	3.2E-02	6.7E-02	34,211
811400	Household goods repair and maintenance	9.6E-04	2.1E-02	7.2E-02	29,284
812100	Personal care services	9.4E-04	8.6E-02	2.6E-01	38,865
812200	Death care services	9.4E-04	2.4E-02	5.8E-02	13,953
812300	Drycleaning and laundry services	9.4E-04	6.0E-02	1.1E-01	23,465
812900	Other personal services	9.4E-04	4.3E-02	1.1E-01	52,311
813100	Religious organizations	3.9E-03	2.7E-01	4.4E-01	64,380
813A00	Grantmaking, giving and social advocacy organizations	3.9E-03	4.3E-02	7.3E-02	27,608
813B00	Civic, social, professional and similar organizations	3.9E-03	1.4E-01	2.5E-01	63,477
814000	Private households	6.0E-03	0.0E+00	0.0E+00	12,516
S00102	Other Federal government enterprises	6.0E-03	0.0E+00	0.0E+00	2,970
S00201	State and local government passenger transit	6.0E-03	0.0E+00	0.0E+00	0
S00203	Other state and local government enterprises	0.0E+00	0.0E+00	0.0E+00	52,060
S00300	Noncomparable Imports	0.0E+00	0.0E+00	0.0E+00	0
S00401	Scrap	0.0E+00	0.0E+00	0.0E+00	5,215
S00402	Used and Secondhand Goods	6.0E-03	0.0E+00	0.0E+00	0
S00500	General Federal Defense	6.0E-03	0.0E+00	0.0E+00	380,797
S00600	General Federal non-defense government industry	6.0E-03	0.0E+00	0.0E+00	209,856
S00700	General state and local government services	0.0E+00	0.0E+00	0.0E+00	1,042,157
S00800	Owner-Occupied Dwellings	0.0E+00	0.0E+00	0.0E+00	959,446
S00900	ROW Adjustment	0.0E+00	0.0E+00	0.0E+00	0
	Total	6.8E+02	6.8E+02	6.8E+02	19,177,862

Below are plots summarizing the values assigned to each sector by the three allocation methods. It can be seen that the building footprint assumption for Manufacturing sectors tends to be the high end of the range of values, while the opposite is true for Service sectors indicating that there are less employees per area for Manufacturing industries and vice versa for Service sectors. Calculated building footprint was determined to be the most appropriate allocation proxy as it was the only value directly related to area. Additional data would be beneficial for more accurately assigning area to these sectors, particularly in smaller-scale analyses.





Figures A.1. and A.2. Range in Area Due to Allocation Methods: Manufacturing Sectors 31-33 (n=280).

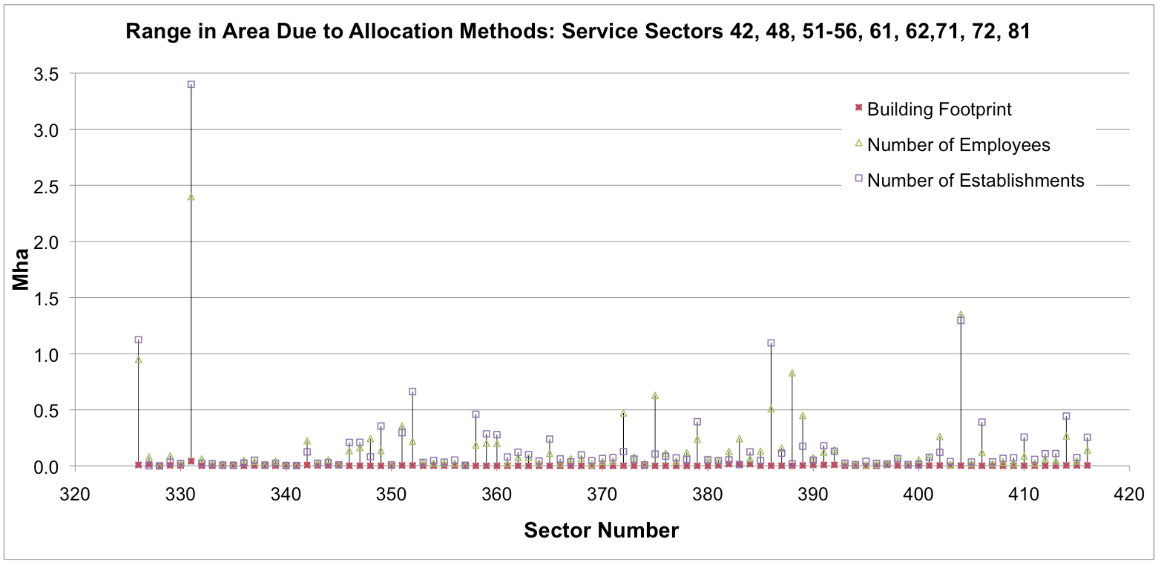


Figure A.3. Areas Due to Allocation Methods: Service Sectors 42, 48, 51-56, 61, 62, 71, 72, 81 (n=100).

2 Disaggregation of Input-Output Tables

2.1 Additional adjustments to the disaggregation

Purchases from sector 325310 – Fertilizer manufacturing by disaggregated grain sectors were disaggregated using fertilizer consumption data [11] rather than the adjusted ratio used elsewhere. This was done to provide a more accurate indication of fertilizer used by crop given more detailed data. Table A.3. includes the difference in the two allocation methods. The **Z** matrix was also adjusted so that purchases from the Wet Corn Milling sector were only made by the Corn farming sector; Wheat, Rice and Other grain farming were assigned a value of zero. See the main body of this dissertation for more detail.

Table A.3. Allocation ratios for Disaggregated Grain Sector Purchases from Fertilizer manufacturing

Sector	% by Adjusted Disaggregation Ratio	% by Fertilizer Consumption
Corn farming	71.3	65.8
Wheat farming	16.5	24.4
Rice farming	3.2	3.2
Other grain farming	8.9	6.6

3 Commodity Group Descriptions

In order to present the modeled results in a more readable format the 434 sectors were assigned to 13 commodity groups based on similarities across the type of commodity produced, Table A.4. describes the NAICS codes included in each commodity group. In some cases there was sufficient overlap in commodities produced by a particular sector that the sector was allocated to two commodity groups.

Table A.4. NAICS Codes included in each Consumption Group

Consumption Group	NAICS Codes	Number of Sectors
Plant Food Products	111 (except 1119B0a), 3112-3114, 3118-3119 (0.5 – 311225, 311410, 311910, 311990), 3121-3122	37
Animal Food Products	1119B0a, 112, 114-115, 3111, 3115 – 3117, (0.5 – 311225, 311410, 311910, 311990)	20
Wood Products	113, 321, 322 (0.5 – 32222A)	19.5
Communication/Services	323, 42, 49, 4A, 51 – 56, 71, 81	79
Healthcare	62	8
Textiles/Footwear	313 – 316	20
Education	61	3
Restaurants/Hotels	72	3
Transportation	48	7
Other Manufactured Goods	324 (except 324110) – 327, 331 –339, (0.5 – 32222A)	204.5
Utilities/Mining	324110, 21 – 22	15
Construction	23	7
Government	S00	11

Note: The following sectors were split evenly between two consumption groups due to products overlapping the two consumption groups included in the sector: Sectors 311225 – Fats and oils refining and blending, 311410 – Frozen food manufacturing, 311990 – All other food manufacturing, 32222A – Coated and laminated paper, packaging materials and plastic films manufacturing and 311910 - Snack food manufacturing.

