VALUING CRITICAL ZONE SERVICES IN INTENSIVELY MANAGED LANDSCAPES

BY

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THESIS

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Abstract

The critical zone (CZ) includes the range of biophysical processes occurring from the top of the vegetation canopy to the weathering zone below the groundwater table. CZ services provide a measure to value processes that support the goods and services from landscapes. In intensively managed landscapes (IML), the provisioning, supporting, and regulating services are altered through anthropogenic energy inputs so as to derive more agricultural productivity from these landscapes. Land use change and other alterations to the environment result in positive and/or negative net CZ services. Through studies in the Critical Zone Observatory for Intensively Managed Landscapes (IML-CZO), this research seeks to answer questions such as: Which production system provides the least negative environmental impacts - corn for feed or corn for fuel? How much extra products and services are obtained from the land for the energy and resources put in? Before the economic valuation of CZ services, these questions seemed abstract. However, with developments such as CZ services and Life Cycle Assessments (LCA's), they are becoming more concrete. To evaluate the trade-offs between positive and negative impacts, LCA's are used to create an inventory of all the energy inputs and outputs in a landscape management system. Total energy is computed by summing the mechanical energy used to construct tile drains, fertilizer, and other processes involved in IML and the chemical energy gained by the production of ethanol from corn. Multi-layer soil, canopy, and nutrient models are coupled to compute water, carbon, and nitrogen fluxes, which can be translated into CZ services. These values are then viewed alongside the energy inputs into the system to show the relationship between agricultural practices and their corresponding ecosystem and environmental impacts. The LCA and resulting CZ services for corn feed and corn-based ethanol developed in this study conclude that feed production systems are more energy efficient and less environmentally costly than ethanol production systems.

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List of Abbreviations

AEE	Anthropogenic Energy Efficiency
BMP	Best Management Practice
CCS	Corn-Corn-Soybean crop rotation
CZ	Critical Zone
CZO	Critical Zone Observatory
EPA	Environmental Protection Agency
EBAMM	Energy Research Group Biofuel Analysis Meta-Model
EBI	Energy Biosciences Institute
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model
IML	Intensively Managed Landscapes
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MLCan	Multi-Layer Canopy-Soil-Root Model
NEV	Net Energy Value
PALMS	Precision Agricultural-Landscape Modeling System
PAR	Photosynthetically Active Radiation
SCC	Social Cost of Carbon
USDA	United States Department of Agriculture

CHAPTER 1

INTRODUCTION

The critical zone (CZ) is the area from the tree canopy to the bottom of the groundwater table [National Research Council, 2001]. CZ processes are natural geologic or hydrologic dynamics and changes that occur over long time scales, such as soil formation, biogeochemical cycling, and hydrologic partitioning. CZ services are categorized as benefits that the CZ produces through these processes for humans and the surrounding environment, such as productive soil and clean water [Field et al., 2015]. CZ observatories (CZO's) are research teams composed of multiple universities and research organizations aimed at learning more about the CZ. The Critical Zone Observatory for Intensively Managed Landscapes (IML−CZO) studies the Midwest and its industrial agricultural practices. Study sites in the IML−CZO include the Clear Creek watershed in Iowa, the Upper Sangamon River Basin in Illinois, and the Minnesota River Basin in Minnesota. In IML, various human alterations are made to the landscape aimed at reducing the limitations of rate-limiting processes for more productive farming. These practices include tile drain installation, channel straightening, channel head extension, tillage, and fertilizer application. The CZ, as depicted for the IML, is schematically represented in Figure 1.1.

This study focuses on assessing the value of CZ services in the context of two crop uses, corn feed and corn ethanol. Life Cycle Assessment (LCA) techniques are utilized to build a full inventory of all processes involved, generating an equal currency in terms of energy for the lifetime of the product from materials acquisition and production all the way to its use and waste management. CZ services are then quantified by varying techniques for each nutrient pollution process such as social costs of carbon and costs of cleaning nitrate-contaminated water. This quantification normalizes all services to the US dollar, allowing

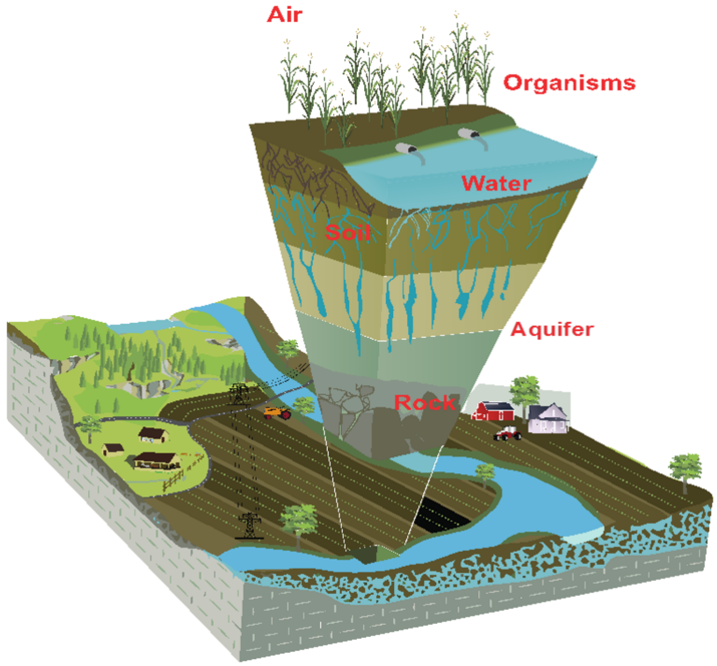

Figure 1.1: The Critical Zone as depicted for IML[a]

for fair comparison across various service types. The normalized comparison allows for a clear analysis of the impact of human agricultural changes on the existing CZ.

1.1 Motivation

In 2005, the Energy Policy Act including the Renewable Fuels Standard was released, mandating a minimum biofuel percentage of transportation fuels [United States Congress, 2005]. In February 2010, President Obama updated this standard, requiring total US biofuel production to increase from 11 billion to 36 billion gallons per year by 2022 [US Environmental Protection Agency, 2012]. This desperate push for renewable energy put pressure on the crop-producing states of the Midwest to convert from traditional crops to crops for biofuel production. The conversion of these croplands to alternate cropping systems creates responses throughout the biogeochemical soil system and the hydrologic cycle that are im-

[a]Adapted from Chorover et al, Art by Pamela Burroff-Murr, Jennifer Meek and Phong Le with input from Tim Filley and Praveen Kumar

portant in the future structure and study of the CZ.

In 2001 the amount of transportation fuels made from biomass in the US was only 0.5% [Hess et al., 2003]. After the Energy Policy Act was passed, that number increased to almost 3% by 2007 [Coyle, 2007]. According to the proposed standards, the amount of land conversion necessary for the required biofuel production would be over three times larger than the entire US corn acreage [Hess et al., 2003]. As of 2006, the amount of US cropland designated for corn-based ethanol production was 20% of the total corn acreage, and its subsidies totaled more than $6 billion [Pimentel et al., 2011]. With all of this cropland converting from corn for food to corn for the purpose of transportation, it has become more prevalent of a question to ask how efficient this process really is. As land management techniques differ, the environmental implications of all land use change must be considered. The push for biofuels has created new issues that could be large enough to actually offset the avoided fossil fuel emissions.

Although many previous studies have been done on this topic, the research done for this thesis attempts to categorize the environmental impacts of both agricultural corn production and ethanol production monetarily in addition to assessing their energy balance. Environmental impacts are quantified in terms of valuing CZ services and include both emissions that have been traditionally accounted for and other agricultural issues such as nitrate leaching, carbon storage, and nitrous oxide emissions. Illinois practices are compared with United States averages, exemplifying how land management practices affect both energy balance and environmental responses. Solar energy is also viewed alongside anthropogenic energy inputs to put the total system efficiency into perspective.

1.2 Literature Review

This study compares energy balances for corn production and ethanol production in Illinois with the United States average. While the Illinois environmental impact assessment is developed from observational and modeling results data, the energy balance and the US impact assessment is mostly derived from the literature. This section summarizes the relevant data and conclusions from previous studies for the development of the crop production and ethanol production inventory analyses. Additionally, review papers highlighting CZ science and ecosystem and CZ services are discussed.

1.2.1 Corn Ethanol Energy Balance

Production Overview

The agricultural energy balance for corn production varies across the US based on climate, soil fertility, and best management practices (BMP's). In Illinois, there are several major differences between the agricultural energy inputs and those in the rest of the US. First, the climate and topography remove the need for irrigation due to the abundance of precipitation in the region. The landscape in IML actually receives enough water to negatively affect crop productivity. In order to prevent standing water pooling upon the flat landscape, tile drains are implemented in fields about 1-2 meters beneath the surface to transport water quickly out of the soil system and increase crop productivity [Gilliam et al., 1979]. These two major differences along with other minor changes between the Illinois and average US agriculture production systems lead to alternate energy balance results. Thus, the two systems must be evaluated separately.

