THE WATERSHED-SCALE OPTIMIZED AND REARRANGED LANDSCAPE DESIGN MODEL (WORLD) FOR CELLULOSIC FEEDSTOCK PRODUCTION AND ADVANCED LOCAL BIOMASS PROCESSING DEPOTS (LBPD) FOR SUSTAINABLE BIOFUEL PRODUCTION: INTEGRATED LIFE CYCLE ASSESSMENTS

By

Pragnya Lavanya Eranki

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ABSTRACT

THE WATERSHED-SCALE OPTIMIZED AND REARRANGED LANDSCAPE DESIGN MODEL (WORLD) FOR CELLULOSIC FEEDSTOCK PRODUCTION AND ADVANCED LOCAL BIOMASS PROCESSING DEPOTS (LBPD) FOR SUSTAINABLE BIOFUEL PRODUCTION: INTEGRATED LIFE CYCLE ASSESSMENTS

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Interest in commercially viable cellulosic biofuel production has greatly increased due to concerns regarding the sustainability of petroleum fuels. These biofuels can help fulfill escalating demands for liquid fuels and mitigate the environmental impacts of petroleum-derived fuels. Two key factors in their successful large- scale production are pretreatment (in biological conversion processes) and a consistent supply of feedstock. While research into solving the technical issues is ongoing, much less attention has been paid to solving supply chain challenges such as low bulk density of cellulosic biomass, compositional variability and seasonality of the feedstock.

Currently large biorefineries face many logistical problems because they are centralized facilities in which all units of the conversion process are present in a single location. These logistical problems can be addressed using a system of distributed processing networks called Regional/Local Biomass Processing Depots (RBPDs, LBPDs or depots). These depots are strategically distributed facilities that procure, pre-process /pre-treat and densify biomass into stable intermediate products that are compatible with existing bulk commodity logistical systems.

On the agricultural production side, an array of feedstocks such as corn stover, switchgrass, miscanthus, native prairie grasses etc. are being evaluated as potential raw materials

for cellulosic biofuel production. Additionally, management practices such as the use of marginal lands, no-till and double-cropping, riparian buffers, when incorporated in the feedstock module of the biofuels supply chain, may enhance overall system sustainability. However, thorough assessments are required in real landscape settings on regional levels before these feedstocks can be cultivated and sustainable practices can be implemented. Likewise biofuel production should be maximized and negative environmental impacts should be minimized in growing these new feedstocks.

This research has two primary objectives: to propose designs of sustainable optimized cellulosic feedstock landscapes for biofuel production and to conduct integrated systems-wide life cycle analyses of these optimized landscapes combined with distributed processing and associated auxiliary processes (such as transport operations). It also aims to address pertinent current issues in the bioenergy production sector such as: avoiding indirect land use change impacts (iLUC) and the “feed vs. fuel” controversy, maximizing ecosystem services and improving the quality of water bodies. The watershed-scale optimized & rearranged landscape design (WORLD) model was created to estimate land allocations for different cellulosic feedstocks at biorefinery scale while paying attention to the aforementioned issues.

In summary, this research answers several key questions in the biofuel production process regarding the advantages of distributed processing systems, the technical potential of landscapes and maximizing the benefits of these landscapes plus processing systems for environmental, economic and social incentives. The WORLD model and integrated LCAs can be used as decision making tools by growers, industries or policy makers.

DEDICATION

I dedicate this dissertation to my loving family- my parents, my sister and my husband.

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“The important thing in science is not so much to obtain new facts as to discover new ways of thinking about them.”- Sir William Henry Bragg

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LIST OF SYMBOLS AND ABBREVIATIONS

RBPD- Regional Biomass Processing Depot

AFEX™ - Ammonia Fiber Expansion (pretreatment process)

NEY- Net Energy Yield (MJ)

NCER- Net Carbon Emission Reduction (kg or Mg CO_2 e.)

TPD- Tons per day

GHG- Greenhouse gas

SOM- Soil organic matter

SOC- Soil organic carbon

WSS- Web soil survey

LCA- Life cycle assessment

IBSAL- Integrated Biomass Supply Analysis and Logistics

GREET- Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation

LBPD- Local biomass processing depot

HUC- Hydrologic unit code

NEG- Net energy gain (GJ)

iLUC – Indirect land use change

BASINS- Better Assessment Science Integrating Point and Non-point Sources (model)

EPIC- Environmental policy integrated climate (model)

NLCD- National land cover database

LPC- Leaf protein-concentrate (extraction process)

RIMA- Regional intensive modeling area

WORLD- Watershed-scale optimized and rearranged landscape design (model)

AL, PL, ML- Arable, pasture and marginal lands

ESV- Early succession vegetation

TDN- Total digestible nutrients

TNPDN- Total non-protein digestible nutrients

ΔSOC- Change in soil organic carbon

CWUE- Crop water use efficiency

FGE- Farm GHG emissions

N, P loss- Nitrogen, Phosphorus losses

BM- Biomass multiplier (ratio)

$(NEY)_{rel}$, $(NEY)_{abs}$- Relative and absolute net energy yields

$(NGER)_{rel}$, $(NGER)_{abs}$- Relative and absolute net GHG emission reductions

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

The reliance on fossil fuels all over the world has triggered socio-economic crises in recent time such as:

A. Economic disorder due to high and variable costs: Average national gasoline prices increased by $0.46 per gallon between the end of December 2011 and the end of February 2012 [1]- in just a two month period. Gasoline consumers in the United States are particularly feeling the effects of oil shocks [2] because of high consumption and endure the consequences of these increasing prices. Rising gasoline prices have also been pointed out as one of the reasons for the current global economic recession [3]. Figure 1.1 shows parallels between economic recessions in the past and spikes in oil prices [4].

B. Declining fossil fuel supplies: There are large differences in the assumed size of oil resource in different existing projections. However, these dissimilarities make relatively little difference to the timing of a global peak in oil production. A significant risk has been predicted due to the peaking of conventional oil production before 2020. Forecasts that predict the delay of this peak to beyond 2030 may be optimistic but inaccurate [5].

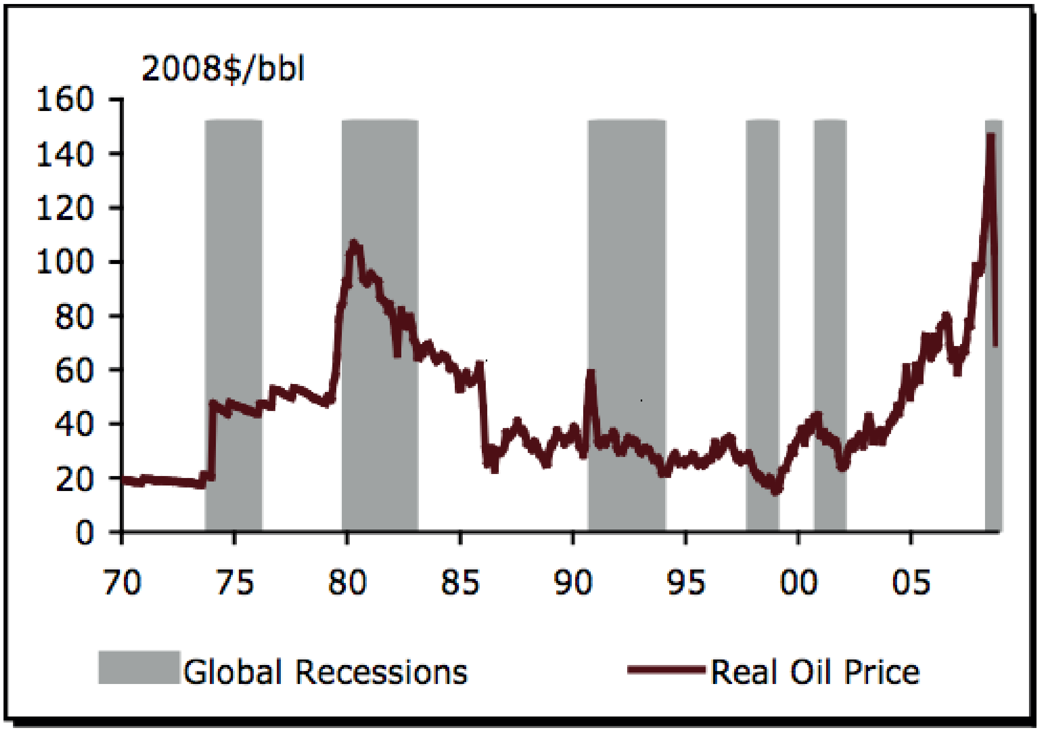

Figure 1.1: Parallels between past recessions and oil price spikes. For interpretation of the references to color in this and all other figures, the reader is referred to the electronic version of this dissertation.