Appendix B

Table B.1. Sectors in Food Consumption Categories

Food Consumption Category	Sectors Included
Beverages	311920 - Coffee and tea manufacturing; 311930 - Flavoring syrup and concentrate manufacturing; 312110 - Soft drink and ice manufacturing; 312120 - Breweries; 312130 - Wineries; 312140 - Distilleries
Cereals/Carbohydrates	311210 - Flour milling and malt manufacturing; 311230 - Breakfast cereal manufacturing; 311810 - Bread and bakery product manufacturing; 311820 - Cookie, cracker and pasta manufacturing; 311830 - Tortilla manufacturing
Poultry/Eggs	311615 - Poultry Processing; 20% of 311410 - Frozen food manufacturing; 9% of 311990 - All other food manufacturing
Dairy	311513 - Cheese manufacturing; 311514 - Dry, condensed, and evaporated dairy products; 31151A - Fluid milk and butter manufacturing; 311520 - Ice cream and frozen dessert manufacturing
Fruit/Vegetables	111200 - Vegetable and melon farming; 1113A0 - Fruit farming; 411420 - Fruit and vegetable canning, pickling and drying; 60% of 311410 - Frozen food manufacturing
Oils/Sweets/Condiments	311225 - Fats and oils refining and blending; 31122A - Soybean and other oilseed processing; 311313 - Beet sugar manufacturing; 31131A - Sugar cane mills and refining; 311320 - Confectionery manufacturing from cacao beans; 311940 - Seasoning and dressing manufacturing; 7% of 311990 - All other food manufacturing
Other/Miscellaneous	311221 - Wet corn milling; 31161Ab - Other animal (except poultry) slaughtering; 311700 - Seafood product preparation and packaging; 311910 - Snack food manufacturing; 80% of 311990 - All other food manufacturing
Red Meat	31161Aa - Cattle slaughtering and processing; 20% of 311410 - Frozen food manufacturing
Pet Foods	311111 - Dog and cat food manufacturing; 311119 - Other animal food manufacturing

Table B.2 summarizes the assumed calories per dollar of output for each of the food consumption categories listed as generated by Weber and Matthews [12]. These estimates are based on household consumption statistics and required a number of assumptions regarding the mapping of processed foods to food categories. Further, food waste is not accounted for and is estimated to be 27% of total food production by weight [49]. Therefore, these values do not represent all calories generated in the U.S., but rather represent estimates for households specifically.

Table B.2. Assumed Calories per Dollar for Food Consumption Categories

Food Consumption Category	cal/$
Beverages	NA
Cereals/Carbohydrates	528
Chicken/Fish/Eggs	244
Dairy Products	418
Fruit/Vegetable	191
Oils/Sweets/Condiments	1600
other misc	NA
Red Meat	221

Values were adopted from those used by Weber and Matthews [12].

Table B.3. Input Values for Food Choice Scenarios

Sector Number	Sector Name	Scenario Demand in Personal Expenditures ($M)
Scenario 1		
311210	Flour milling and malt manufacturing	0
311230	Breakfast cereal manufacturing	0
311810	Bread and bakery product manufacturing	0
311820	Cookie, cracker and pasta manufacturing	0
311830	Tortilla manufacturing	0
311513	Cheese manufacturing	25,556
311514	Dry, condensed, and evaporated dairy products	21,627
31151A	Fluid milk and butter manufacturing	32,447
311520	Ice cream and frozen dessert manufacturing	19,481
Scenario 2		
311410	Frozen food manufacturing	0
311513	Cheese manufacturing	0
311514	Dry, condensed, and evaporated dairy products	0
31151A	Fluid milk and butter manufacturing	0
311520	Ice cream and frozen dessert manufacturing	0
311615	Poultry processing	0
31161Aa	Cattle slaughtering and processing	0
31161Ab	Other animal (except poultry) slaughtering and processing	0
311210	Flour milling and malt manufacturing	12,595
311230	Breakfast cereal manufacturing	18,198
311810	Bread and bakery product manufacturing	42,073

311820	Cookie, cracker and pasta manufacturing	24,452
311830	Tortilla manufacturing	12,468
Scenario 3		
311410	Frozen food manufacturing	0
311513	Cheese manufacturing	0
311514	Dry, condensed, and evaporated dairy products	0
31151A	Fluid milk and butter manufacturing	0
311520	Ice cream and frozen dessert manufacturing	0
311615	Poultry processing	0
31161Aa	Cattle slaughtering and processing	0
31161Ab	Other animal (except poultry) slaughtering and processing	0
311210	Flour milling and malt manufacturing	7,022
311230	Breakfast cereal manufacturing	12,626
311810	Bread and bakery product manufacturing	36,501
311820	Cookie, cracker and pasta manufacturing	18,880
311830	Tortilla manufacturing	6,895
111200	Vegetable and melon farming	37,397
1113A0	Fruit farming	32,507
311420	Fruit and vegetable canning, pickling and drying	44,279
Scenario 4		
311615	Poultry processing	29,288
31161Aa	Cattle slaughtering and processing	0

Appendix C[2]

1 Description of Model Distributions

Each of the variables included in Equations 4.1 through 4.9 in Chapter 4 were assigned a distribution based on data found in the literature and government documents. The model parameters are all assumed to be independent. Table C.1 below describes each distribution and the sources used to create the distribution. In many instances data were unchanged from Miller et al. [13], these values are shown in italics in Table C.1.

Each of the variables included in Equations 4.1 through 4.9 in Chapter 4 were assigned a distribution based on data found in the literature and government documents. The model parameters are all assumed to be independent. Table C.1 below describes each distribution and the sources used to create the distribution. In many instances data were unchanged from Miller et al. [13], these values are shown in italics in Table C.1.

[2] Much of the text in Appendix C is copied from the Supporting Information accompanying the following published paper: Costello, C. Griffin, W. M., Matthews, H.S., and Landis A. E. Impact of Biofuel Crop Production on the Formation of Hypoxia in the Gulf of Mexico. Environmental Science and Technology. 43(20); 7985-7991.

Table C.1. Information used to generate Monte Carlo distributions[1]

Parameter	Description	Distribution Type	Distribution Parameters	Reference(s) Used for Distribution	Details Regarding Distribution Creation	Notes
Input Parameters						
H_c	Crop Yield Corn[2]	2007 & 2022: Weibull; 2015: Beta	2007: Location: 2,690 kg/ha, Scale: 6,900 kg/ha, Shape: 5.67; 2015: a = 2.67, b = 1.88; 2022: Location: 5,560 kg/ha, Scale: 5,276 kg/ha, Shape: 4.44.	National Corn Growers Association, 2006 [14]; United States Department of Agriculture (USDA) [15]; USDA Projections Report [16]	Best fit regressions using data from the 1997-2007 growing seasons. 2015 & 2022 used adjusted USDA projections as described in the main text.	All distributions truncated at: 4,275 (actual minimum), Maximum: 28,290 (based on theoretical max). Theoretical max derived from [17].
H_S	Crop Yield Soybean[3]	2007 Beta; 2015 Student's t distribution; 2022 Gamma	2007: a: 4.4; b: 2.6; minimum: 812 kg/ha; maximum: 3630 kg/ha; 2015: midpoint: 2750, scale: 470, degrees of freedom: 30; 2022: location: 1910, scale: 220, shape: 4.68.	United Soybean Board, 2003 [18]; USDA NASS, 2007 [14]	Best fit regressions using data from the 1997-2007 growing seasons. 2015 & 2022 used adjusted USDA projections as described in the main text.	All distributions truncated at: 1,210 (actual minimum), Maximum: 16,840. Theoretical max derived from [17].
H_{SWG}	Crop Yield Switchgrass	2007, 2015 & 2022 Gamma	2007: Location: 360; Scale: 1560; Shape: 9.11 2015: Location: 460, Scale: 2010; Shape 9.11; 2022: location: 570, scale: 2510, shape: 9.11.	Fike et al., 2006 [19]; McLaughlin and Kszos, 2005 [20]; Schmer et al., 2008 [21]; Lemus et al., 2002 [22].	Best fit regression. Data used to generate the switchgrass yield distribution was collected in the following states: AL, GA, IA, KS, KY, NC, ND, NE, TN, TX, VA, WV over years 1992 – 2001.	All distributions truncated at: 5,100 (minimum from 260 yield values), Maximum: 47,000. Theoretical max derived from [20].
$N_{f,C}$	Fertilizer Input Corn[2]	Triangular	Minimum: 69.7 kg/ha; Likeliest: 173.9 kg/ha; Maximum: 205.1 kg/ha	USDA ERS, 2007 [11]	Best fit regression using data from 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2005	Data is collected every other year starting in 2003. Data not available for all states every year. An average of 97% of corn was treated with N