The energy balance of corn-based ethanol production varies depending on which type of milling process is used. During dry milling, corn is first shelled and smashed to a mash. Water is added to promote liquefaction of the starches. Then, the mash is cooled and fermented to ethanol and distilled [Graboski, 2002]. During wet milling, corn is first shelled and soaked in sulfur dioxide solution. The solution is then de-germed, hydrolyzed, and the sugars are fermented to ethanol and distilled [Graboski, 2002]. Wet mills produce more usable coproducts, including corn oil, germ, fiber, gluten feed, and gluten meal, while dry mills produce mainly dried grains with solubles [Kim and Dale, 2005]. Dry milling tends to be used for smaller production scales, while wet milling is designed for mass production. The ethanol production technologies used throughout this study are assumed to consist of 33% wet mill and 67% dry mill [Farrell et al., 2006, Shapouri and McAloon, 2004].

Globally, other crops are continually being researched for ideal biofuel production, such as wheat, sugar beets, cassava, rape seed, potatoes, and soybean (biodiesel) [von Blottnitz and Curran, 2007, Kim and Dale, 2004]. Each of these cropping systems yields its own production efficiency, economics, and environmental impacts. As the most prevalent crop utilized for biofuel production in the US, corn cropping systems are used as the basis for this study.

Biofuels can also be created from the cellulosic plant matter of crops, including corn stalks and the entire aboveground plant matter of leafy second generation bioenergy crops, such as switchgrass and miscanthus. According to pioneering studies, the conversion of biofuel production from first generation annual crops, such as corn and soybean, to second generation perennial crops will result in higher ethanol conversion efficiencies and less total required land [Tilman et al., 2006, Heaton et al., 2008]. Recent articles have performed research demonstrating the changes that cellulosic biofuels will have on the environment and CZ services, such as hydrologic cycling, biogeochemical cycling and soil structure, and ecosystem sustainability: [Liebig et al., 2008, Clifton-Brown et al., 2007, Le et al., 2011, Woo et al., 2014, Costello et al., 2009]. As current technologies stand, cellulosic biofuels are not yet feasible for mass industry production, but extensive research and development efforts are making strides in this direction [Ragauskas et al., 2006, Hess et al., 2003, Chomvong et al., 2014]. Due to available technologies, for the purposes of this study, only corn-based biofuel is analyzed.

Energy Balance

As one of the major agricultural players throughout the crop-producing economies of the Midwest, corn's economics have been analyzed dozens of times over the years [Hill et al., 2006, Kaltschmitt et al., 1997, Hill, 2007]. After the introduction of the Energy and Policy Act, the push to study biofuel production systems became more prevalent. Many recent papers have studied the energy balance and efficiency of these systems. These are discussed below.

The corn-based ethanol production energy balance has resulted in both positive and negative net energies [Shapouri and McAloon, 2004, Pimentel et al., 2011, Shapouri et al., 2004, von Blottnitz and Curran, 2007]. LCA's have become a widely-used, appropriate technique to identify and characterize the entire life and manufacture of corn-based ethanol [Davis et al., 2009, Kim and Dale, 2005, Liska et al., 2009]. Studies are identifying ways to improve the biofuel industry to make corn biofuel production more efficient and to improve policy for better practices going forward [Kim and Dale, 2004, Drewry et al., 2014, Himmel et al., 2007]. Additionally, environmental impacts affecting air quality (emissions) in addition to energy balance of the production system are continually evaluated [Searchinger et al., 2007, Liska et al., 2009, von Blottnitz and Curran, 2007]. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) was developed by Argonne National Laboratory for research accounting of energy and corresponding emissions in transportation fuels [Wang, 2001]. GREET 1.6 is the most recent version, modeling all sects of the production system from feedstock to fuel to vehicle operation. Numerous studies have utilized this model in computing energy and emissions in their LCA's [Shapouri and McAloon, 2004, Farrell et al., 2006, Huo et al., 2009].

After extensive research of the most cited and widely accepted research articles, one review paper proves to have the most comprehensive analysis. The paper, *Ethanol Can Contribute to Energy and Environmental Goals*, studies six of the most widely accepted papers on corn and ethanol production in the US [Farrell et al., 2006]. In addition to reviewing the similarities and differences between these six papers, Farrell delves into the data sources and values for each energy input. After adjusting them all to incorporate the same system boundaries, new net energy values (NEV: Output Energy – Input Energy) are calculated for clear comparison. The original and adjusted NEV's, as well as the changes made to create consistency among system boundaries, are presented in Table 1.1.

Comparisons among NEV's of these studies show large variations that are only slightly minimized after boundary system adjustments. The major differences between the life cycle system boundaries are the lack of coproduct credits and inclusion of human energy sources.

Study	Net Energy Value (MJ/L)	Boundary Subtractions	Boundary Additions	Adjusted Net Energy Value (MJ/L)
[Patzek, 2004]	-5.0	human labor and human food energy	agricultural inputs packaging, refinery capital, process water, effluent restoration, and **coproduct credits**	-1.6
[Pimentel and Patzek, 2005]	-6.1	human food energy	agricultural inputs packaging, and **coproduct credits**	-3.1
[Shapouri and McAloon, 2004]	8.9	–	agricultural inputs packaging, farm machinery, refinery capital, process water, and water restoration	7.95
[Graboski, 2002]	3.9	–	agricultural inputs packaging, refinery capital, process water, and water restoration	3.1
[De Oliveira et al., 2005]	1.59	–	agricultural inputs packaging, farm machinery, refinery capital, process water, water restoration, and **coproduct credits**	4.8
[Wang, 2001]	6.9	–	agricultural inputs packaging, farm machinery, refinery capital, process water, and water restoration	5.9
Ethanol Today [Farrell et al., 2006]	4.6	–	–	–

Table 1.1: Energy Balance Articles

Coproducts are the additional materials that are produced in addition to the ethanol yield considered as output at the end of the analysis. These materials, such as corn oil and gluten, can be put to other uses such as feed for cattle where it will be considered a positive energy output. Human energy sources, including food energy and labor energy, are not considered within the boundaries of the production system analyzed due to the lack of concrete data and the resulting subjectivity involved. Thus, energies and processes included consist of those that are concrete and easily judged within the context of the production system.

Key papers to note in this table are the Patzek and Pimentel studies, both containing negative NEV's. These studies have both of the differences discussed above, causing the net energy of the system to be negative. Alternatively, De Oliveira does not include coproduct credits or human energy sources, and the study's net energy is positive, but much smaller than the rest of the papers analyzed. After combining system boundaries, each paper's NEV shifts closer to the collective average (2.84 MJ/L) but still slightly skewed towards the negative scenarios. The final row in Table 1.1 contains the *Ethanol Today* scenario created from a culmination of the data that was considered the best from all of these papers [Farrell et al., 2006]. This scenario, incorporating the same system boundaries as the adjusted values, is used to represent the average energy balance for both corn and ethanol production across the US throughout this study.

As noted above, Farrell's *Ethanol Today* scenario is used for evaluating the average energy balance of the US. Similarly, Illinois is represented by the energy balance developed by Dhungana, which modifies Farrell's data to represent an Illinois agricultural system [2007]. The source similarity allows for an even comparison between the two systems. The only major missing piece of Dhungana's analysis is the implementation of tile drains. This additional energy input is calculated and included along with the rest of the energy balance in Chapter 2.

1.2.2 Critical Zone Science

Study of the CZ was first introduced as a high priority research need by the National Research Council in 2001. This announcement drew attention to a gap found in the integration of multidisciplinary research among researchers of the earth sciences. A call was made to combine ecology, biogeosciences, plant biology and physiology, geology, hydrology, and other land surface sciences for collaboration in creating an integrative view of the entire CZ system. By 2015, leading scientists in these fields joined together to create a framework for defining CZ science along with goals and future steps for the CZ research community [Field et al., 2015]. This paper attempts to create a shift away from the valuation of traditional ecosystem services as was previously used [Costanza et al., 1997, Haygarth and Ritz, 2009], and towards a more comprehensive definition of services categorized on both short and long time scales. This broader context of services creates a better tool for land management, not only in understanding the services associated with landscapes, but also in predicting services for the future.

For the purposes of this study, a few types of ecosystem and CZ services are restated here for convenience. Provisioning services provided by the CZ are defined as what the CZ is able to yield for consumption, such as food and water supply. The concepts of food and water security expand these values from ecosystem services to CZ services [Field et al., 2015]. Supporting services are defined by what the land can produce or provide apart from the provisioning services. Examples include nutrient cycling and land productivity – crop production for livestock feed and bioenergy production, timber production, etc. [Field et al., 2015]. Lastly, regulating services are defined as products of the CZ process interactions, providing a balanced and stable atmosphere, climate, or water supply [Field et al., 2015]. The concept of quantifying these provisioning, supporting, and regulating services into currency is still a new area in the CZ science field. In this study, the currency utilized to value and compare the CZ services is the actual US dollar. The process of assigning the currency values to each of the relevant services is developed and analyzed in Chapter 2.