C. Unstable imports: Petroleum imports in the United States increased from about 20% in 1960 to nearly 60% in 2005. However, with a decline in consumption in 2008, and enlarged domestic production, reliance on imports decreased to 45% in 2011 [6]. In 2011, the crises in the Middle East and North Africa contributed to higher crude oil prices, consequently increasing gasoline prices. In 2012 again, tensions with Iran have contributed to rising crude prices, which in turn are increasing gasoline costs [1]. Such instabilities place a great deal of stress on both prices and supplies of transportation fuels.

D. Climate and health concerns: The combined climate-change and health costs of producing and combusting gasoline amount to $469 million (quantified based on billion ethanol-equivalent gallons of fuel produced) in the USA [7]. Particulate matter emission, a form of air pollution, from gasoline combustion has been related to cardiovascular disease and premature mortality [8]. Greenhouse gas (GHG) emissions from petroleum combustion have been linked with global climate change [9]. Furthermore, the Exxon Valdez oil spill in 1989 and the BP oil spill in 2010 were the biggest and most environmentally destructive of oil discharges in the history of North America [10], that lead to questions regarding both direct and indirect environmental impact concerns of fossil fuels.

1.1. The rationale behind alternate energy production, specifically biofuels.

In spite of these concerns, the world energy consumption of liquid fuels continues to grow steadily with projected increases to 97.6 million barrels per day in 2020 and 112.2 million barrels per day in 2035 from 83.6 million barrels per day in 2005 and 85.7 million barrels in 2008. The United States is the chief consumer of transportation energy among the organization for economic co-operation and development (OECD) nations [11]. As seen in Figure 1.2, steady increases are projected in energy consumption as well as CO_2 equivalent emissions in the energy sector [15]. In the liquid fuel consumption sector, light duty vehicles (dominated by gasoline powered vehicles in the US) are projected to consume about 56% of energy among all modes of transportation [12].

In order to mitigate these problems and diversify liquid transportation fuels it is necessary to seek alternatives. Biofuels (generated from natural organic matter such as plants) are a favored alternate source of liquid transportation fuels since they are easy to transport, compatible with existing infrastructure and possess relatively high energy densities. The most commonly used biofuel in the United States currently is ethanol mainly due to its property of blending with gasoline in “Flex Fuel” vehicles (that are able to combust E-85: 85% ethanol and 15% gasoline) [13]. In 2011, using 5 billion gross bushels of corn, 13.9 billion gallons of ethanol and greater than 39 million metric tons of livestock feed (distiller’s grain, corn gluten feed and meal) were generated in the US [14].

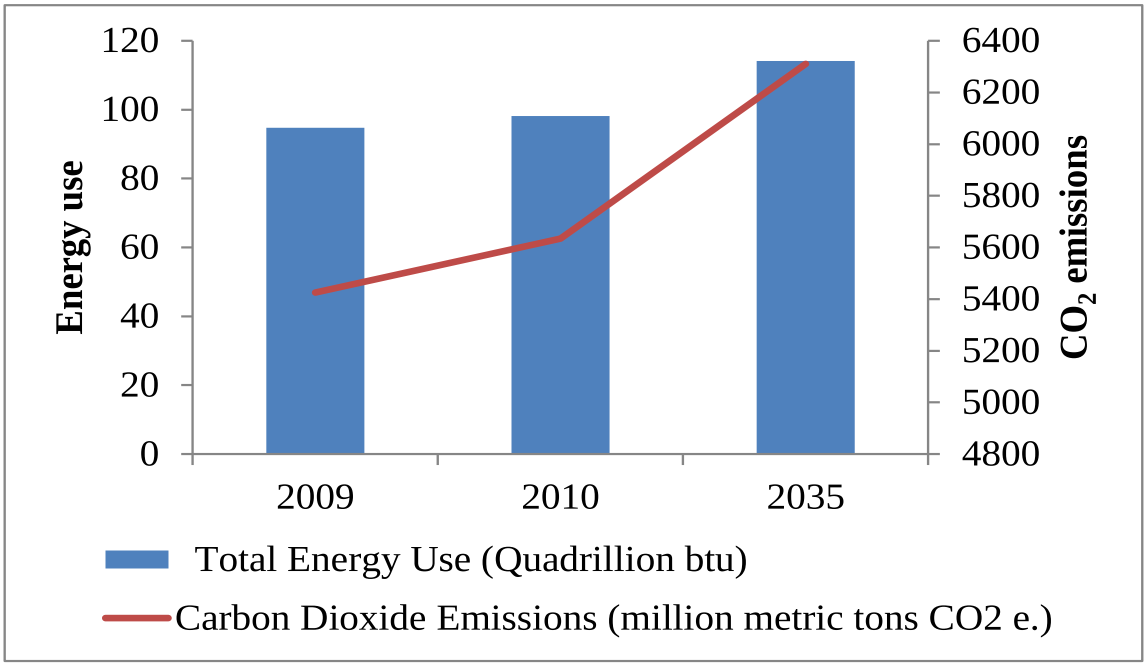

Figure 1.2: Total energy consumption and CO_2 e. emissions (historical and projected values) in the United States.

1.2. From grain ethanol to cellulosic ethanol

The production of an alternate fuel from a food crop has been a source of great disagreement in recent times with the two chief, albeit questionable, arguments being the “food vs. fuel” controversy [16] and that biofuel generation from food crops cause long-term GHG emission increases due to indirect land use change impacts [17]. Due to these negative connotations to grain ethanol as well as due to limits on amounts of crop lands in the United States, it became necessary to examine other sources of biofuel production from non-food components of agricultural crops (such as residues) as well as non-food crops (such as grasses).

The Energy Independence and Security Act [18] mandated a Renewable Fuel Standard (RFS-2) to produce 36 billion gallons of biofuels in 2022, of which no more than 15 billion gallons can be generated from grain ethanol and requires the production of 16 billion gallons of biofuel from cellulosic feedstock [19]. In addition it imposes a 60% life cycle GHG reduction threshold (compared to gasoline) on cellulosic biofuels as well as emphasizes the use of feedstocks expected to have minimal land use change impacts such as agricultural and forest residues, secondary annual crops such as winter cover crops and perennial grasses. Moreover, certain pieces of legislation and regulations such as the Renewable Portfolio Standard (RPS), and the regional Greenhouse Gas initiative (RGGI) have also been formulated that appear to have some probability of being enacted in the near future [20, 21].

Based on the negative perception of grain biofuels, some characteristics of desirable biofuel raw-materials are stability in price and availability, low cost, consistent composition, generating favorable co-products, being either environmentally neutral or beneficial, being storable and posing no threat to food production. Cellulosic feedstocks already possess most of these characteristics and have been gaining impetus in the past decade. Corn stover is one of the most abundant lignocellulosic resources available in the U.S and is widely considered to be a primary feedstock for cellulosic biofuels [22, 23]. Sheehan et al. [24] showed in a study that corn stover ethanol in E85 fuel reduced total fossil energy use and GHG emissions by 102% and 113% respectively on a life-cycle basis considered in that study. The perennial grasses switchgrass and miscanthus have also been attracting interest as potentially important feedstocks for biofuel production and are also known as dedicated energy crops [25-29]. These grasses require lower inputs (such as fertilizers, etc.) compared to conventional annual crops and monocultures and are also known to improve soil quality [30]. Moreover, Schmer et al. [31]

showed that using switchgrass in field trials of 3–9 ha on marginal cropland, with average yields of 5.7 -12.21 tons / ha, 540% more renewable energy is generated than non-renewable energy consumed (equivalent to a Fossil Energy Ratio of 5.4). It was also estimated that the GHG emissions were 94% lower compared to gasoline. More recently, unmanaged (low-input high diversity) native prairie grasses [32] are also under investigation as potential biofuel feedstocks. Such grasslands can offer valuable ecosystem services such as improved carbon sequestration, wildlife habitat conservation, pollination, recreational benefits, water quality maintenance and nitrogen fixation. However, a chief concern regarding the use of these grasslands as a biofuel feedstock is whether or not they can provide sufficient biomass and processing yields. Garlock et al. [33] suggest that these grasses may have the potential to produce yields equal or greater than certain grass monocultures, generate significant quantities of sugars at pretreatment conditions similar to corn stover, be highly profitable to both the biorefinery and the farmer. Other crops that are currently under consideration as potential feedstocks for cellulosic ethanol production include sweet sorghum, energy sorghum [34, 35].