$N_{f,C}$	Fertilizer Input Corn[2]	Triangular	Minimum: 69.7 kg/ha; Likeliest: 173.9 kg/ha; Maximum: 205.1 kg/ha	USDA ERS, 2007 [11]	Best fit regression using data from 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2005	Data is collected every other year starting in 2003. Data not available for all states every year. An average of 97% of corn was treated with N fertilizer over all data.
$N_{f,S}$	Fertilizer Input Soybean[3]	For all: Decision as to whether fertilizer has been applied Custom 25% yes (1), 75% no (2). Fertilizer Application Rate Gamma	Location: 11.9; Scale: 9.3; Shape: 1.58	USDA ERS, 2007 [11]	Best fit regression using data from 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2005	Data is collected every other year starting in 2003. Data not available for all states every year.
$N_{f,SWG}$	Fertilizer Input Switchgrass	Triangular	Min. 0; Likeliest 74; Max. 212	Schmer et al., 2008 [21]	Selected triangular distribution due to lack of data for fitting a distribution.	Additional References: McLaughlin & Kszos, 2005 [20]
$N_{min,C}$	*Soil Mineralization Corn*	*Lognormal*	*Mean: 146 kg/ha; Standard Deviation: 57*	*Cassman et al., 2002 [23]; Goolsby et al., 1999 [24]*	*Best fit regression.*	*Data collected at 64 locations throughout central U.S. Distribution unchanged from Miller et al., 2006 [13]; values compared well with Goolsby et al., 1999 [24]*
$N_{min,S}$	*Soil Mineralization Soybean*	*Lognormal*	*Median 87 kg/ha; Mean 101 kg N/ha; Standard Deviation: 57*	*Gentry et al., 1998 [25]; Goolsby et al., 1999 [24]*	*Best fit regression.*	*Mineralization rates of corn are generally 45 kg N/ha higher than for corn planted after soybeans due to soybean credit; soybean distribution was shifted left 45 kg N/ha. Distribution unchanged from Miller et al., 2006 [13]; values compared well with Goolsby et al., 1999 [24].*
$N_{min,SWG}$	Soil Mineralization	Lognormal	Mean 27 kg/ha; Standard deviation: 9.2	Wedin et al., 1990 [26]	Best fit regression.	Data is for C4 prairie grasses; controlled field study.

f_{fix}	*Nitrogen from BNF*	*Triangular*	*25-60% range; 50% most likely value*	*Gentry et al., 1998 [25]*	*25-50%; 50% is a reasonable estimate*	*and highly variable. Usually assumed to be a percentage of the nitrogen contained in a mature plant. This parameter was calculated by taking the range of calculated nitrogen content (generated by Monte Carlo) and multiplying it by this parameter. Distribution unchanged from Miller et al., 2006 [13].*
				Sheehan et al., 1998 [27]	*15-310 kg N/ha*	
				Boyer et al., 2002 [28]; Gentry et al., 2001[29]; Howarth et al., 2002 [30].	*80-100 kg N/ha*	
Export Parameters						
$f_{grain,c}$	*Nitrogen Content in Grain Fraction Corn*	*Triangular*	*Min:. 0.0120; Likeliest: 0.0140; Max. 0.0145*	*Cassman et al., 2002 [23]*	*Regression relating grain yield and nitrogen accumulation:* $y = -3710 + 995x^{0.5}$ *where* y *= grain yield (kg/ha),* x *= plant N (kg/ha)*	*Distribution unchanged from Miller et al., 2006 [13].*
$f_{grain,S}$	*Nitrogen Content Grain Fraction Soybean*	*Triangular*	*Min.: 0.061; Likeliest: 0.064; Max.: 0.069*	*Schepers and Mosier, 1991 [31]*	*6.1%-6.9% per dry mass of grain*	*Distribution unchanged from Miller et al., 2006.*
$f_{grain,SWG}$	Nitrogen Content Grass Fraction Switchgrass	Logistic	Mean: 0.0125; Scale: 0.0022	Thomason et al., 2005 [32]	Best fit regression.	Data includes 156 values from 2 locations in Oklahoma, 4 harvest years, nitrogen fertilizer applications were 0, 112, 224, 448, and 896 kg N/ha and switchgrass was harvested 1, 2, or 3 times per season.
$f_{residue,C}$	*Nitrogen Content in Residue Fraction Corn*	*Triangular*	*Min.: 0.0058; Likeliest: 0.007; Max.: 0.008*	*Delucchi, 2003 [33]*	*Selected triangular distribution due to lack of data for fitting a distribution. 0.58-0.8% N per dry mass of residue.*	*Distribution unchanged from Miller et al., 2006.*

	Fraction Soybean		*0.024; Max.: 0.025*		*data for fitting a distribution. 2.3-2.5% N per dry mass of residue.*	*Miller et al., 2006.*
HI_C	*Crop Residue Ratio Corn*	-	*1.0*	*IPCC 1996 [34]*		*Distribution unchanged from Miller et al., 2006.*
HI_S	*Crop Residue Ratio Soybean*	-	*2.1*	*IPCC 1996 [34]*		*Distribution unchanged from Miller et al., 2006.*
HI_{SWG}	Crop Residue Ratio Switchgrass	-	0			It is assumed that all cut switchgrass is harvested and that there is a negligible amount of residue left on the field.
$f_{NO3,C\&S}$	*Nitrate Fraction Corn & Soy*	*Lognormal*	*Mean: 0.24 of applied fertilizer; Standard Deviation: 0.08. Range from 8-70% with 80% of values between 15-36%*	*IPCC, 1996 [34]*	*10-80% of applied fertilizer with 30% the most likely value*	*Distribution unchanged from Miller et al., 2006. Nitrogen runoff is highly variable and difficult to quantify. Generally a percentage of applied fertilizer is used as a surrogate variable to estimate leaching. The distribution used in this study used a mean of 24% applied fertilizer identified as a reasonable estimate in several studies, with a range (8-70%) similar to observed measurements.*
				Howarth et al., 2002 [30]	*3-80% of applied fertilizer, with 20% a reasonable estimate*	
				Howarth et al., 2002 [30]	*Statistical analysis of exports suggesting a 32% of applied fertilizer average leading rate.*	
				Gentry et al. 1998 [25], Matson et al. 2002 [35], Patni et al. 1996 [36], Wang et al., 1999 [37]	*24-30% of applied fertilizer*	
$f_{NO3,SWG}$	Nitrate Fraction Switchgrass	Lognormal	Mean: 0.13; Standard Deviation: 0.1	Babcock, 2007 [38]	Selected lognormal distribution assuming that the shape of the distribution would be similar to that of corn and soy.	Nitrate output was simulated for the Maquoketa River Watershed in Iowa using the Soil and Water Assessment Tool assuming all croplands were converted to perennial warm-season grasses receiving N fertilizer application of 110