As shown through this brief literature review, CZ science has become a contemporary topic in the earth science research community in recent years. That being established, however, the affects of intense human interaction alterations to the CZ are still not completely understood. This study attempts to categorize the impacts of human-induced changes to CZ services in current intensively managed agricultural landscapes in order to better predict environmental and CZ processes in the future.

1.3 Thesis Structure

- Chapter 2 describes the materials and methods involved throughout the study. The process of an LCA is documented, and the water and nutrient soil process models along with site-specific information and forcing data are introduced. The energy balance inventory analysis is developed for corn grain and ethanol production, and the impact assessment is defined through CZ services.
- Chapter 3 compares the observed solar energy inputs with the energy balance data from the literature, and alternate scenarios of crop use are contrasted through energy comparisons (anthropogenic energy efficiency values) and environmental impact assessments (CZ services). The social debate of corn for food versus fuel is also briefly discussed.
- Chapter 4 compares alternatives and discusses the conclusions of this study.

CHAPTER 2

METHODS: LIFE CYCLE ASSESSMENT

The LCA was developed to create a standard system for accounting all processes involved in a product's development. This standardization allows for study and comparison of the economics and subsequent impacts resulting from all processes in the product's "cradle to grave" lifetime, including everything from production and acquisition of input materials to waste management. This study develops LCA's for corn feed and corn-based ethanol produced from crops grown in Illinois and across the United States on average. LCA's have four main steps: Goal Definition and Scope, Inventory Analysis (LCI), Impact Assessment (LCIA), and Interpretation [Scientific Applications International Corporation, 2006]. All of these steps must be fully documented in order to create a complete LCA. The first three steps of the LCA are developed throughout this chapter. The fourth step, Interpretation, includes results and discussion of the developed production systems and is presented in Chapter 3.

The two main phases of the LCA are documented separately in this study: the agricultural phase where corn is grown and the refinery phase where corn grain is converted into ethanol. The agricultural energy inputs vary with best management practices (BMP's) for each location based on climate, topography, soil type, and soil nutrient content. Those inputs documented for either an average of the entire US or a specific region must be represented separately. Thus, an individual location cannot represent or be represented by an average of the entire US. Alternatively, the refinery phase is the same for both the Illinois and US systems. This similarity is due to the process of transport and shipment of crops to refineries. The energy inputs involved in the transformation of corn grain to ethanol is not solely dependent upon location, so an average of all known inputs is sufficient to represent ethanol produced from crops grown from all locations in the US.

2.1 Goal Definition and Scope

The first step of the LCA, Goal Definition and Scope, involves creating assessment criteria and boundaries necessary to achieve the desired project goals. The goal of the study is to classify the impacts of corn and biofuel production in terms of human energy economics and resulting environmental impacts. This goal is achieved by defining a functional unit (kJ/m^2) to create consistency and compare each crop use across various scales. Accounting is done for all energy inputs into the system and the resulting energy outputs. Each of these inputs involves different impacts, either positive or negative, upon the surrounding environment. These environmental impacts can be assessed by putting a dollar value on each of these impacts, creating a currency to quantify and compare CZ services.

The boundaries of both systems are taken as those defined for the *Ethanol Today* case and described in Section 1.2. This includes the processes within the production of both agricultural and ethanol systems as well as all coproducts produced in addition to the ethanol yield. Offsets for avoided fossil fuels and corn feed supporting services must also be included.

2.1.1 Model and Forcing Data

The data for the US system was obtained from six different papers discussed in Section 1.2 and consolidated into adjusted data sets with similar boundary conditions and scope. The best of this data was then used as inputs into the Energy and Resources Group Biofuel Analysis Meta-Model (EBAMM), which produced three different scenarios: *Ethanol Today*, *CO_2 Intensive*, and *Cellulosic* [Farrell et al., 2006]. The results from the *Ethanol Today* scenario were utilized for the US system as a basis for comparison with the Illinois system.

The data for the Illinois system was obtained from a combination of observed and simulated data from the Energy Biosciences Institute (EBI) field site at the University of Illinois at Urbana-Champaign in the Sangamon River Basin (40.06°N, 88.20°W). This site has four equal parcels of 3.8 ha, each containing different crops: corn-corn-soybean crop rotation (CCS), miscanthus, switchgrass, and natural prairie. The current study uses observational data from the CCS parcel. All four parcels could be utilized in future studies to compare alternate crop types. Additional forcing data was taken from the AmeriFlux tower (http://ameriflux.ornl.gov/) located 6 miles away in Bondville, Illinois (40.01°N, 88.29°W). This data includes radiation, precipitation, soil moisture, and temperature used as inputs into the models used. The study period includes the 2008 through 2011 growing seasons during which corn is grown in 2008, 2009, and 2011, and soybean is grown in 2010.

Two models were implemented to attain the required data for the entire Illinois LCI. First, the Precision Agricultural-Landscape Modeling System (PALMS) [Molling et al., 2005] was coupled with a carbon-nitrogen nutrient model [Woo et al., 2014] to simulate carbon, nitrogen, and water fluxes throughout the soil system. The control volume of the system consists of 25 soil layers down to 4.5 meter depth at square meter intervals across the entire CCS plot. Inputs from the EBI site, including vegetation type, weather, tile drainage information, and soil characteristics, were evaluated to output variables such as soil moisture, tile drainage, and plant water uptake. These outputs were then directly inputted into the nutrient model to produce results for carbon and nitrogen storage and fluxes through the soil system. Many of the output variables were compared with observed data from the study site [Anderson-Teixeira et al., 2013, Smith et al., 2013] for additional model validation. The nutrient results for this study site and study period were first introduced by Woo et al. in 2014 and are continually analyzed in this study.

A multi-layer canopy-soil-root model (MLCan) [Drewry et al., 2010, Le et al., 2011] utilized observational and relevant forcing data from the Bondville and EBI sites to calculate photosynthetically active radiation (PAR) for comparison of anthropogenic energy inputs. MLCan contains a complicated control volume consisting of multiple soil and plant layers that can be altered based on data availability, allowing for accurate calculation of system parameters. Table 2.1 summarizes the data sources used for simulation of the Illinois system.

Table 2.1: Data sources for modeling the Illinois system

Data	Source	Reference
Radiation	Bondville site	AmeriFlux (http://ameriflux.ornl.gov/)
Intercepted PAR	MLCan	[Drewry et al., 2010, Le et al., 2011]
2008 Prairie Soil Nutrient content	EBI site	[Smith et al., 2013]
Nitrogen Flux	PALMS + nutrient model	[Molling et al., 2005, Woo et al., 2014]
Carbon Storage and Flux	PALMS + nutrient model	[Molling et al., 2005, Woo et al., 2014]
Corn Yield	EBI site	[Smith et al., 2013]

2.2 Inventory Analysis

Development of the LCI involves documenting and consolidating all processes within the scope in terms of the functional unit, energy. To ensure inclusion of the entire production system, the processes are classified into four stages: Raw Materials Acquisition, Manufacturing, Use/Reuse/Maintenance, and Recycle/Waste Management [Scientific Applications International Corporation, 2006]. For corn and ethanol production, this includes all stages from the production of fertilizer to the production and use of ethanol and its coproducts.

Across the US, different amounts of irrigation are necessary for sustaining crops. Due to the greater annual rainfall and the flatter topography fit to store water for long periods of time, much of Illinois and other states in the IML have only rainfed crops, so no energy input for Illinois irrigation is included in Table 2.2. As mentioned in Section 2.1, the flat topography and high annual rainfall can cause excessive wetness in the soil, decreasing productivity. The installation of tile drains creates an easy flowpath for water to drain from the soil into nearby ditches. The result is extra production and labor implementation costs. The energy for the entire tile drain production and implementation process is included in the corresponding value of Table 2.2. The overall sum of anthropogenic energy inputs is smaller in Illinois than the US, but its corn yield is greater per unit area. This discrepancy is important to note when the energy efficiency of each system is evaluated and compared in Chapter 3.