Additionally, the implementation of sustainable practices such as the use of marginal lands (defined as any land not being used to grow commercial or conventional crops or abandoned and degraded cropland that may be capable of growing low-maintenance biomass feedstocks [36]) and no-till farming for erosion abatement can help obtain greater environmental benefits associated with lignocellulosic biomass production [31, 37-39]. The use of cover crops (such as rye, winter wheat and hairy vetch) either as double crops or as “green manure” to maintain or increase soil carbon reserves and to reduce nitrate seepage and phosphorus runoff after harvesting agricultural residues has also been attracting great interest [40-43].

1.3. Integration of cellulosic biofuel production with livestock feeding operations

Grain ethanol has been favored as a biofuel not only because of its compatibility with gasoline but also because it provides an equally important co-product in the form of distiller's grain for livestock feeding operations. Similarly it is also possible for cellulosic feedstocks to produce animal feed along with biofuels. Bals [44] stated that it is possible for early harvest switchgrass to generate nearly as much protein (0.5-1.5 Mg protein/ ha) as soybean which is the leading source of the protein component in animal nutrition. Producing protein concentrates from high protein cellulosic biomass has also been reported in literature by Enochian et al. [45] since more than two decades ago, however such processes have not been commercially successful as stand-alone operations. Integrating animal feeding operations with biofuel production may act as a secondary income source for biorefineries and help in reducing the economic risks involved in this new industry [44, 46].

Sendich et al. [47] compared several crop and animal simulation models such as DayCent [48], IFSM [49] and I-Farm to incorporate the most suitable one (IFSM) in an integrated analysis of biorefinery and farming operations. Sendich and Dale [50] then reported a model called the Biorefinery and Farm Integration Tool (BFIT) in which a basic economic and environmental analysis was conducted for the integrated biofuel production system. The model reported that the Midwest United States is particularly suitable for a cellulosic ethanol industry and that integrating such a refinery with agricultural operations augments farm incomes and decreases feedstock emissions. However, this model included only individual farm-level operations. In more realistic scenarios, biomass production modeling must be developed on regional and local scales i.e. an aggregation of local farms.

1.4. The logistics of cellulosic biofuel production

Just like petroleum refining, biorefining is the integrated, industrial scale production of fuels and higher value products but from biomass feedstock [51]. The current model for large biorefinery contains all operations at a single centralized location, handling enormous tonnages of mixed biomass per day. This may be unfeasible from a logistical standpoint, since although biofuel production is centralized, biomass production is decentralized and local. For instance, Perlack et al. [52] estimated that for a facility handling 4000 dry tons/day of feedstock for 300 operating days and with 10% storage and handling losses, a collection area (for corn stover only) of 14250 mi^2 would be required. This translates to a one way haul radius of 62 mi, including a 30% road winding factor. Additionally, the impending and rapid growth in the cellulosic biofuel industry presents many questions related to reaction of societies, environmental concerns, and benefits to local and rural communities. Whether biofuels can simultaneously contend and assist with current and potential production scenarios while meeting societal requirements has become a global question [53].

There are some disadvantages associated with cellulosic feedstocks particularly from the logistical standpoint. They do not possess the inherent property of flow-ability akin to grain crops such as corn. Moreover they have low bulk densities resulting in inefficient transport. Other problems with feedstocks include their compositional variability and tendency to decompose over time. These concerns have an impact on feedstock costs since they are not just dependent on processing but also on biomass quality specifically sugar content and recalcitrance of biomass as well as on logistics issues such as storage, transport and handling efficiencies [54]. While there is adequate focus on improving conversion technology, supply chain challenges remain largely unsolved.

Nonetheless, the importance of connections between farms, logistics and processing is a familiar one and the problems associated with delivering feedstock to biorefineries have been acknowledged. Whereas certain biomass such as forest material may be left in its place of origin and acquired as needed, herbaceous cellulosic feedstocks including perennial grasses with comparatively delayed harvest timings, need to be stably stored before they can be used by the biorefinery. One solution to this challenge has been offered in the form of intermediate facilities known as satellite storage locations, satellite storage facilities or satellite depots. These sites are either confined storage locations for the transitory storage and loading of round bales typically using hauling equipment from farms [55, 56] or sometimes include moderate processing, usually densification of biomass, before delivering it to the biorefinery [57]. Such depots are been being employed by the Tennessee Biomass Supply Co-operative (part of the University of Tennessee Biofuels Initiative) [58]. The Idaho National Laboratory bioenergy program is also focusing on developing an 'advanced uniform format feedstock supply system' to create a homogenized, consistent and stable commodity from cellulosic biomass [59].

1.4.1. Regional Biomass Processing Centers

While the concept of distributed storage and intermediate facilities in the supply chain of biomass may be a familiar one, none of these facilities employs processing steps more advanced than basic size reduction and densification which usually take place at the farm-gate; nor do they include any form of chemical pretreatment. Carolan et al. [46] proposed the concept of distributed biomass preprocessing and pretreatment facilities called 'regional biomass preprocessing centers' (RBPC) in 2007 to bridge the gap between feedstock suppliers and biorefineries. This study evaluated the technical and financial feasibility of a simple RBPC using the ammonia fiber expansion (biochemical) pretreatment (AFEX^{TM}) process and integrating animal feed and biorefinery operations.

The study suggested that RBPCs can provide solutions to the logistical concerns of centralized biorefineries such as contracting with thousands of individual farmers, potentially interrupted feedstock supplies, large transport and storage costs of feedstock and other business and market power issues. These centers are envisioned to interact with growers on a local scale and contract with them individually thus reducing complications in transactions. The proposed RBPCs are isolated preprocessing (namely cleaning, separating and sorting, chopping, grinding, mixing/blending, moisture control) and pretreatment facilities. In their simplest configuration these centers produce pretreated biomass that can be supplied to the biorefinery for further conversion. In their mature form the RBPCs are hypothesized as flexible processing facility pretreating and converting biomass into various intermediate and final products such as fuels, chemicals, electricity, and animal feeds. Figure 1.3 shows this original RBPC concept where the facility interacts with other modules in the biofuel production supply chain [46].

This study suggested biorefinery capacities in the range of 5000-10000 tons/day but considered only corn stover (which has significantly lower biomass yields compared to perennial grasses) as raw-material and predicted large land area requirements (in the order of 0.875-1.75 million acres of corn land).

The results showed capital and operating costs of the centers and specified that RBPCs can be economically feasible with gross margins of $3.32/ton in the worst case and $31.71/ton in the best case scenarios. The study also stated that co-products such as animal feeds may reduce ethanol prices by 9-20 cents per gallon, thereby supporting the concept of integration of animal feeding operations with biorefineries. However, this study did not include energetic or environmental evaluations of RBPCs. It suggested the need for further analyses of more complex centers that are location specific and supply to a multitude of industries.