$f_{NO3,SWG}$	Nitrate Fraction Switchgrass	Lognormal	Mean: 0.13; Standard Deviation: 0.1	Babcock, 2007 [38]	Selected lognormal distribution assuming that the shape of the distribution would be similar to that of corn and soy.	Nitrate output was simulated for the Maquoketa River Watershed in Iowa using the Soil and Water Assessment Tool assuming all croplands were converted to perennial warm-season grasses receiving N fertilizer application of 110 lb/acre.
r	Reduction in nitrate concentration (inflow vs.	Beta	a: 0.846; b: 0.482; minimum: 12.86; maximum: 100.00	Dosskey, 2001 [39]; Lee et al., 1999 [40]; Lowrance et al.,	Best fit distribution from 70 field measurements of vegetative buffer strips of various design across the	

Notes:
1. Values that were not changed from Miller et al., [13] are shown in italics.
2. The following states were included in the corn yield and fertilizer rate distributions Iowa, Illinois, Nebraska, Minnesota, Indiana, Ohio, South Dakota, Wisconsin, Kansas, Missouri, Texas, North Dakota, Pennsylvania, Kentucky, and Colorado.
3. The following states were included for the soy yield and fertilizer distributions: Iowa, Illinois, Nebraska, Minnesota, Indiana, Ohio, South Dakota, Wisconsin, Kansas, Missouri, Arkansas, North Dakota, Michigan, Kentucky, North Carolina, Tennessee, and Louisiana.

2 Model Validation

2.1 Annual Total Nitrogen Load Delivered to the NGOM

Modeled nitrate output was modified using the assumptions and values described in the main text, Equation 9, to approximate the annual total nitrogen (TN) load delivered to the NGOM. Figure C.1 shows the range of modeled annual TN loads and the reported annual TN loads. In two instances the recorded annual TN does not fall within the modeled range of TN. The river flow was extremely low in the year 2000 with an annual average of 464,000 cubic feet per second (cfs) while the average annual discharge over the period 1985-2002 was 771,500 cfs [45]. It is less clear why the modeled range of TN in 1993 does not overlap the observed value. The model may have under-predicted in 1993 for two reasons, corn production was very low and the river flow was fairly high with an average annual discharge of 939,000 cfs [45]. The model used to approximate nitrate output for a given year is determined based on crop production inputs, therefore fallow lands, which may have been harvested in the prior year and contributing nitrate, are not accounted for in this year.

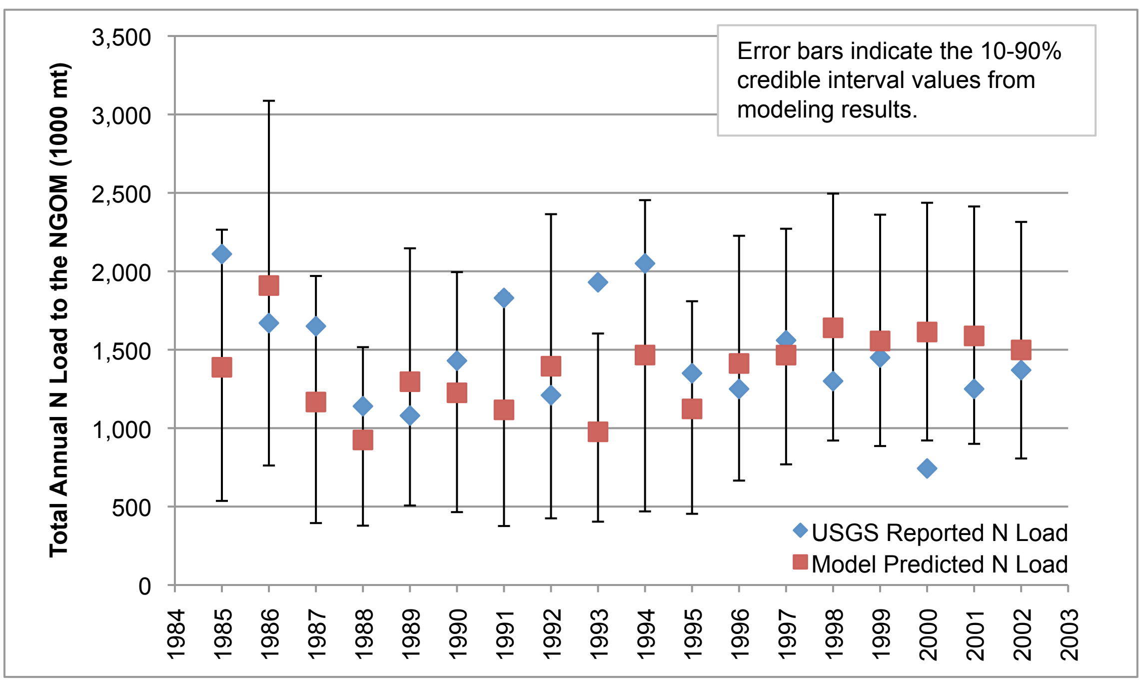


Figure C.1. Modeled and Recorded Annual Total Nitrogen Load to the NGOM, 1985-2002

2.2 Daily May/June TN Load Value

The model used to approximate the size of the hypoxic zone requires that the annual TN load modeled be converted to a May/June daily load. Annual TN loads were divided by 365 days/yr and then scaled up by 1.44 to adjust for increased loading in May/June. The May/June adjustment factor was derived from monthly TN flux to the NGOM over the years 1985 to 2002 [45]. The range of May/June daily loadings generated from the 80% C.I. of modeled nitrate were compared to the May/June daily flux provided by Scavia et al. in Figure C.2 [46]. Figure C.4 compares the 80% C.I. of modeled nitrate to the May/June daily flux derived using the approach described above applied to the annual TN load reported by the USGS [47]. Again, the observed values fall within the modeled range with the exception of 1993 and 2000 for reasons stated above.