Table 2.2: Agricultural Anthropogenic Energy Inputs

Agricultural Input	**United States (kJ/m²)**[a]	**Illinois (kJ/m²)**[b]
Nitrogen	852.26[c]	906.22
Diesel	271.94[c]	130.95
Gas[d]	271.29[c]	127.75
Herbicides/Insecticides	105.99[c]	94.27
Electricity	81.97[c]	21.09
Potassium	68.94[c]	31.26
Phosphorous	59.20[c]	65.64
Labor	57.39[c]	76.33[e]
Transport	50.37[f]	70.71
Machinery	31.99[g]	154.68
Seeds	22.82[c]	20.03[e]
Lime	5.60[c]	13.99
Tile Drains	–	106.34[h]
Irrigation	4.94[c]	–
Other	7.37[g]	–
Total Anthropogenic Energy Inputs	**1,892.07**	**1,819.26**
Corn Yield	16,788.23	21,205.41

Table 2.3 contains three different types of energy for each refinery input. First, the energy inputs required for one liter of ethanol are the same for both Illinois and the US since location is assumed to be irrelevant in determination of refinery inputs. Alternatively, the energy required by land area is different for each system since land productivity varies by region. Since the observed corn yield in Illinois is larger than the documented US average as indicated in Table 2.2, the volume of ethanol produced per unit area will also be larger than the US average. Thus, corn yields of 16.79 and 21.21 MJ/m^2 for the US and Illinois, respectively, result in corresponding volumetric fuel yields of 0.35 and 0.49 L/m^2. Due to this inconsistency, the energy inputs for the refinery phase per unit of land area will be larger

[a] Primary source is Farrell et al., 2006; additional original source documentation indicated
[b] Primary source is Dhungana, 2007; additional original source documentation indicated
[c] [Shapouri and McAloon, 2004]
[d] Includes gasoline, liquified petroleum gas (LPG), and natural gas
[e] Shapouri and McAloon, 2004 has both US and IL values. This data is adapted from the Illinois values.
[f] [Wang, 2001]
[g] [Graboski, 2002]
[h] Calculated annualized cost from $500 present value cost, assuming 20-year lifetime and 5% interest rate. Energy calculated based on machinery energy/cost proportion

Table 2.3: Refinery Anthropogenic Energy Inputs

Refinery Input	Energy by Ethanol Volume (MJ/L)[i]	United States Energy by Land Area (kJ/m^2)[j]	Illinois Energy by Land Area (kJ/m^2)[k]
Transportation of Grain to Refinery	0.59[l]	204.53	289.62
Coal	8.31[l]	2,878.83	4,076.50
Natural Gas	5.54[l]	1,919.22	2,717.66
Capital[m]	0.13[n]	46.37	65.66
Process Water	0.38[n]	130.42	184.67
Water Restoration[o]	0.29[n]	99.99	141.58
Total Refinery Inputs	**15.24**	**5,279.36**	**7,475.7**
Ethanol Yield	25.3	8,773.04	10,232.8

Table 2.4: Corn to Ethanol Conversion Factors

Refinery Input	United States	Illinois
Crop Yield (kg/m^2)	8,746	12,261
Refinery Yield (L/kg corn)	0.40	0.40
Volumetric Fuel Yield (L/m^2)	0.35	0.49
Energetic Fuel Yield (MJ/m^2)	7.34	10.40

for Illinois even though the conversion process from corn grain to ethanol is assumed to be the same. Table 2.4 indicates necessary data for conversions from agricultural to refinery phases for the two systems.

2.3 Impact Assessment

The LCIA assesses the human and ecological effects of the LCI. The impacts for this study are defined through both supporting and regulating CZ services. These services are normalized to the US dollar, creating an equal currency for comparison across various service types. Each service or process requires specific techniques for conversion to monetary terms,

[i] Primary source is Farrell et al., 2006; additional original source documentation indicated
[j] Calculated with Farrell et al., 2006 corn yield
[k] Calculated with Smith et ak., 2013 corn yield
[l] [Shapouri and McAloon, 2004]
[m] [Patzek, 2004]
[n] Includes all powerplant and equipment annualized energy costs
[o] Energy required to restore effluent process water to minimum standards

Table 2.5: Marginal Service Costs[p]($/kg)

Service	2008	2009	2010	2011
Carbon Storage	-0.0204	-0.0209	-0.0214	-0.0219
Carbon Respiration	0.0204	0.0209	0.0214	0.0219
Nitrate Leaching	53.60	53.60	53.60	53.60
N_2O Flux	6.0792	6.2282	6.3772	6.5262
N Fertilizer Production Emissions	0.0809	0.0829	–	0.0869
Other Agricultural Emissions	21.66	22.19	22.72	23.25
Refinery Emissions	95.58	97.92	100.26	102.61

which will be described in detail throughout the remainder of this section. The agricultural services specifically included in this study are soil carbon storage, soil carbon respiration, nitrate leaching, nitrous oxide (N_2O) soil emissions, and carbon dioxide (CO_2) emissions from nitrogen fertilizer production. These nutrient fluxes are considered nutrient cycling supporting services. N_2O and CO_2 emissions are considered as CZ disservices, or negative regulating services. Other CO_2 equivalence emissions found in the literature that were not simulated are included for completeness. Finally, supporting services for corn feed and corn-based ethanol fuel are included to represent the societal value of each crop use.

In the following sections, each of these services will be defined in terms of its impacts upon the CZ as well as its societal value, documented in $/ha. The marginal cost of each service is documented in Table 2.5. Simulated services are available for the Illinois soil system. Other agricultural processes, refinery processes, and all emissions representing the US system are derived from Farrell et al.'s CO_2 calculator and will be described in more detail throughout the section.

2.3.1 Carbon Sequestration & Respiration

Atmospheric stabilization is a major CZ process that is continually affected by the changing CO_2 emission rates. The sequestration of carbon in a landscape is important for the mitigation of rising atmospheric CO_2 levels. Carbon sequestration can refer to the long-term storage of carbon either deep beneath the surface or in the superficial soil layers. Agri-

[p]Social costs are assumed to be positive and social benefits are assumed to be negative.

cultural landscapes hold value with respect to carbon storage since they are able to store carbon within the soil layers, where other land uses or land use change might release the naturally-present soil carbon into the atmosphere.

Carbon sequestration as an ecosystem service has been defined in terms of the "social cost of carbon" (SCC). The Interagency Working Group on Social Cost of Carbon of the United States Government was organized to create a metric for accounting for the environmental effects of increased atmospheric CO_2 on both current and future generations. The resulting quantification is represented by a cost recorded in 2007 US dollars in a technical support document of Executive Order 12866 [Interagency Working Group on Social Cost of Carbon, 2010]. The SCC is taken as an actual estimated social cost of induced climate change, including changes in agricultural productivity, human health, and property damages in terms of increased flood risks and changes in energy systems [US Environmental Protection Agency, 2015]. The idea of the SCC is based upon the concept that each year as more CO_2 is released into the air, the marginal value of one unit of CO_2 increases as the accumulated amount imparts more environmental and societal harm. As a result, each year the present value, represented in dollars, increases. The agency created multiple scenarios of varying degrees of accumulation impacts represented by discount rates. For this study, the 3% discount rate was chosen. This is the middle value of the discount rates, taking into account both conservative estimates and extreme damage possibilities. The SCC values presented in the Executive Order started in year 2010 and increased by about $0.50 each year. Since the study begins in 2008, SCC values for 2008 and 2009 are extrapolated based on this marginal increase. Table 2.6 displays the assumed social cost of carbon for this study in terms of 2007 dollars per metric ton of carbon released into the atmosphere.

The coupled PALMS and nutrient models output soil carbon storage and soil carbon respiration for 2008 through 2011. Soil carbon respiration refers to the process of CO_2 releasing from the soil from organisms such as microbes or plant roots. In terms of CZ services, the carbon storage is a positive CZ regulating service, and carbon respiration is a

Table 2.6: Social Cost of Carbon

Year	SCC ($/mt)
2008	20.4
2009	20.9
2010	21.4
2011	21.9

negative CZ service, or disservice. The total load for the carbon respiration was taken as the cumulative weight of carbon leaving the soil for the whole year. The load for the soil carbon storage was taken as an average of the daily load of carbon in the soil. Additionally, this load was compared to a baseline to avoid double-counting nutrients that would already be stored in the soil in a natural system. The baseline was taken as the measured amount of carbon present to one meter depth in the prairie plot of the EBI field at the start of the 2008 season. The total carbon storage was then taken as the difference of the daily average of carbon storage in the CCS plot down to one meter depth from the natural prairie baseline scenario.

The total load from each scenario is presented in Chapter 3. It is also important to note that the carbon storage service is measured as changes from the natural prairie baseline scenario. Since the soil content of the CCS plot resulted in less carbon storage than the baseline scenario, the services are considered to be negative. If alternative baseline land cover scenarios were used, such as impermeable urban areas, completely different service values would result.

2.3.2 Nitrate Leaching

One of the BMP's for maximum agricultural productivity, especially for corn, involves applying large amounts of nitrogen fertilizer onto the soil shortly after planting. This process for increasing productivity also increases nutrients leaving the control volume of the soil system in other forms besides plant matter. The largest flux of nitrogen out of the control volume is in the form of nitrate (NO_3^-) dissolved in water. This nitrate leaves the control volume through the bottom towards the groundwater table and out the sides through tile drains towards nearby streams and ditches. Nitrate leaching measured leaving through the bottom of the 4.5 meter control volume base is assumed to continue on towards the groundwater table and eventually contribute to contamination of water bodies. Excessive nitrate in water bodies can lead to nitrate buildup downstream, causing environmental damage including depletion of important ecosystem and regulating processes of the CZ.