Regional biomass processing: Supply chains

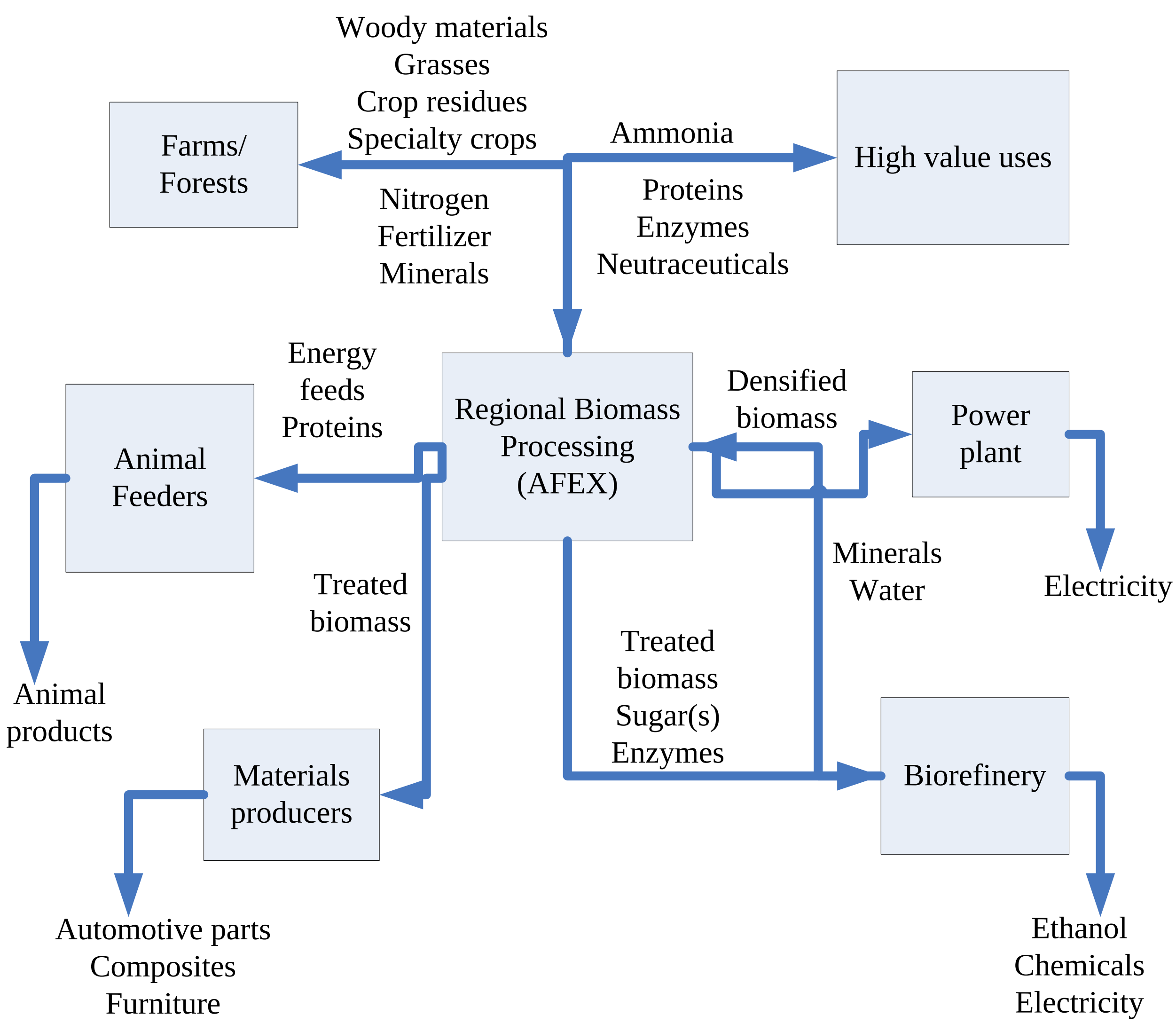

Figure 1.3: A flow-diagram representation of the original RBPC configuration proposed by Carolan et al. in 2007.

The following section contains portions of a reformatted version (to fulfill the dissertation document requirements) of the paper: Biofuels Done Right: Land Efficient Animal Feeds Enable Large Environmental and Energy Benefits. Dale, B.E., Bals, B.D., Kim, S., Eranki, P.L., *Environmental Science and Technology*, 2010, 44, 8385–8389.

1.5. Land efficient biofuel and animal feed production

As mentioned previously, there has been some strong opposition to biofuel production in the form of the "food vs. fuel" controversy. The argument is regarding what the potential scale of biofuel production could be without creating adverse effects on food supply. However, the proponents of this argument assume that biofuel production is imposed on an agricultural system that is static. The premise of the "biofuels done right" model proposed by Dale et al. [41] conversely is that agriculture can change, utilizing new technology and approaches to meet and reconcile demands for food, biofuels and environmental services. The model was designed to investigate the technical potential for changes in US agriculture to meet the demand for large scale biofuel production. It was developed keeping current food production and exports constant and using a combination of existing and emerging technologies. Soil fertility was maintained or increased and large GHG reductions were obtained simultaneously. Producing the same amount of food on current agricultural land eliminates the so-called indirect land use change (iLUC) effect. Over 80% of total agricultural acreage in the U.S is currently used to feed animals (especially ruminants) [60]. Therefore, two land-efficient animal feed technologies are considered in the study: ammonia fiber expansion (AFEX$^{\mathbf{TM}}$) pretreatment to produce highly digestible cellulosic biomass and leaf protein concentrate (LPC, an animal feed protein) production. Only 114 million ha of current U.S cropland (amounting to less than one third of the current U.S cropland, grassland and range) was used in order to produce animal feed, corn ethanol, and exports. The feedstocks used were corn grain and stover, soy, canola, winter wheat as a double crop, alfalfa and cellulosic biomass crops. Cellulosic biomass crops (CBCs) were also considered including perennials, annual or a mixture of both (e.g., mixed prairie species) that can be processed for animal feed or biofuel production. The DayCent model [48] was used to simulate environmental impacts of all the feedstocks. Animal feeding operations were adapted to the new feeds, thereby freeing land for biofuel production under three basic feed constrains to balance animal diets – digestible energy (calories), protein, and rough fiber. A nonlinear optimization model was then used to determine the two main of the greatest importance: maximum biofuel production and maximum GHG reduction.

The current use of 114 million ha used to produce food, feed, and some biofuels when coupled with a more land efficient approach, uses that same acreage to generate an equal amount of food and animal feed while also providing much larger quantities of biofuels of approximately 400 GL/y. Additionally, the two main objectives stated above (ethanol and GHG reductions) harmonize well with each other and also with production of land efficient animal feeds as seen in Figure 1.4.

However, the model also predicted that nitrate releases may increase by 60% in the future scenario compared to base-case. These results, based on DayCent model simulations, should be validated with other biogeochemical models. These increases can be combated with better agricultural practices and landscape design. The study also suggested that some candidate cellulosic biomass crops such as *Miscanthus* × *giganteus* have reported increased nitrogen use efficiencies and might exhibit low nitrate emissions.

The biofuels done right study concluded that by using enhanced forage feeds for ruminants including leaf protein concentrates, pretreated forages, CBCs and double crops, it is possible to maximize the productivity of the United States farmland. Using less than 30% of total US cropland, pasture, and range, 400 billion liters of ethanol can be produced annually without decreasing domestic food production or agricultural exports. This approach also reduces US greenhouse gas emissions by 670 Tg CO_2-equivalent per year, or over 10% of total US annual emissions, while increasing soil fertility and promoting biodiversity.

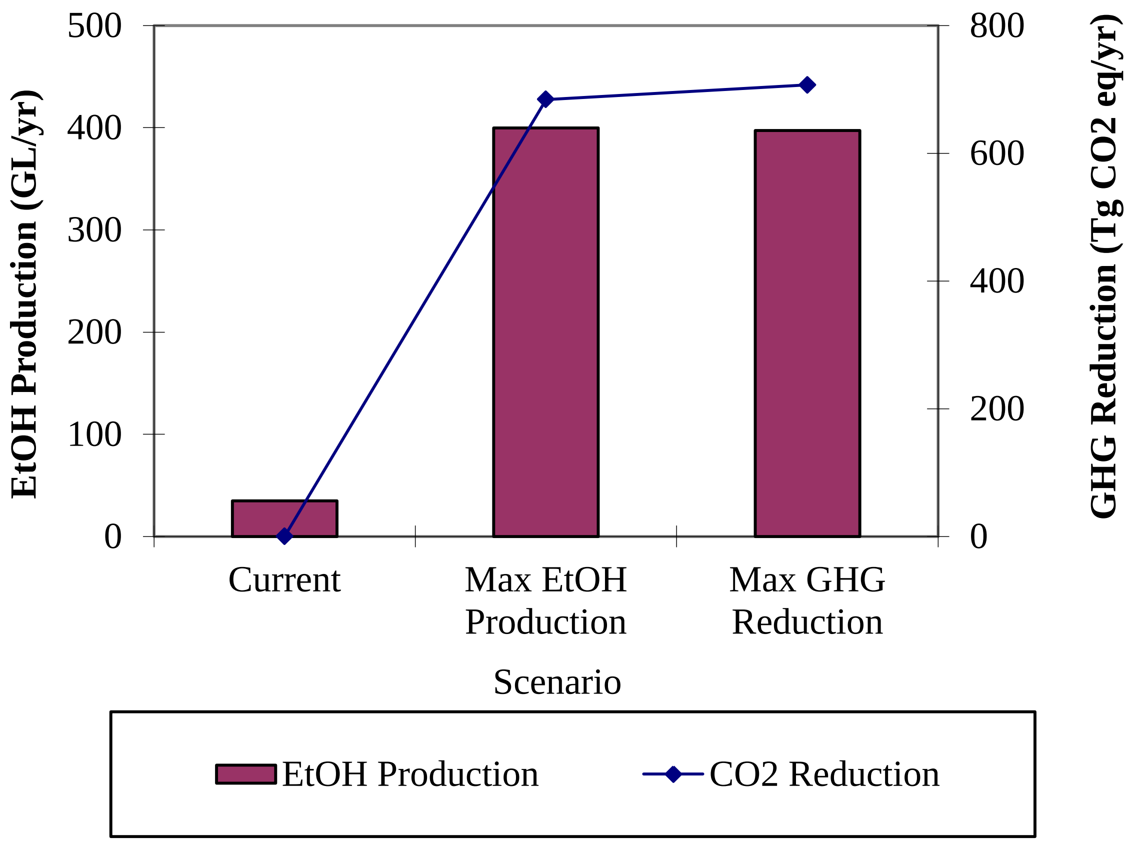

Figure 1.4: Ethanol production and GHG reductions from the current US agricultural system considered in this analysis (114 million ha), that same acreage configured for maximizing ethanol production, and that same acreage configured for maximizing GHG reductions.