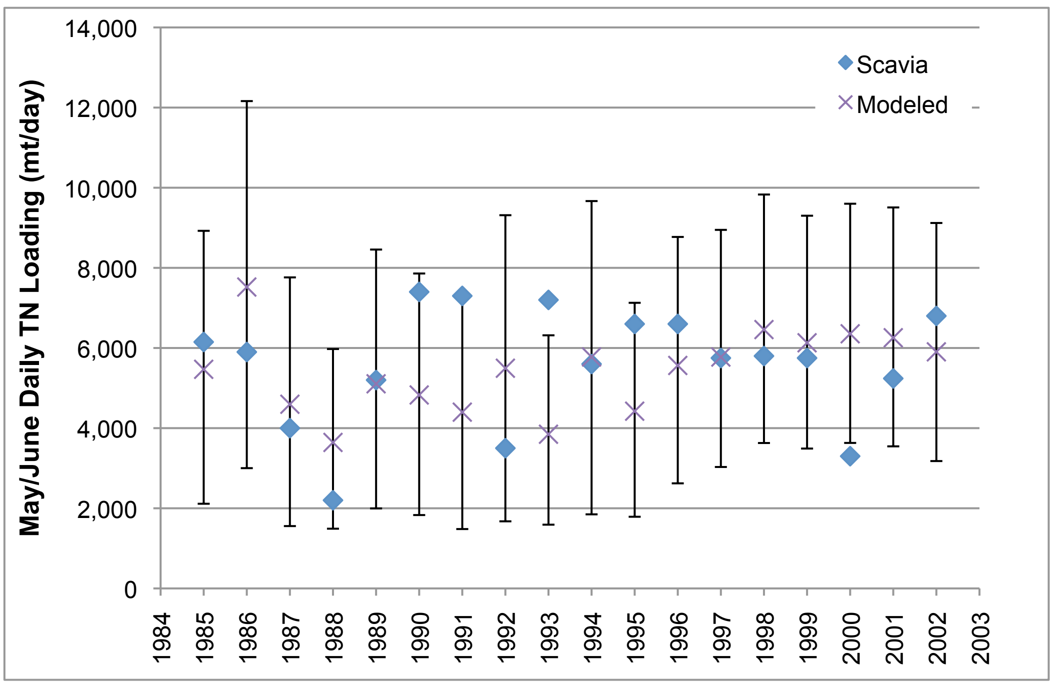


Figure C.2. Comparison of modeled range of May/June daily loading values and average observed May/June daily loading values

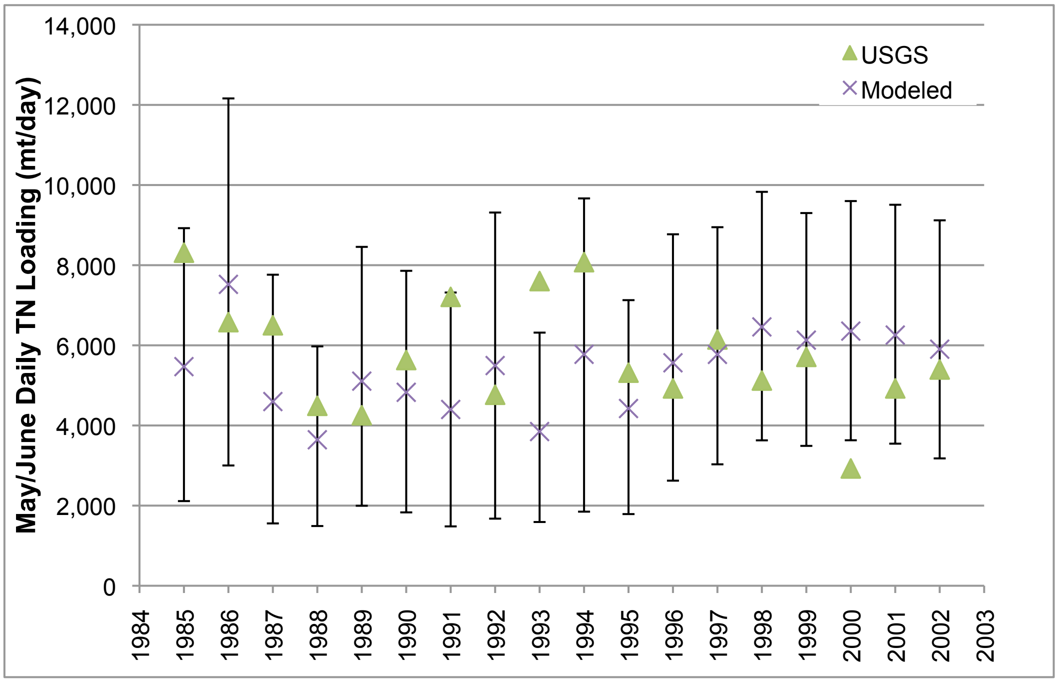


Figure C.4. Comparison of modeled range of May/June daily loading values and May/June daily loading values derived from USGS annual TN values

2.3 Areal Extent of Hypoxia

Observed May/June average daily flux values were used to calculate the areal extent of hypoxia using the Scavia et al. model, Equation 10 [46]. The results are presented in Figure C.5. The observed hypoxic areas and those modeled by Scavia et al. are both shown on this figure [46]. Low river discharge and nutrient flux in 1988 and 2000 explain the reduced size of the hypoxic zone and no data was collected in 1989 [48].

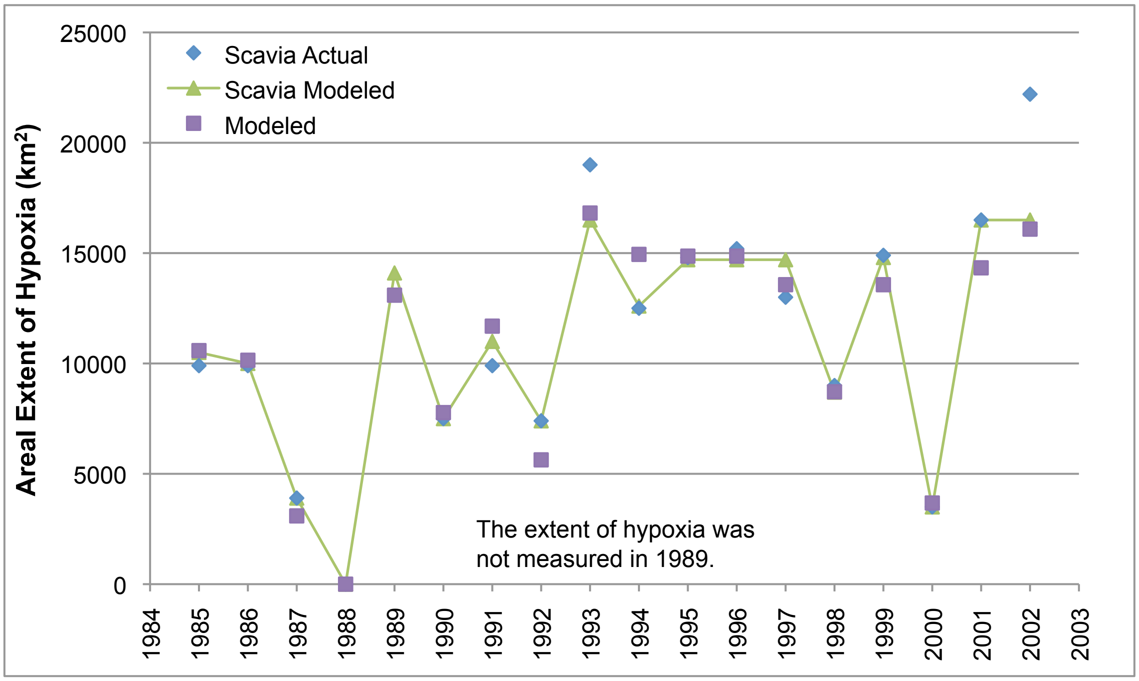
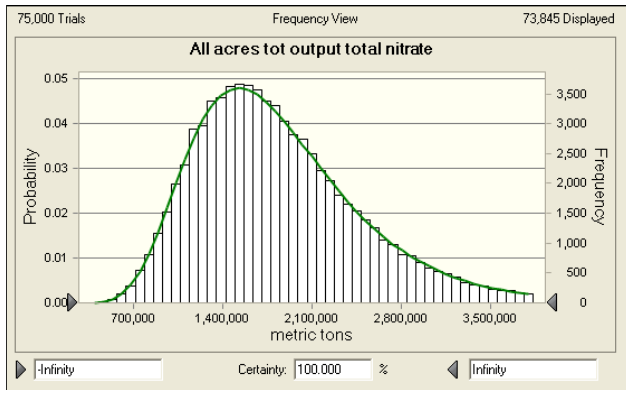