In order to quantify nitrate leaching as a CZ service to compare with other values such as the social cost of carbon, standards were chosen for the allowable nitrate load leaving the system without penalty. Two scenarios were evaluated: 25% and 50% reductions from observed leaching loads each year. The reduction cost for each unit of nitrate leaving the system was determined by the water treatment costs for each associated unit. The most popular mechanism for water treatment of nitrate is ion-exchange [Ghafari et al., 2008, Shrimali and Singh, 2001]. According to the most widely referenced review paper on nitrate removal, the cost for water treatment using ion-exchange technology is $3 per pound of nitrate (in 1987 US dollars) [Kapoor and Viraraghavan, 1997]. After conversions, the cost for treatment of nitrate is $53.60 per kg of nitrogen (in 2007 US dollars). It is important to note that no discount rate is applied. The nitrate calculations assume the same treatment costs every year. Inflation does not need to be incorporated since all service costs are managed in 2007 US dollars.

2.3.3 Nitrous Oxide Emissions

In addition to nitrate leaching, agricultural lands are considered large sources of N_2O emissions. The mass application of nitrogen fertilizer across agricultural landscapes leads to nitrification and denitrification, causing large amounts of N_2O leaving the soil system and entering the atmosphere. As a greenhouse gas, N_2O stays in the atmosphere longer and is even more detrimental to atmospheric stabilization than CO_2.

N_2O has been defined by the US EPA as a greenhouse gas with an atmospheric lifetime of 114 years and a global warming potential of 298, meaning that it is 298 times more harmful to the atmosphere than CO_2 [Myhre et al., 2013]. To calculate the CZ services of N_2O, the cumulative yearly flux measured by the coupled PALMS and nutrient models is multiplied by the GWP (298) to get a CO_2 equivalence value. That CO_2 equivalence is multiplied by the corresponding SCC values in Table 2.6. This gives a negative value to the service, representing the contribution of the societal and environmental harm for each unit of N_2O.

2.3.4 Other Agricultural/Refinery Emissions

The coupled PALMS and nutrient models are only designed to measure and simulate nutrient and water fluxes through the soil system. There are other environmental impacts involved in the production of corn and ethanol that do not occur in the soil system and cannot be simulated by the model. Rather than ignoring these emissions, this study uses the CO_2 equivalences produced by Farrell et al. corresponding to energy inputs, such as herbicide production and diesel and gas emissions, introduced in Section 2.2. These CO_2 equivalences are then multiplied by the SCC for each year in Table 2.6.

The emissions generated during nitrogen fertilizer production for Illinois are developed through a combination of observed data from the EBI site and theoretical emission averages. An estimated emissions of 3.9674 kg of CO_2 equivalence is assumed for every kg of nitrogen fertilizer produced [Farrell et al., 2006]. This assumption, along with the observed nitrogen fertilizer used on the EBI site's CCS plot, was used for the quantification of the CZ service for the Illinois system.

Other CZ services not included in this analysis could be incorporated into future studies to more accurately quantify environmental impacts of agricultural systems. The mass installation of tile drains across landscapes has large impacts on the river systems both immediately adjacent to and hundreds of miles downstream from these intensively managed farms. Rainfall events occurring on tile drained land cause increased volumes of water to immediately flow into the river systems rather than percolating deeper into the soil and draining to streams or groundwater at a smoother rate. This altered timing changes the hydrograph of the river system, causing increases in erosion and sediment transport, and decreases in evapotranspiration. The faster and larger volume of water entering the rivers removes the ability of the water to infiltrate deep into the soil, decreasing groundwater recharge. The impacts of the reallocation of water from groundwater to surface water systems would be a valuable CZ service for additional study.

CHAPTER 3

RESULTS AND DISCUSSION

This chapter represents the Interpretation step of the LCA. The energy inputs for the LCA's are compared for the Illinois and US systems. These results are also viewed alongside available solar energy data to better characterize the efficiency of the whole system. The environmental and societal impacts of the two crop uses, quantified monetarily in terms of CZ services, are compared across both Illinois and US systems.

3.1 Energy Balance

3.1.1 Anthropogenic Energy

The IML anthropogenic energy inputs for corn production are processes that are implemented to speed up rate-limiting processes and increase land productivity. These inputs include the production and implementation of tile drains, energy associated with labor and machinery for mechanical harvesting, and fertilizer applications. The largest portion of anthropogenic energy input comes from the process to produce nitrogen fertilizer. Figure 3.1 displays charts summarizing the allocation of average energy inputs for the US and Illinois systems developed in Chapter 2 (Table 2.2). Note that the total energy inputs for the US and Illinois are 1,892 and 1,819 kJ/m^2, respectively. The two systems have the same general trends, differing in a few categories. The Illinois energy requirements for nitrogen production are larger due to the greater use of nitrogen fertilizer in IML. In fact, the application rate as well as the actual percentage of corn acreage with applied fertilizer are much higher in Illinois than the US average [Economic Research Service, 2013]. Alternatively, it is surprising that

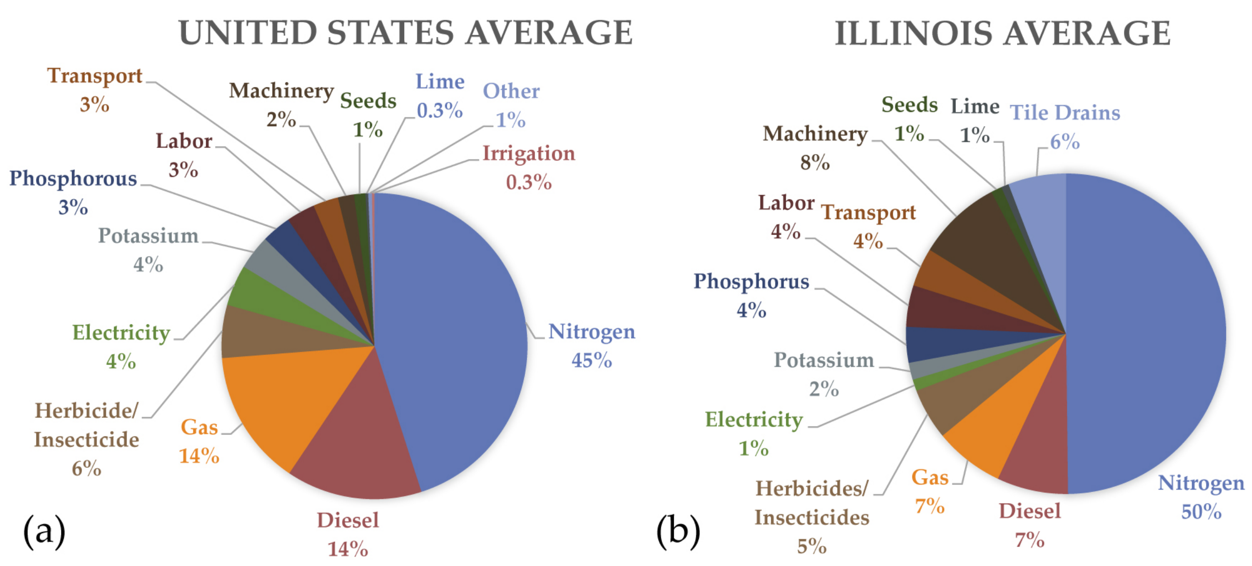

Figure 3.1: Agricultural Anthropogenic Energy Input Comparison: (a) United States and (b) Illinois

the gas and diesel portions are smaller in Illinois while the machinery energy inputs are significantly larger. Overall, the major differences in input energy between the systems are in gas and diesel, machinery, electricity, and tile drains.

The energy inputs for ethanol production mostly occur in the biofuel conversion facility, but also include corn grain – which consists only of the starchy parts of the crop that are easily converted into ethanol – and corn transport and biofuel distribution to and from the facility. The largest anthropogenic inputs for ethanol production are the forms of primary energy required to fuel the milling and fermentation processes (Figure 3.2a), typically coal and natural gas [Shapouri and McAloon, 2004, Wang, 2001]. Other major energy consumers include the inputs involved in the corn grain itself derived from the entire corn production phase. These energy inputs are not included in the refinery input diagrams and tables to avoid double-counting. As mentioned in Chapter 2, the refinery energy inputs for the US and Illinois systems are taken as the US average due to the similar biofuel conversion processses across the Midwest and the US. For the entire LCA from seed to ethanol, most of the anthropogenic energy inputs (74%) are created during the refinery phase of this process (Figure 3.2b).