1.6. Research approach

This project is divided into three categories based on the research needs identified in literature. A representation of the research needs and how these gaps are filled is shown in Figure 1.5. The Carolan et al. study [46] formed the basis for a further investigation into the concept of distributed processing of biomass. First, it was necessary to compare the basic energetic and environmental performance (in terms of energy yields and GHG emissions, respectively) for the distributed processing network vs. the current paradigm of centralized processing. In Chapter 2, a comparative life cycle assessment (LCA) of distributed and centralized processing systems combined with farm-scale multi-feedstock landscapes is presented. After concluding from this study that a simple depot setup consisting only of pretreatment and densification processes is fundamentally feasible, an exploration of the concept of potential advanced depot configurations containing more technologies and generating valuable co-products via synergies among these technologies was essential. Chapter 3 describes this concept of advanced regional biomass processing depots as a potential solution to the logistical challenges of the cellulosic biofuel industry.

It was established in the Dale et al. study [41] that generating feed and biofuel from the same land area on national-scales using new biomass feedstocks is beneficial not only from the energy yield perspective but also from the environmental standpoint. But, conditions such as climate, soil, etc.) vary to a large extent on national scales. Moreover, the Sendich et al. study [50] showed that the integration of biorefinery and animal operations is advantageous in maximizing farm profits as well as in minimizing GHG emissions. However this study was conducted on a farm-scale whereas in reality biomass feedstock comes from an aggregation of many local farms.

Additionally, since there are multiple crops, grasses, legumes, forages and woody material under consideration as suitable biofuel feedstock, an analysis into the land areas that should be allotted to a combination of these feedstocks within biofuel generating landscapes is required. Therefore, it was essential to create a regional/local scale model based on biofuel, animal feed and environmental constraints to maximize land use efficiency and avoid iLUC impacts that can allot optimized land areas to various biofuel feedstocks.

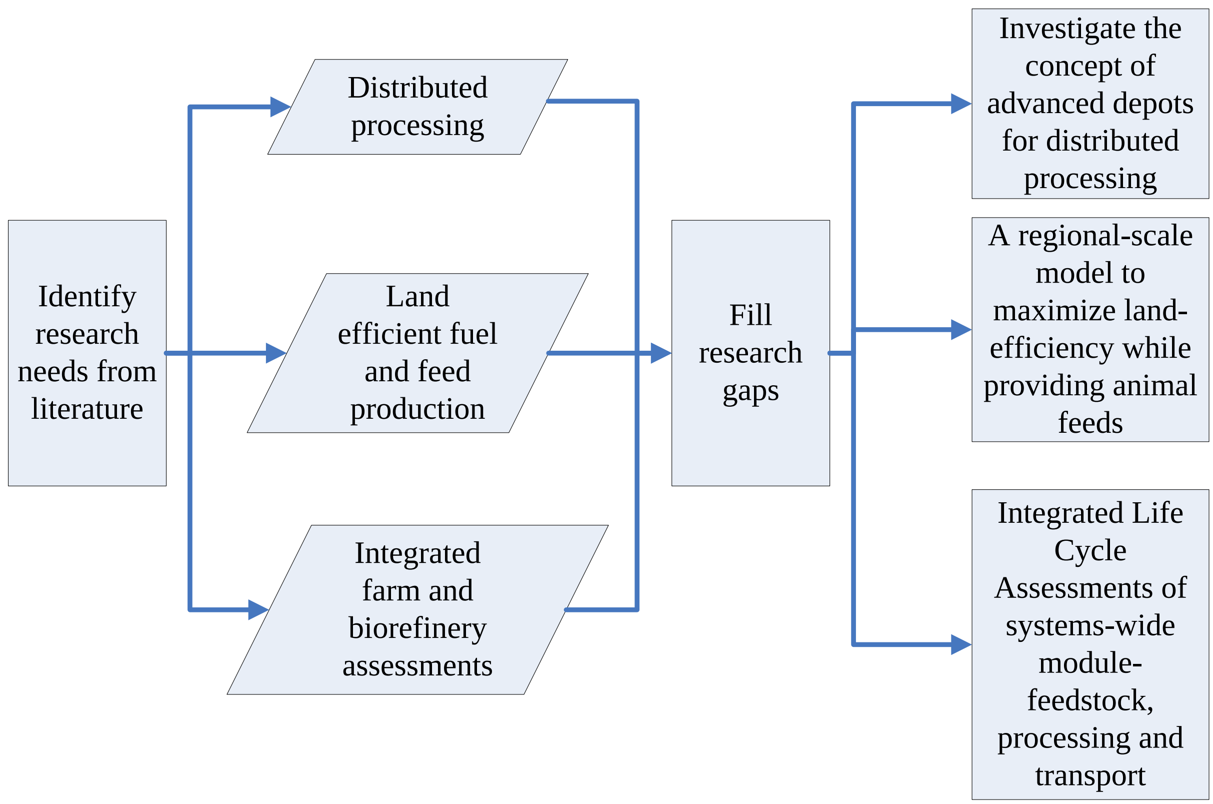

Figure 1.5: A flowchart depicting the research approach for this project

Furthermore, thorough LCAs are also required to estimate the renewable fuel energy returns on investment of fossil fuels and various environmental impacts in addition to GHG reductions for the overall feedstock-processing-transport arrangement in biofuel production. In Chapter 4, an LCA was conducted for watershed-scale cellulosic feedstock landscapes integrated with local biomass processing depots. In this study, land areas were allocated manually under different scenarios to the different feedstocks. This study formed a basis for the watershed-scale optimized and rearranged landscape design (WORLD) model and the integrated LCA including advanced depot configurations, described in Chapter 5. Chapter 6 presents conclusions from this project and provides recommendations for future analyses.

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The following chapter is a reformatted version (to fulfill the dissertation document requirements) of the paper: Comparative life cycle assessment of centralized and distributed biomass processing systems combined with mixed feedstock landscapes. Eranki, P.L., Dale, B.E., *Global Change Biology Bioenergy*, 2011, 3(6), 427-438.

CHAPTER 2: COMPARATIVE LIFE CYCLE ASSESSMENT OF CENTRALIZED AND DISTRIBUTED BIOMASS PROCESSING

2.1 Introduction

Lignocellulosic biofuels are an environmentally superior alternative to petroleum-derived fuels. Abundant and renewable cellulosic feedstocks provide important solutions to fulfill escalating demands for alternate liquid fuels. However their highly complex physical structure impedes conversion into useful end-products when using biological conversion routes. As a result, pretreatment forms the core of biomass conversion processes [1]. Biorefining is the integrated, industrial scale production of fuels and higher value products from biomass feedstock, similar to the petroleum refining approach [2]. A centralized, fully integrated biorefinery includes all biomass conversion processes (i.e. size reduction, pretreatment, hydrolysis, fermentation, distillation) in a single location. Production of large quantities of biofuels at optimal scales for efficient capital investment requires biorefineries handling enormous tonnages, probably of mixed feedstocks. This implies contracting with thousands of individual farmers, potentially interrupted feedstock supplies (due to drought, etc.), large transport and storage costs of feedstock and other business and market power issues [3].

This gap between feedstock suppliers and biorefineries can be bridged by a network of smaller scale pre-processing facilities called "Regional Biomass Processing Depots" (RBPDs), or just "depots" in this paper. These strategically distributed depots interact with farms producing feedstock and with animal production operations as well as with the biorefinery and power plants [3]. RBPDs can potentially provide benefits in environmental, economic and social sustainability. In one simple configuration a depot procures, pre-processes/pre-treats, densifies and delivers feedstock to the biorefinery and also returns animal feed to farms.