Figure C.5. Model Validation: Modeled and Observed Areal Extent of Hypoxia

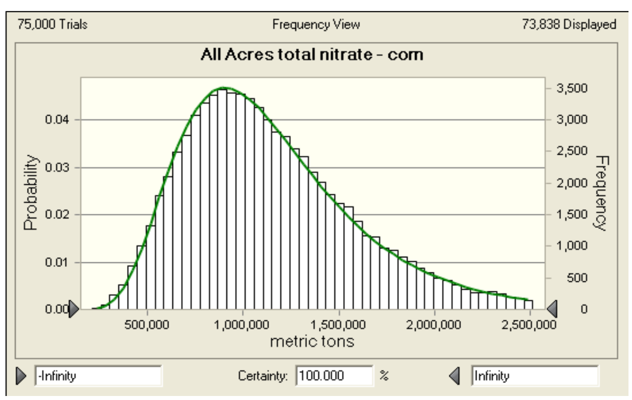
3 MCA Output Distributions

Each MCA simulation (75,000 iterations) generated a distribution of the nitrate output for each considered crop as well as the total nitrate output to the MARB for each Scenario. Below are example nitrate output distributions generated by Crystal Ball for individual crops, total nitrate output and 50% and 100% Buffer Scenarios.



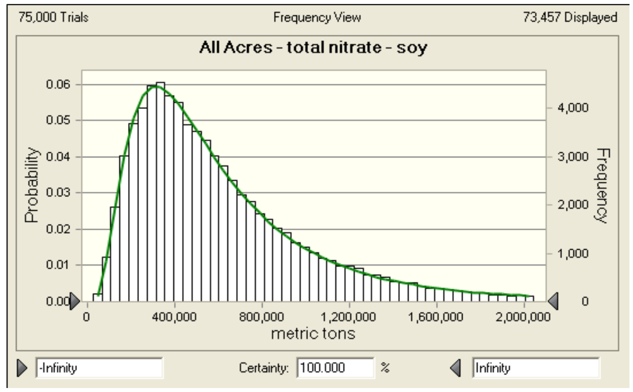
Lognormal mean= 1,855,000, std dev= 695,000
GOF: A-D: 1.81313; Ch-Square: 224.5933; K-S: 0.0041

Figure C.6. Scenario 2015corn/stover – Total Nitrate Output



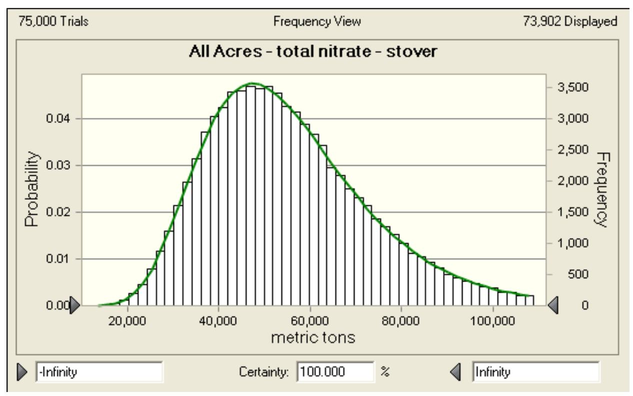
Lognormal: mean = 1,159,997 std. dev. = 494,292
GOF: A-D: 9.2828; Ch-Square: 284.9004; K-S: 0.0079

Figure C.7. Scenario 2015corn/stover –Nitrate Output for Corn



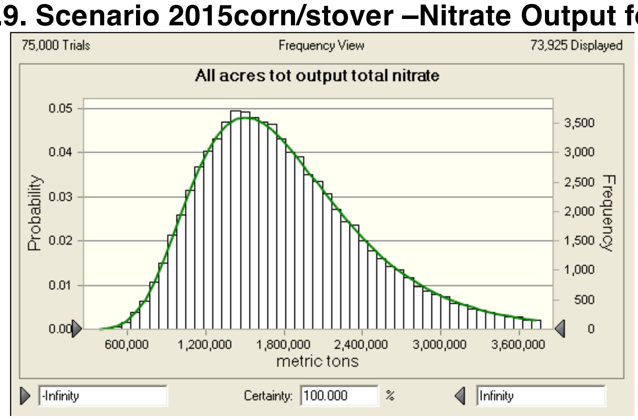
Lognormal: mean = 643,045; std dev. 509,053
GOF: A-D: 3.2515; Ch-Square: 214.8272; K-S: 0.0053

Figure C.8 Scenario 2015corn/stover –Nitrate Output for Soy



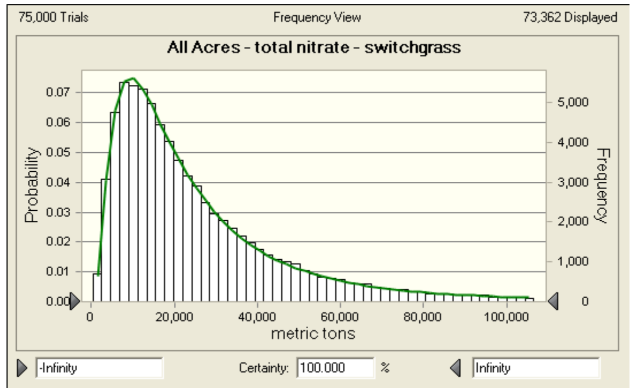
Lognormal: mean = 55,779, std. dev. = 18.995
GOF: A-D: 0.3578; Ch-Square: 195.1880; K-S: 0.0022

Figure C.9. Scenario 2015corn/stover –Nitrate Output for Stover



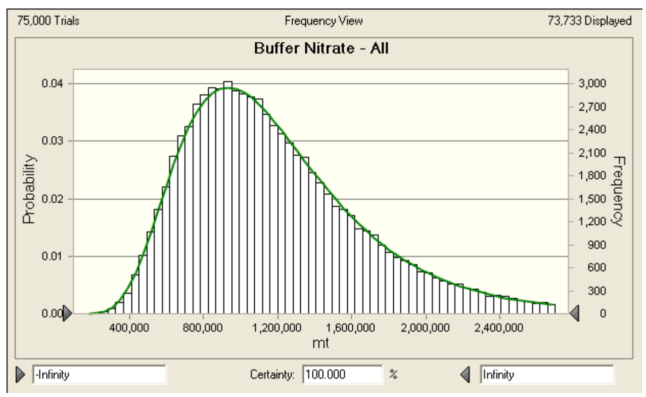
Lognormal: mean = 1,826,381; std. dev. = 680,543
GOF: A-D: 2.4451; Ch-Square: 224.0589; K-S: 0.0039

Figure C.10. Scenario 2015corn/switchgrass - Total Nitrate Output



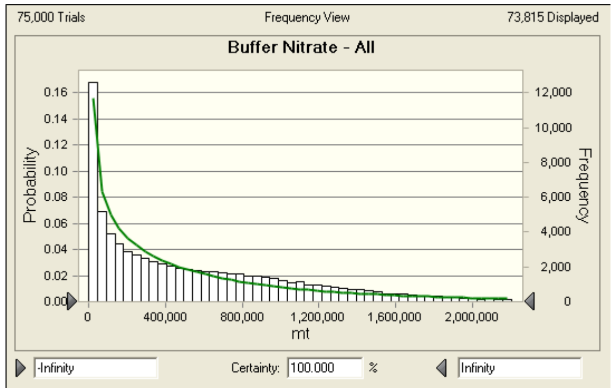
Lognormal: mean = 27,919; std. dev. = 29,202
GOF: A-D: 2.9429; Ch-Square:204.2015; K-S: 0.0046