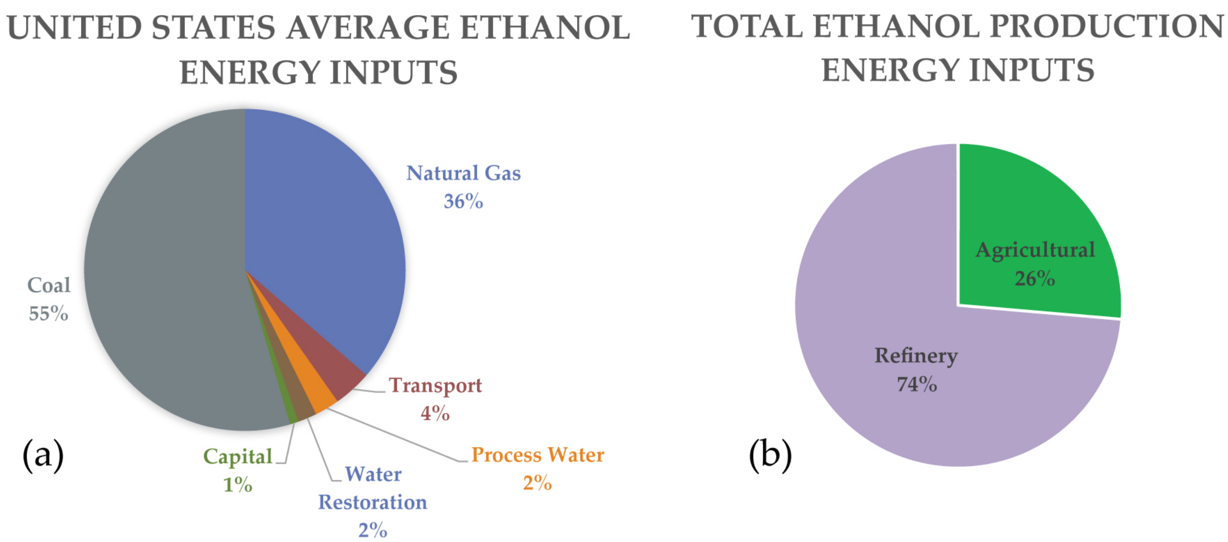

Figure 3.2: (a) US average anthropogenic refinery energy Inputs; (b) US average total ethanol production energy breakdown between agricultural and refinery phases

3.1.2 Solar Energy

When merely looking at anthropogenic energy, the inputs for corn production only account for a fraction of the inputs for ethanol production. However, when solar radiation is considered, the total energy inputs for corn production increase dramatically. The global and net radiations in Figure 3.3a are the average of the observed data for the study period in Illinois. The intercepted PAR was modeled using MLCan for three different crops at the EBI site (Figure 3.3b). The average intercepted PAR for corn over the 4-year period was 952 MJ/m^2. A recent paper calculated the average interception efficiency for corn in Illinois as 32.5% [Dohleman and Long, 2009]. The MLCan-simulated interception efficiency was 37%, validating the accuracy of the model. The average corn photosynthetic conversion efficiency – the percent of intercepted PAR that can be converted by the crop to usable energy – was calculated as 4.3% [Dohleman and Long, 2009]. Using this calculation, the actual usable energy converted by the plant is 40.92 MJ/m^2, represented in Figure 3.3a.

The total energy balance, including both anthropogenic and solar energy inputs as well as corn and ethanol energy outputs, is documented in Figure 3.4. This chart allows easy

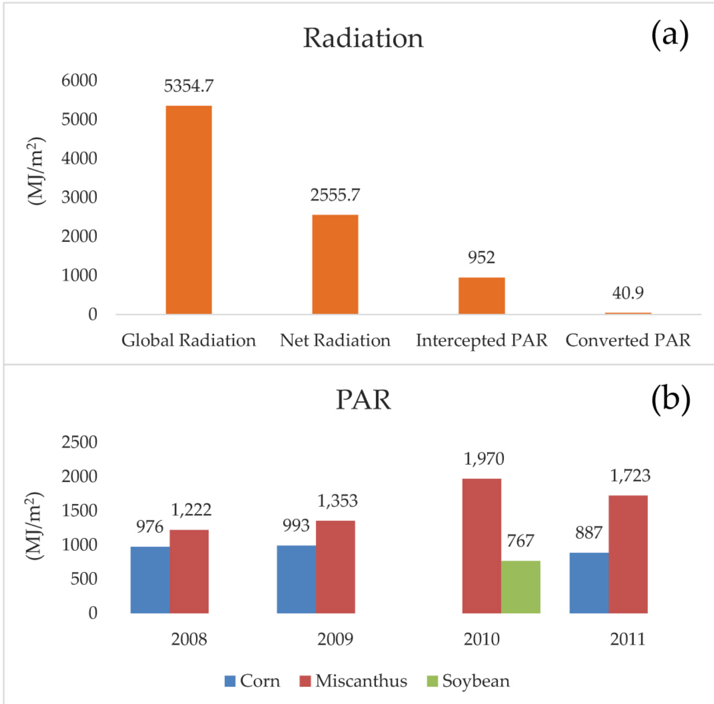

Figure 3.3: (a) Observed and modeled radiation for the Illinois system; (b) Intercepted PAR modeled with MLCan from incoming global and net radiation in Illinois

visualization of the various inputs and outputs of the production systems with respect to both land area and fuel volume produced. These two metrics must be documented separately in order to fully represent both systems without the results appearing skewed. Since Illinois has a higher crop yield per unit area, it has also has larger volumetric and energetic fuel yields even though the refinery yield is the same (Table 2.4). This means that Illinois requires less land area than the US for each unit of biofuel produced. Due to this fact, when using the land area metric (Figure 3.4a) to look at refinery inputs, the Illinois energy required is more than the US since more ethanol yield is produced from each unit of land.

For the energy comparison with respect to land area (Figure 3.4a), the anthropogenic inputs for both corn and ethanol production are placed alongside the converted PAR to more readily display the ratio of the human-generated energy to the solar energy that is “free”. The anthropogenic energy associated with corn production in Illinois consists of about 4% of converted PAR (US 5%), ethanol production makes up about 18% (US 13%), and total

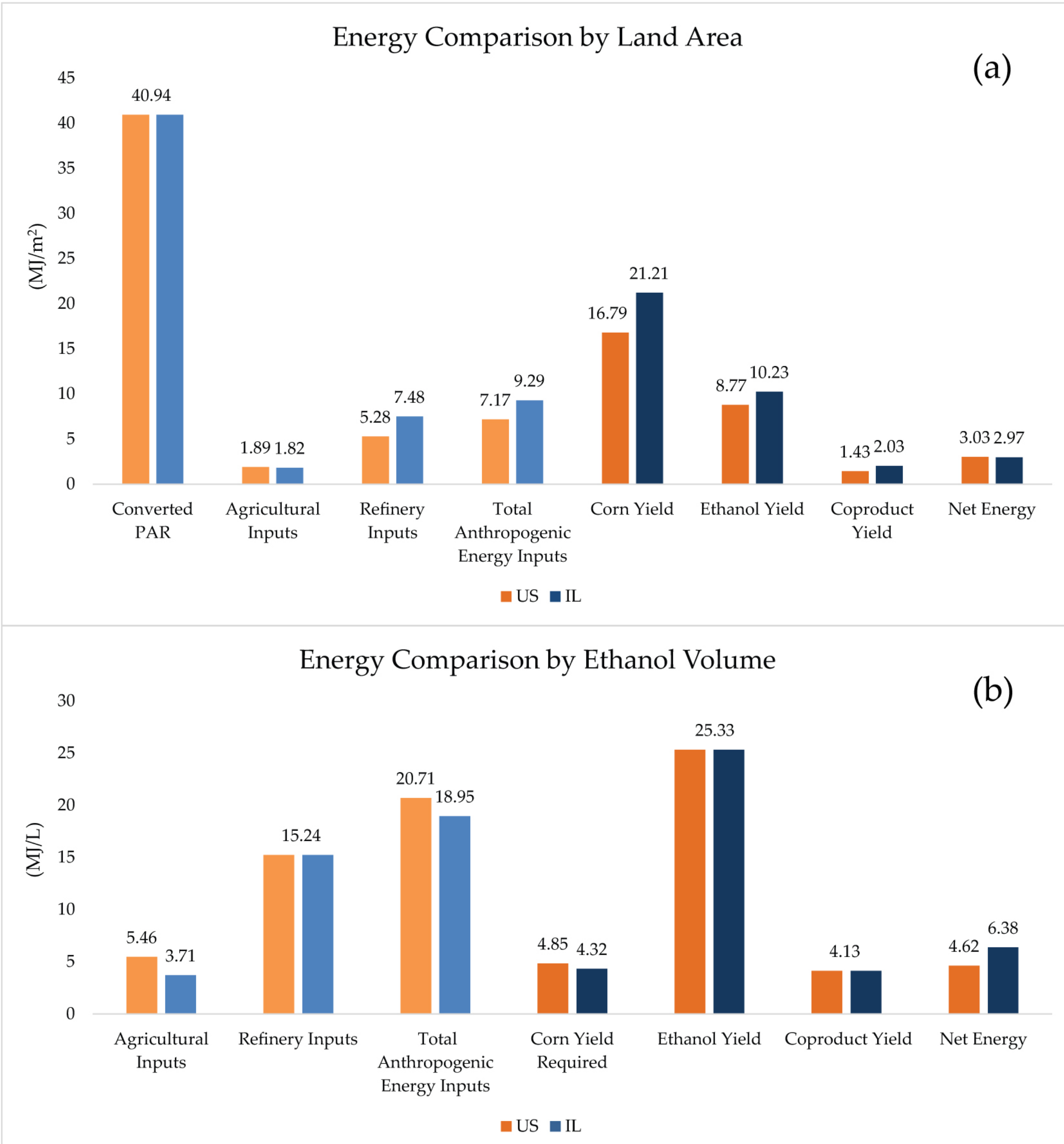

Figure 3.4: US system represented by orange-based colors; Illinois system represented by blue-based colors. Lighter shades indicate inputs; darker shades indicate outputs, or yields; Net Energy (Ethanol Yield + Coproduct Yield - Total Anthropogenic Energy Inputs) is indicated on the far right (a) Energy comparison with respect to agricultural land area required (b) Energy comparison with respect to corn-based ethanol volume produced

production energy is about 23% (US 18%). Likewise, the corn yield consists of 52% of converted PAR in Illinois and 41% across the US. This means that by increasing total energy inputs in the landscape from 41 to 43 MJ/m^2 through human-induced changes (Agricultural Inputs in Figure 3.4a), the percentage of usable output energy – energy available in corn grain – is about 50% of the usable energy from the sun. Comparisons such as these provide new insights into the concept of human alterations to the landscape with the purpose of increasing supporting CZ services.