This study focuses on this simple depot configuration consisting of feedstock pretreatment for bioethanol production and return of a single by-product (animal feed) to farms. Biomass is procured from farms and undergoes conditioning and size reduction. Employing the Ammonia Fiber Expansion Process (AFEX™) [4, 5] in the processing depots offers multiple advantages as described in the previous chapter [3].Transporting the pretreated solids over long distances requires densification to reduce transport costs and its associated environmental impacts as well as to facilitate handling of pretreated biomass. Therefore a densification step such as pelletization is imperative in the depots. AFEX™ pretreatment prior to densification can improve the binding properties of lignocelluloses and enhance pellet characteristics, thereby providing stability during storage and transport[6, 7]. Part of the pretreated solids is used as animal feed [8]. A block diagram of this proposed RBPD is shown in Figure 2.1. Depots can also be configured to accommodate multiple technologies such as leaf protein concentrate production, thermochemical conversion and stem-leaf separation to deliver additional valuable by-products to end users. For example, if wet biomass is acquired from farms it can be pulped and pressed to extract protein concentrate [9], before being sent to the pretreatment reactor.

The primary objective of this study is to perform a comparative life cycle assessment of distributed and centralized processing systems. Additionally, the effect of apportioning land area to different feedstocks within a landscape on the net energy yields and greenhouse gas emissions of the combined landscape-processing systems is assessed.

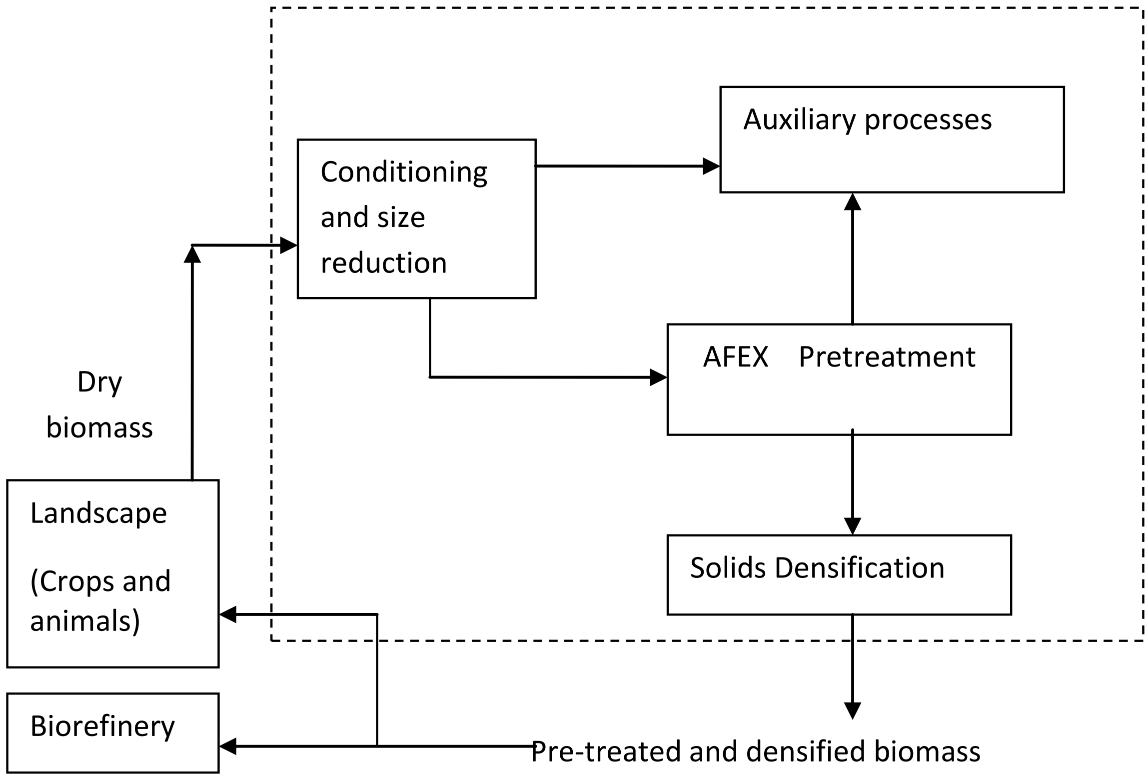


Figure 2.1: Block diagram of a simple Regional Biomass Processing Depot (RBPD) used in this study. All processes confined within the dashed line represent operations present in the RBPD.

2.2. Structure and methods

2.2.1 Calculations

1. Net Energy Yield (NEY) is calculated as the difference between total energy outputs from and inputs to the cropping, transport and processing systems. All inputs are considered only in terms of non-renewable fossil fuel energy used. Energy embodied in the feedstock is included in the outputs only in the form of ethanol, electricity and co-product feeds generated.

2. Net Carbon Emissions Reduction (NCER) is calculated as the difference between CO_2 equivalent greenhouse gas emission (GHG) outputs from the transport and processing systems and the carbon sequestration effects of the agricultural systems. In this study the carbon sequestration effect of the agricultural system is essentially the net carbon (kg CO_2 equivalent) resulting from gasoline displacement by ethanol plus the soil organic matter (SOM) sequestration due to crop residue and no-till practices and carbon emissions during cultivation and harvest plus annual soil organic matter losses (based on an yearly SOM maintenance parameter for different farm location). All SOM values are converted to soil organic carbon (SOC).

3. Calculation of relative differences of NEY and NCER between distributed and centralized processing systems:

i) % difference in NEY (%Δ NEY) = $[((NEY_{cent} – NEY_{dist})/NEY_{cent})*100]$

ii) % difference in NCER (%Δ NCER) = $[((NCER_{cent} – NCER_{dist})/NCER_{cent})*100]$

Where *cent* represents the centralized processing system and *dist* represents the distributed processing system.

All values are in terms of dry tons wherever applicable. Co-product credit calculations, explained further in section 2.2.2, show the conversion of non-energy co-products into energy and emission -compatible values which are subsequently included in the NEY and NCER calculations respectively.

2.2.2 Landscape analysis and LCA description

All energy and emission parameters are calculated on the basis of one kg dry feedstock. The functional unit is a 5000 TPD (tons/day) biorefinery and the systems for comparative LCA are: *System 1*: 9 RBPDs, 500 TPD each (with pelletization) + a 5000 TPD Biorefinery that contains a single (10^{th}) 500 TPD RBPD (with no pelletization).

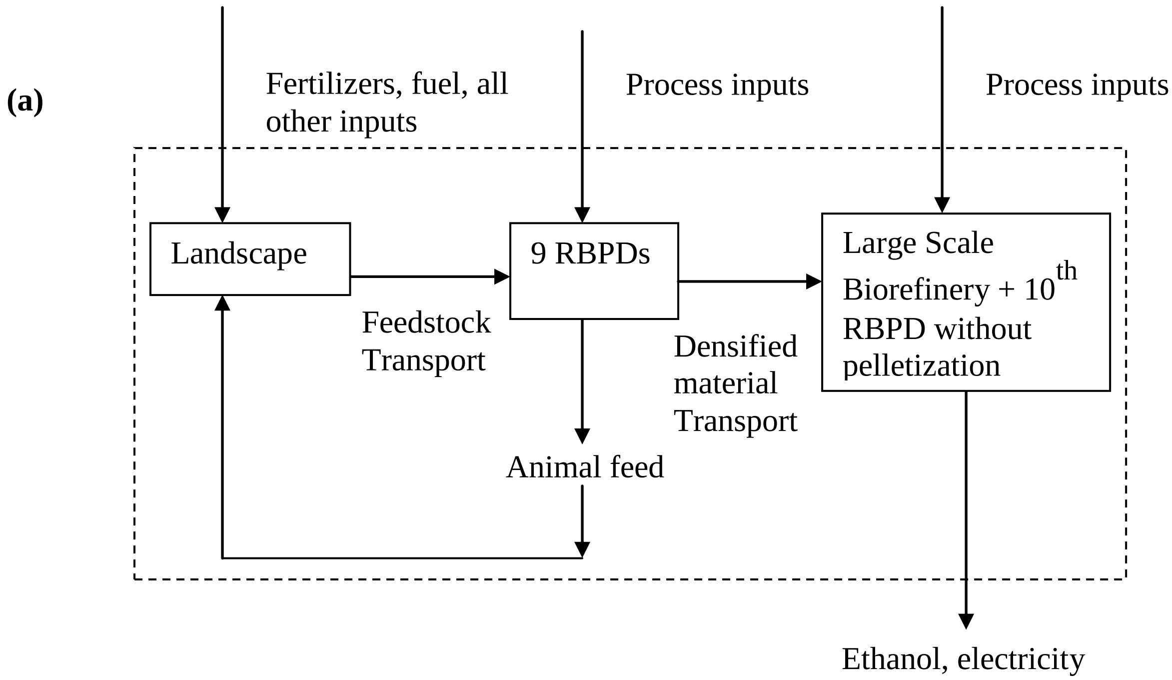
System 2: Centralized 5000 TPD biorefinery (no pelletization). Figure. 2.2 a, b show the system boundaries of both systems under consideration for LCA.