Figure C.11. Scenario 2015corn/switchgrass - Total Nitrate Output



Lognormal: mean = 1,207,000; std. dev. = 525,000
GOF: A-D: 3.6029; Ch-Square: 201.3024; K-S: 0.0051

Figure C.12. Scenario 2015corn/switchgrass - Total Nitrate Output with 50% Buffer



Gamma: Location = -60; Scale = 895,000; Shape = 0.646
GOF: A-D: 623.57; Ch-Square: 6,428.98 ; K-S: 0.0676

Figure C.13. Scenario 2015corn/switchgrass - Total Nitrate Output with 100% Buffer

4 Nitrate Output Sensitivity

Sensitivity Analyses were conducted using Crystal Ball for Scenarios 2015corn/stover and 2015corn/swg; results are similar for all other modeled Scenarios. Results in figures C.14 to C.20 are displayed as contribution to variance, which is the percent of forecast variance due to each assumption. Discussion of sensitivity analysis for corn, soy, stover, and switchgrass nitrate outputs is included in the main body of the paper. Sensitivity analyses for total nitrate output are provided below (Figure C.14), not surprisingly the nitrate fraction variable for corn is very significant, corn is the largest contributor of nitrate output in all scenarios, second is mineralized nitrogen from soy another large source of nitrate in the system; subsequent large contributors to sensitivity are related to these two outputs. Total nitrate output for Scenario 2015corn/stover given 50% Buffer is most sensitive to the nitrate fraction variable for corn and secondly the nitrate concentration reduction factor, r (Eq 8), the remaining variable are similar to the "No Buffer" scenarios. However, in the 100% Buffer scenario (Figure C.20), the total nitrate output are most sensitive to the nitrate fraction variable by far. This is not surprising given that this variable is heavily skewed toward the right (see Table C.1 for distribution information for r).

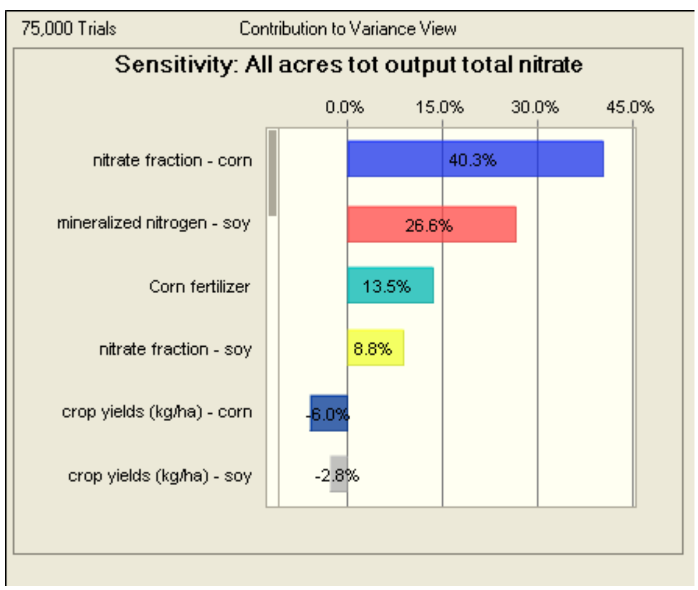


Figure C.14. Example of Sensitivity Analysis for Total Nitrate Output (Scenario 2015corn/stover)

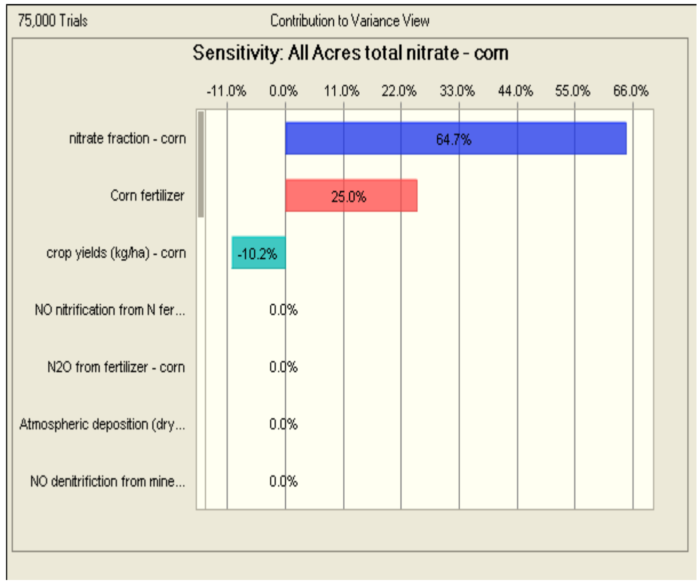


Figure C.15. Example of Sensitivity Analysis for Nitrate Output due to Corn (Scenario 2015corn/stover)

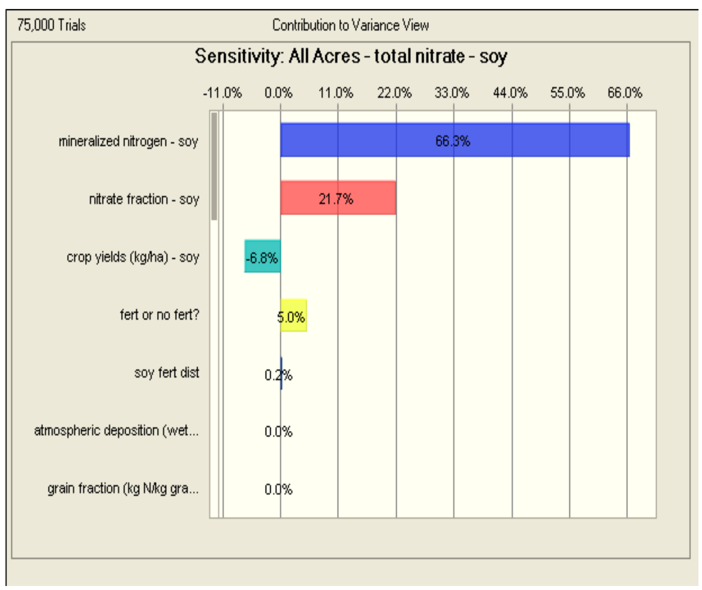


Figure C.16. Example of Sensitivity Analysis for Nitrate Output due to Soy (Scenario 2015corn/stover)

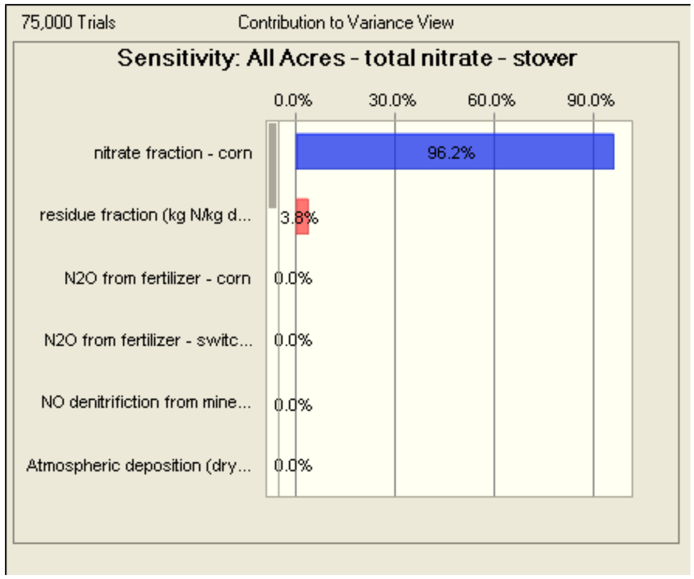


Figure C.17. Example of Sensitivity Analysis for Nitrate Output due to Stover (Scenario 2015corn/stover)