3.1.3 Net Energy Value and Anthropogenic Energy Efficiency

Further study of the LCI energy balance can be obtained by creating an anthropogenic energy efficiency (AEE) for the four production systems. The introduction of this parameter (defined by Equation 4.1) creates an assessment tool for total system efficiency.

$$AEE = \frac{\text{Output} - \text{Input}}{\text{Input}} \tag{3.1}$$

The inputs and outputs for the production systems are plugged into this equation to create feed production and biofuel production AEE's. As discussed in previous sections, the feed production system should be evaluated in terms of area, and the biofuel production system should be evaluated in terms of volume unless fully understood in order to create a clear reference for comparison of each production system. Table 3.1 includes both metrics for all production systems to allow for comparison and consistency. From this metric, it is clear that in terms of energy, Illinois productions of both feed and biofuel are more efficient than the average US production systems. US feed is negative by volume because it has a smaller volumetric fuel yield (L/ha), so more agricultural energy must go in for every liter (used as a metric, not actual fuel volume in this case). Furthermore, if solar energy inputs were included, then all corn feed AEE's by area and volume would be negative.

This metric could be also used to determine better land use scenarios. For example, assume a land-manager was to choose between two corn plots, which should be used for corn feed

Table 3.1: Anthropogenic Energy Efficiency in the United States and Illinois

Type		**United States**	**Illinois**
By Area (MJ/m^2)	Feed	7.87	10.66
	Biofuel	0.42	0.32
By Volume (MJ/L)	Feed	-0.113	0.166
	Biofuel	0.223	0.337

and which should be used for biofuel production – one plot in Illinois and another plot with the same statistics as an average US plot. According to the AEE's, the Illinois plot should be used for feed, and the average US plot should be used for biofuel production. Illinois is the preferable choice for feed due to its significantly larger efficiency for both metrics and the US's negative feed AEE by volume.

3.1.4 Energy Discussion

The results from the energy balance of corn and ethanol production yield important information for decision-makers of land management alternatives. In terms of solely human, or anthropogenic energy, the corn and ethanol yields are larger than their input counterparts. Corn yield is about 12% and 9% larger than its anthropogenic inputs by land area for Illinois and the US, respectively. Ethanol yield is only 1.3% and 1.2% larger than its anthropogenic inputs by volume for Illinois and the US, respectively. However, the overall yield of the corn and ethanol systems make up only fractions of the usable solar radiation going into the system (Corn: 41-52%; Ethanol: 21-25%). This is an input into the system that is considered "free", and utilizing as much of it as possible is useful in the economics of the entire production system. From both of these viewpoints, corn production has a more efficient energy balance.

In addition to percentages, the AEE can be used as a normalized decision tool for land management options. From these values, it is also clear that the production of corn feed is much more efficient than the production of corn-based ethanol. However, if energy balances and AEE metrics are reproduced in various areas of the country, different efficiencies and trends might emerge based on climate and BMP's. In addition to the inclusion of a US comparison, a similar analysis done in alternate regions could be performed to determine whether these results are applicable to areas outside IML as well.

Based on the results of the LCI, the preferable production system in terms of energy is corn feed. Both the net energy and AEE metrics support this result. When comparing land choices, the Illinois agricultural system is more productive than the average US system. Its greater productivity yields more feed and ethanol products, representing the more efficient land choice for energy inputs required.

3.2 Critical Zone Services

In addition to energy efficiency, production systems are also characterized by their environmental and societal effects. Chapter 2 introduced marginal social cost metrics for CZ services as a function of load (Table 2.5). These values can be used as a currency for assessing the environmental impacts to the CZ from the human alterations associated with sustaining productive agricultural systems.

3.2.1 Social Costs of Production

US social costs were derived from the CO_2 calculator accompanying Farrell's assessment of ethanol production's energy balance. These CO_2 equivalences were combined with the SCC's documented in Chapter 2 to achieve discounted CZ services costs based on land area, land productivity, and ethanol yield (Table 3.2). The Illinois agricultural CZ services were calculated based on simulated nutrient loads for each year documented in Table 3.3. Illinois SCC values were derived from these simulated services as well as the agricultural and refinery CO_2 equivalences not covered in simulations (Table 3.3).

From Tables 3.2 and 3.3, it is clear that the Illinois system has social costs that are orders of magnitude larger than the US system. This is due in part to several key differences. First, the nitrogen fertilizer production emissions are higher in Illinois than the US system

Table 3.2: United States Yearly Service Costs

Agricultural Phase	**CO_2 Equivalence Load (g CO_2e/L)**	**CO_2 Equivalence Load (kg CO_2e/ha)**	**SCC 2008 ($/ha)**	**SCC 2009 ($/ha)**	**SCC 2010 ($/ha)**	**SCC 2011 ($/ha)**
Nitrogen Fertilizer Emissions		1,637.9	33.41	34.23	35.05	35.87
Phosphorous		102.4	2.09	2.14	2.19	2.24
Potassium		70.4	1.44	1.47	1.51	1.54
Lime		228.2	4.66	4.77	4.88	5.00
Herbicides		69.5	1.42	1.45	1.49	1.52
Insecticides		5.4	0.11	0.11	0.12	0.12
Transportation		39.3	0.80	0.82	0.84	0.86
Gasoline		113.8	2.32	2.38	2.44	2.49
Diesel		248.1	5.06	5.18	5.31	5.43
Natural Gas		46.3	0.94	0.97	0.99	1.01
LPG		60.9	1.24	1.27	1.30	1.33
Electricity		56.3	1.15	1.18	1.21	1.23
Irrigation		3.6	0.07	0.08	0.08	0.08
Machinery		20.9	0.43	0.44	0.45	0.46
Total Agricultural Phase		**2,703.1**	**55.14**	**56.49**	**57.85**	**59.20**
Refinery Phase						
Grain Transportation to Refinery	49.46	171.30	3.49	3.58	3.67	3.75
Coal	885.36	3,066.01	62.55	64.08	65.61	67.15
Natural Gas	364.90	1,263.63	25.78	26.41	27.04	27.67
Capital	8.75	30.31	0.62	0.63	0.65	0.66
Process Water	24.62	85.25	1.74	1.78	1.82	1.87
Water Restoration	19.84	68.70	1.40	1.44	1.47	1.50
Total Refinery Phase	**1,352.9**	**4,685.2**	**95.58**	**97.92**	**100.26**	**102.61**
Total Production System	–	**7,388.3**	**150.72**	**154.41**	**158.11**	**161.80**

Table 3.3: Illinois Yearly Service Costs

Agricultural Phase	**Nutrient Load 2008 (kg/ha)**	**Nutrient Load 2009 (kg/ha)**	**Nutrient Load 2010 (kg/ha)**	**Nutrient Load 2011 (kg/ha)**	**SCC 2008 ($/ha)**	**SCC 2009 ($/ha)**	**SCC 2010 ($/ha)**	**SCC 2011 ($/ha)**
Carbon Storage Change	-8.23	-7.43	-7.54	-8.37	167.89	155.29	161.36	183.30
Carbon Respiration	5,161.43	11,108	12,035	6,071.43	386.08	851.26	944.33	487.54
Nitrate Leaching (25% Reduction)	0.46	1.72	0.65	1.24	24.74	92.37	34.85	66.34
Nitrate Leaching (50% Reduction)	0.92	3.45	1.30	2.48	49.47	184.73	69.71	132.69
N_2O Flux	0.31	1.87	2.41	1.15	1.88	11.62	15.39	7.47
N Fertilizer Production Emissions	1,251.6	1,504.9	–	1,341	101.30	124.78	–	116.51
Other Agricultural Emissions				1,061.53[a]	21.66	22.19	22.72	23.25
Total Agricultural Phase (25% NO_3 Reduction)					**713.55**	**1,257.51**	**1,178.65**	**884.42**
Total Agricultural Phase (50% NO_3 Reduction)					**738.29**	**1,349.87**	**1,213.51**	**950.76**
Refinery Phase			**CO_2 Equivalence Load (g CO_2e/L)**	**CO_2 Equivalence Load (kg CO_2e/ha)**	**SCC 2008 ($/ha)**	**SCC 2009 ($/ha)**	**SCC 2010 ($/ha)**	**SCC 2011 ($/ha)**
Grain Transportation to Refinery			49.46	242.59	4.95	5.07	5.19	5.31
Coal			885.36	4,342.03	88.58	90.75	92.92	95.09
Natural Gas			364.90	1,789.54	36.51	37.40	38.30	39.19
Capital			8.75	42.93	0.88	0.90	0.92	0.94
Process Water			24.62	120.73	2.46	2.52	2.58	2.64
Water Restoration			19.84	97.29	1.98	2.03	2.08	2.13
Total Refinery Phase			**1,352.93**	**6,635.10**	**135.36**	**138.67**	**141.99**	**145.31**
Total Production System (25% NO_3 Reduction)					**848.91**	**1,396.18**	**1,320.65**	**1,029.73**
Total Production System (50% NO_3 Reduction)					**873.65**	**1,488.54**	**1,355.50**	**1,096.07**