The feedstocks included in this study are a continuous "corn system" consisting of corn grain, stover and a winter double crop (rye in this case) as well as two perennial grasses – switchgrass and miscanthus. Corn stover removal rates of 70% are based on literature values [10]. Both perennial grasses are assumed to have average stand lives of 10 years [11, 12]. Stover is one of the most abundant lignocellulosic resource available and is widely considered to be a primary feedstock for cellulosic biofuels [13, 14]. Switchgrass and miscanthus have also attracted interest as potentially important feedstocks for biofuel production [15-18]. Part of the pre-treated perennial grasses and stover is also used as animal feed.

A total landscape area of 280 hectares (~700 acres) (in Barry County, SW Michigan) was selected using the Web Soil Survey (WSS) (a Geographic Information System tool provided online by the United Stated Department of Agriculture Natural Resources Conservation Service (USDA NRCS)). Although the biorefinery size is fixed at 5000 TPD, for purposes of comparison only a fraction of the biomass generated from the land area under consideration is investigated here. This area is considered as a representative fragment of a larger landscape that would be required to satisfy biorefinery feedstock requirements. It is intended to compare the energy yield and greenhouse gas (GHG) emissions for this fixed land area but with different acreage distributions among the primary crops of interest. To achieve this objective, different configurations with varying acreages allotted to different feedstocks are combined individually with each processing system and these landscape-processing systems are then compared with each other.

The amount of biofuel (bioethanol in this case) and electricity generated from each of these configurations is the same irrespective of the type of feedstock used because of the unchanging scale of biorefinery; therefore they can be compared without ambiguity. Similarly, the basis of 1 kg dry feedstock was chosen since one of the two most important aspects of this study is feedstock allocation within a given landscape. This allows for fair comparison because the land area used remains constant for all configurations.

For this fixed land area three configurations were formulated to evaluate the effect of decreased acreage in the corn system and increased perennial grasses. It is assumed that this fixed land area is a “clean-slate” where any crops grown on this land area prior to this analysis are ignored. This assumption is valid based on the impetus that the use of marginal lands to grow cellulosic biofuel feedstocks is gaining [19, 20]. Marginal land is defined as any land not being used to grow commercial or conventional crops or abandoned and degraded cropland [21] that may be capable of growing low-maintenance biomass feedstocks such as perennial grasses [22].



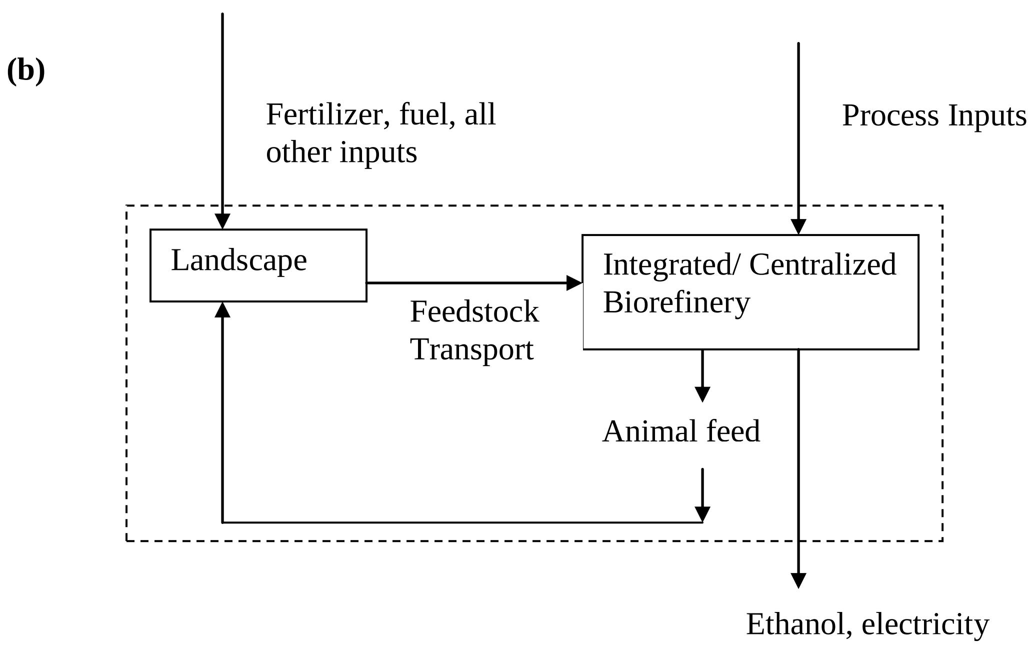


Figure 2.2: System boundaries for comparative LCA - **(a)** Distributed processing system, **(b)** Centralized processing system. Both processing systems are combined with the mixed feedstock landscapes and animal operations for an integrated system-wide analysis

In Configuration 1, 65% of the acreage was dedicated to the corn system and the remaining acreage was divided equally between the two perennial grasses. In Configuration 2 only 15% of the acreage was allotted to the corn system and the remaining 85% was divided equally between the grasses. In Configuration 3 all the acreage was divided equally between these two perennial grasses. There is a subdivision within each configuration acting as an embedded sensitivity analysis to assess the impact of grass yields on the results.

A high grass yield (HG) of 10 tons/ac (24.7 tons/ha) yield was chosen for switchgrass and 12 tons/ac (29.6 tons/ha) for miscanthus while a lower grass yield (LG) of 7 tons/ac (17.3 tons/ha) yield was chosen for switchgrass and 8 tons/ac (19.8 tons/ha) for miscanthus. The high and low yields were selected based on literature values from various publications for switchgrass [23, 24] and for miscanthus [25, 26]. The perennial grasses were assumed to have an "establishment period" of 3 years in which they have negligible yields but post- establishment they have significantly higher yields and much lower maintenance requirements than the annual crops. Yields are assumed to be on a dry mass basis and with moisture contents of 15% at harvest [12, 27]. Yields of both perennial grasses are averaged over their entire stand-life.

Yields for the corn system were obtained from the Web Soil Survey (WSS) for available crops or estimated for unavailable crops based on the yields of similar crops present in the area of interest. For example, winter rye yields were calculated on a weight basis compared to winter wheat and as mentioned previously perennial grass yields were obtained from literature. After obtaining yields crop cultivation and harvest energy and emission values were estimated using crop budgeting spreadsheets (K Thelen, 2010, Personal communication). An extensive literature review was conducted for each crop to obtain inputs including fertilizers, insecticides, fuel used in cultivation and harvest, seeds required or roots transplanted (data available in Tables A1-A4, Appendix A). The budget spreadsheets provide details such as increases in soil organic matter (SOM) when using no-till practices and losses in SOM based on farm locations. Figure 2.3 shows fractions of biomass yields of each crop in each configuration for the fixed land area. The corn system contributes the greatest biomass in Configuration 1 as expected since it occupies the largest portion of land. Moreover, its biomass fraction increases relatively in low grass yield scenarios compared to that in high grass yield scenarios in all the applicable configurations. Similarly, the fraction of biomass from perennial grasses increases with an increase in their land area allowance. On-farm animals form an integral part of these landscape analyses. It is assumed that ruminant animals are present within the landscape at a stocking rate of 2 animals/ac [28].These ruminant animals consume part of the pretreated feedstock and their methane emissions are calculated, converted to CO_2 equivalent and included in the NCE impacts.

Carolan et al. [3] state that animal feed is an important by-product of the AFEX™ pretreatment method. Therefore, co-product credit calculations for animal feed are an important aspect of this LCA. Here it is necessary to calculate displacement ratios for all the lignocellulosic feedstocks included in this study. The displacement ratio is defined as the amount of conventional animal feeds (corn and soybean meal) that pretreated lignocellulosic feedstock can replace based on animal nutritional requirements.