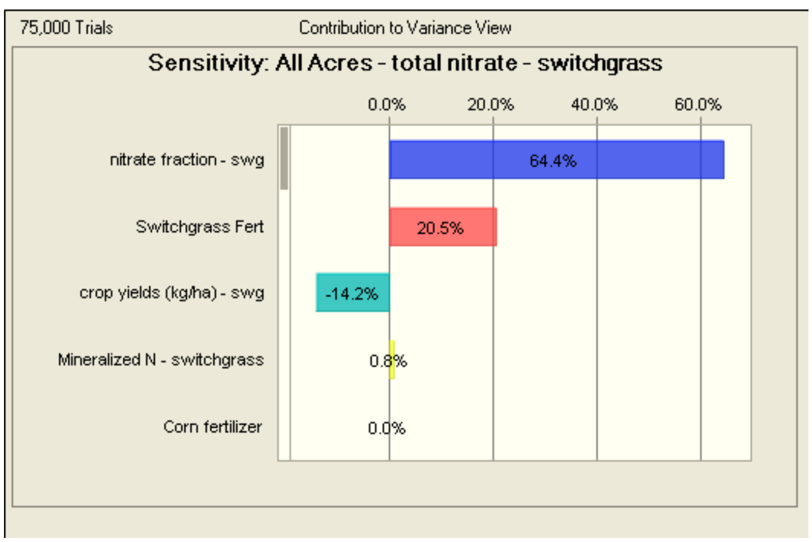


Figure C.18. Example of Sensitivity Analysis for Nitrate Output due to Switchgrass (Scenario 2015corn/swg)

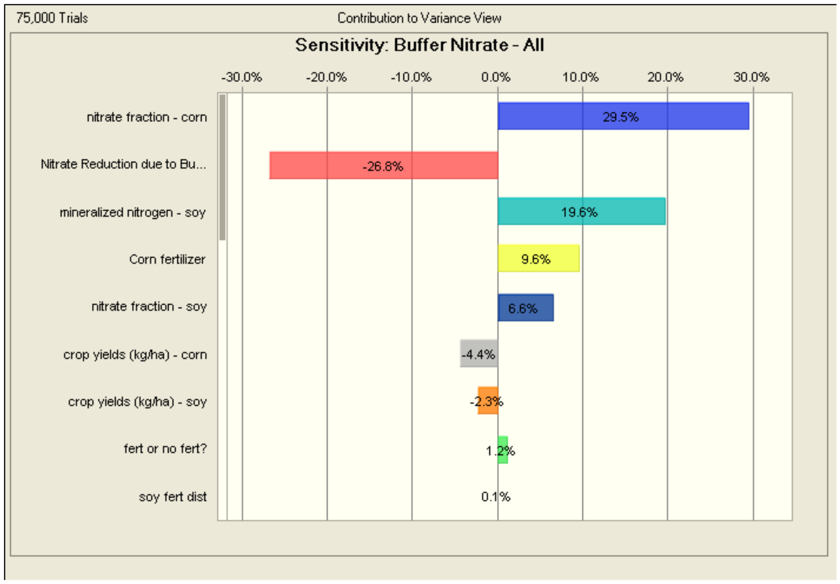


Figure C.19. Example of Sensitivity Analysis for Total Nitrate with 50% Buffer (Scenario 2015 corn/stover)

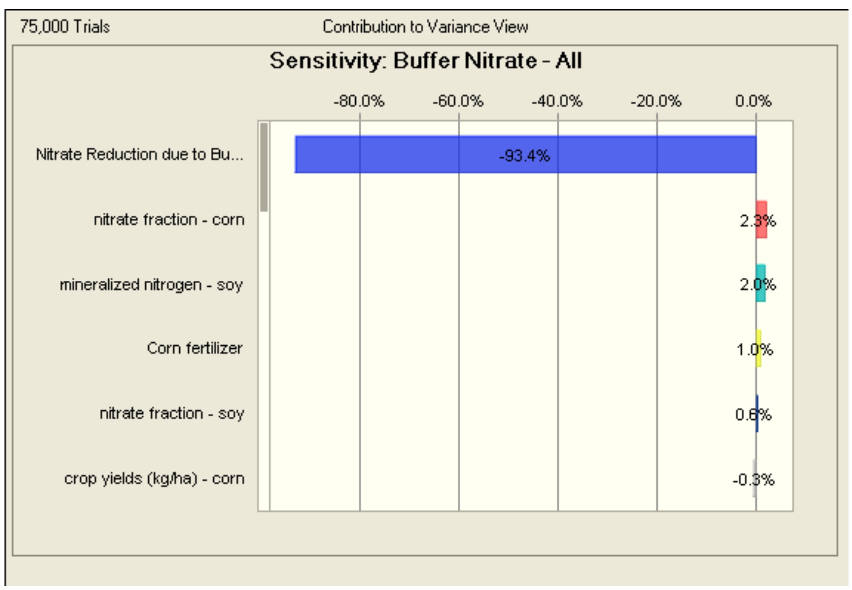


Figure C.20. Example of Sensitivity Analysis for Total Nitrate with 100% Buffer (Scenario 2015corn/swg)

Appendix D

Table D.1. Aggregation and Disaggregation of Sectors For GHG Allocation

1997 Benchmark		2002 Benchmark		USDA Census	
1111A0	Oilseed farming	1111A0	Oilseed farming	1111	Oilseed and grain farming
1111B0	Grain farming	1111B0	Grain farming		
111200	Vegetable and melon farming	111200	Vegetable and melon farming	1112	Vegetable and melon farming
111335	Tree nut farming	111335	Tree nut farming	1113	Fruit and tree nut farming
1113A0	Fruit farming	1113A0	Fruit farming		
111400	Greenhouse and nursery production	111400	Greenhouse and nursery production	1114	Greenhouse, nursery, and floriculture production
111910	Tobacco farming	111910	Tobacco farming	11191	Tobacco farming
111920	Cotton farming	111920	Cotton farming	11192	Cotton farming
1119A0	Sugarcane and sugar beet farming	1119B0	Sugarcane and sugar beet farming	11193, 11194, 11199	Sugarcane, hay and all other crop farming
1119B0	All other crop farming	1119C0	All other crop farming		
112100	Cattle ranching and farming	112120	Milk Production	11212	Dairy cattle and milk production
		1121A0	Cattle ranching and farming	112111 & 112112	Beef cattle ranching and farming & Cattle feedlots
112300	Poultry and egg production	112300	Poultry and egg production	1123	Poultry and egg production
112A00	Animal production, except cattle and poultry and eggs	112A00	Animal production, except cattle and poultry and eggs	1122 , 1124, 1125, 1129	Hog and pig farming, Sheep and goat farming, Animal aquiculture & Other animal production
113300	Logging	113300	Logging	113300	Not included in the USDA Census
113A00	Forest nurseries, forest products, and timber tracts	113A00	Forest nurseries, forest products, and timber tracts	113A00	
114100	Fishing	114100	Fishing	114100	
114200	Hunting and trapping	114200	Hunting and trapping	114200	
115000	Agriculture and forestry support activities	115000	Agriculture and forestry support activities	115000	

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