[a] average United States CO_2 equivalence; assumed the same for all four years

due to much higher application rates. However, the largest difference stems from the fact that the biggest cost sinks in the Illinois system, carbon respiration and soil carbon storage from the simulated soil system, are not included in the US LCIA. This leads to two main takeaways from this analysis. First, the two systems cannot be compared directly without simulation data from an "average US" plot. Second, since the services derived from the soil system alone are twice as much as the total CO_2 emissions typically estimated for ethanol production, the environmental damage deriving from the cropland is essential in properly measuring the total impacts of both ethanol production and corn production systems. In future studies, it will be important to include these valuations, such as soil carbon storage and nitrate leaching, in properly accounting for all environmental impacts in biofuel LCA's.

3.2.2 Supporting Services & Fossil Fuel Offsets

The set of CZ services is not complete without the inclusion of supporting services for each crop use. In other words, what service does the production of corn feed and corn-based ethanol provide society?

Corn supporting services are defined by the selling price of the feed crop ($80.68 per metric ton) [Dhungana, 2007]. The crop price is multiplied by the observed crop yield for each year in Illinois and the average US crop yield [Farrell et al., 2006] in the US system. Table 3.4 documents the corresponding yields and supporting service values for each system. Biofuel supporting services are defined by the total fossil fuel emissions avoided by utilizing the carbon-neutral fuel source. According to Argonne's GREET model, the amount of CO_2 emissions produced for each MJ of energy of conventional gasoline is 94 grams [Wang, 2001, Farrell et al., 2006]. The total avoided fossil fuel emissions converts to 1,991.76 grams of CO_2 equivalence for each liter of ethanol used. If the same amount of crop yield and ethanol yield from Chapter 2 are assumed for each system, the biofuel supporting service is this value multiplied by the volumetric fuel yield in liters per hectare.

Due to the greater land productivity of Illinois, the supporting services for both corn feed and corn ethanol are larger. These services, once set alongside of the rest of the environmen-

Table 3.4: Feed and Biofuel Supporting Services

	United States	**Illinois**
Corn Yield (kg/ha)	8,746	12,261
Feed Supporting Service ($/ha)	**$ 705.62**	**$ 989.19**
Net Energy: Feed (kJ/ha)	1.49	1.94
Avoided Fossil Fuel Emissions (kg CO_2eq/L)	1.99	1.99
Biofuel Supporting Service ($/ha)	**$ 145.90**	**$ 206.59**
Net Energy: Fuel (MJ/L)	4.62	6.38

tal service costs, can be compared for a more thorough understanding of both production systems. A complete accounting of all CZ services, including feed and biofuel supporting services, can be viewed in Tables 3.5 and 3.6. The nitrate reduction scenario for these tables is taken as the 25% reduction of the observed nitrate leaching levels.

3.2.3 Services Discussion

The call from Washington through the Renewable Fuels Standard for energy independence in the form of supporting the biofuel industry brings the question of crop production for food versus crop production for fuel to the forefront [Donner, 2007, Rajagopal et al., 2007]. Is it right to be converting grains that can be used for food to fuel vehicles while people are starving all over the world? Rather than addressing the ethical debate of this subject, my research instead studies the environmental impacts of each crop use. Table 3.4 indicates the developed service benefits of corn feed and biofuel supporting services, in theory, displaying the present culture's view of the monetary worth of each of these crop uses. According to these findings, the worth of feed is over four times that of biofuel. When looking at the environmental impacts of these scenarios, the services for the agricultural production systems are greater than those for the ethanol production systems in terms of both land area and ethanol volume (Tables 3.5 and 3.6). This statement holds even in the Illinois case study where the simulated services are much larger than the estimated average agricultural emissions across the US. Therefore, in terms of environmental sustainability, the benefits of corn-based biofuels are not as favorable as continuing to produce corn for consumption.

Table 3.5: Critical Zone Services by Land Area ($/ha); parentheses represent disservices, or costs

Year	Simulated	Ag CO_2e	Feed	Ag Total	Refinery CO_2e	Avoided Fossil Fuel CO_2e	Refinery Total
United States							
2008	–	$ (55.14)	$ 705.62	**$ 650.48**	$ (95.58)	$ 140.72	**$ (10.00)**
2009	–	$ (56.49)	$ 705.62	**$ 679.13**	$ (97.92)	$ 144.17	**$ (10.24)**
2010	–	$ (57.85)	$ 705.62	**$ 647.77**	$ (100.26)	$ 147.62	**$ (10.49)**
2011	–	$ (59.20)	$ 705.62	**$ 646.42**	$ (102.61	$ 151.07	**$ (10.73)**
Illinois							
2008	$ (691.89)	$ (21.66)	$ 1,185.00	**$ 471.45**	$ (135.36)	$ 199.27	**$ (649.64)**
2009	$ (1,235.32)	$ (22.19)	$ 1,068.52	**$ (188.98)**	$ (138.67)	$ 204.15	**$ (1,192.02)**
2010[a]	$ (1,155.93)	$ (22.72)	$ 989.19	**$ (189.46)**	$ (141.99)	$ 209.04	**$ (1,111.61)**
2011	$ (861.17)	$ (23.25)	$ 714.04	**$ (170.38)**	$ (145.31)	$ 213.92	**$ (815.80)**

Table 3.6: Critical Zone Services by Ethanol Volume ($/L); parentheses represent disservices, or costs

Year	Simulated	Ag CO_2e	Feed	Ag Total	Refinery CO_2e	Avoided Fossil Fuel CO_2e	Refinery Total
United States							
2008	–	$ (0.016)	$ 0.204	**$ 0.188**	$ (0.028)	$ 0.041	**$ (0.003)**
2009	–	$ (0.016)	$ 0.204	**$ 0.187**	$ (0.028)	$ 0.042	**$ (0.003)**
2010	–	$ (0.017)	$ 0.204	**$ 0.187**	$ (0.029)	$ 0.043	**$ (0.003)**
2011	–	$(0.017)	$ 0.204	**$ 0.187**	$ (0.030)	$ 0.044	**$ (0.003)**
Illinois							
2008	$ (0.14)	$ (0.004)	$ 0.242	**$ 0.096**	$ (0.028)	$ 0.041	**$ (0.13)**
2009	$ (0.25)	$ (0.005)	$ 0.218	**$ (0.039)**	$ (0.028)	$ 0.042	**$ (0.24)**
2010[a]	$ (0.24)	$ (0.005)	$ 0.202	**$ (0.039)**	$ (0.029)	$ 0.043	**$ (0.23)**
2011	$ (0.18)	$ (0.005)	$ 0.146	**$ (0.035)**	$ (0.030)	$ 0.044	**$ (0.17)**

[a]soybean year; feed services noted are the average of the three available corn years for consistency

CHAPTER 4

CONCLUSIONS

As civilization continually heads in the direction of intensified mechanization, the consequences and associated changes to the critical zone must be considered. These changes do not just effect the current outputs of the system but also alter the productivity of these processes that could result in shifts in the CZ's ability to regulate itself on very long time scales. CZ services are a means of defining and quantifying these alterations in terms of concrete values that landowners, policy-makers, and members of the general public understand. The services discussed in this paper represent only some of the known consequences to human-induced activities. Major findings of this study indicate how environmental damage deriving from the cropland is significant when compared with total CO_2 emissions typically estimated for ethanol production. Looking forward, these CZ services need to be continually viewed alongside the economics of the entire production system to evaluate whether the economic benefits outweigh the environmental impacts.

As biofuel production increases, both the environmental and economic impacts need to continually be monitored. According to the results of this study, neither energy balance nor environmental impact assessments are favorable for corn-based ethanol production over corn feed. This statement holds even when accounting for avoided fossil fuels – the main incentive for the movement to "greener" transportation fuels. Once the industrial production of cellulosic biofuel technology becomes available, this analysis should be completed again, possibly with different results. As technology stands now, in terms of energy and environmental sustainability, the benefits of switching land uses to the production of corn-based transportation biofuels are not as favorable as continuing to produce corn for consumption.

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