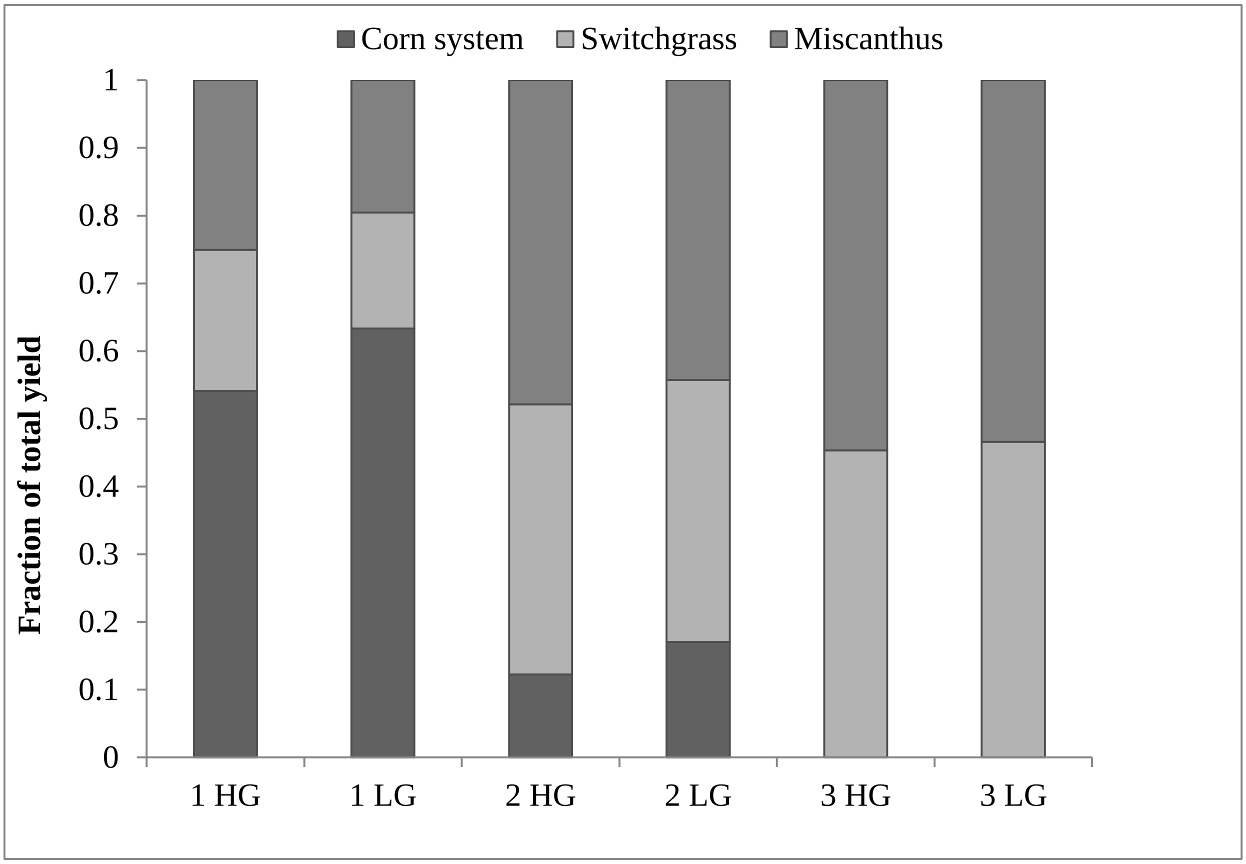


Figure 2.3: Fractional yields of feedstocks in different configurations. The land area remains the same in each configuration but feedstock acreages vary. Yields of cropping systems vary proportionally with their acreages in each configuration. Corn system acreages as % of total land area: Configuration 1 = 65%, Configuration 2 =15%, Configuration 3=0. Combined perennial grass acreage Configuration 1 =35%, Configuration 2 = 85%, Configuration 3= 100%, divided equally between switchgrass and miscanthus. HG represents high yields and LG represents low yields of the two perennial grasses

These calculations were performed for stover, switchgrass and miscanthus based on the amount of energy, protein and fiber (in case of grasses replacing hay) replaced by lignocellulosic feedstock compared to the conventional feedstock. The following illustration shows displacement ratio calculation for stover.

Values for digestible fiber, energy and protein for both replacing and replaced animal feeds are shown in Table 1 (BD Bals, 2010, Personal communication).

Oil content of soybean =0.196, meal = 1-0.196 = 0.804.

Based on equalizing nutritional values:

For corn stover displacing corn and soybean meal:

$0.887*C + (0.654/0.804)*S = 0.756$

$0.094*C + (0.386/0.804)*S = 0.172$

Where C and S represent corn and soybean meal respectively

Solving for C, S:

$C = 0.638476$ and $S = 0.233298$

Similar calculations were performed for perennial grasses. Due to absence of nutritional value data for miscanthus its displacement ratios are assumed to be the same as switchgrass. Displacement ratios were then incorporated in equations (adopted from Edward and Anex [29] and modified for this study) for co-product credit calculations. The following illustration shows co-product credit calculation for stover:

Corn stover energy credit for displacing corn [MJ] = [animal feed production (kg feed/kg stover) * feed displaced (kg corn displaced/kg animal feed)] * corn production energy (MJ/kg corn)

Corn stover energy credit for displacing soybean [MJ] = [animal feed production (kg feed/kg stover) * feed displaced (kg soybean displaced/kg animal feed)] * soybean production energy (MJ/kg soybean)

Table 2.1: Nutritional value of feedstocks

Nutritional value parameter	Corn	Stover[a]	Soybean	Switchgrass[b]	Grass hay
Energy	0.887	0.756	0.654	0.630	
Protein	0.094	0.172 (including non-protein nitrogen)	0.386	0.014	
Fiber	-	-	-	0.819	0.577
Oil	-	-	0.196		

a. Stover is assumed to displace corn and soybean meal.
b. Perennial grasses (switchgrass and miscanthus) are assumed to displace corn, soybean meal and fiber from grass hay.

Assumed animal feed production =1 kg/1 kg of stover, energy inputs for corn production is obtained from literature review and displacement ratios (for feed displaced) are calculated as stated previously. Similarly energy and emission credits were obtained for each lignocellulosic feedstock and included in NEY and NCER calculations.

Displacement ratios are based on direct substitution of un-pretreated feedstock for lack of actual data from animal feed trials (i.e. feeding animals with pre-treated lignocellulosic feedstock used in this study). However, AFEX^{TM} treated rice straw fed to dairy cows has shown higher neutral detergent fiber intake and milk yield [30]. Also, preliminary analysis has suggested that 100% of beef cattle nutritional requirements and up to 70% of dairy cattle nutritional requirements (along with a protein supplement and grain silage) can be met with by using AFEX™ treated animal feed depending on the age of the cattle [8, 31]. Until large-scale animal feed trials are conducted, these displacement ratios are assumed to be applicable. Animal feed is included in system boundaries of both processing systems (as were transportation and landscape values) since this is an integrated system-wide analysis. Although this does not affect comparative calculations in this case, it is possible in future analyses that only certain RBPDs send back animal feed to farms based on their location, feedstock type processed and technologies included, in which case results from comparative studies may vary.

Processing energy and emissions were obtained from the NREL/Dartmouth Aspen plus biorefinery model [8]. This is the principal simulation model for US cellulosic ethanol production in a centralized biorefinery. The model contains all the conversion processes for ethanol production namely feedstock handling, pretreatment, biological conversion (hydrolysis and fermentation), product recovery, utilities production, and waste treatment [32]. The RBPD energy and emissions were calculated by isolating processes applicable to the depots and scaling them to its lower capacity (compared to the fully integrated centralized biorefinery). Processes absent in the depots such as biological conversion and ethanol purification and recovery were excluded from the model. The process energy and emissions for densification were obtained from literature [33] for all 9 depots in the network except for the tenth one which is co-located with the biorefinery. While incorporating densification values from literature, it was ascertained that that the properties of pre-treated feedstock are compatible with the conditions required for densification [34] (densification details available in Table A5, Appendix A). Similarly, energy requirements and emissions generated during transportation of densified or non- densified feedstock were added to the distributed and centralized processing system, respectively, using literature data [33].

The energy and emission inputs and outputs from all the sources discussed above were aggregated and the NEY and NCER values were calculated for each cropping system, combined with distributed or centralized processing and their respective transportation information. Table 2.2 shows all the modules and inputs included in this LCA.

There are two chief assumptions in this study. Firstly, it is assumed that the distributed processing network taken as a whole is as energy self-sufficient as the centralized system.

Accordingly all the energy inputs for the distributed system are estimated as a direct scale-down of the integrated biorefinery model. This is true if lignin-rich process residues are burnt for electricity [32] or if other energy sources such as heat/electricity from thermochemical conversion or methane-rich biogas from anaerobic digestion of manure [35] are present in the distributed networks. Second, the transport differences between the two processing systems are accounted for in terms of transporting bales (where no densification is involved-in the centralized biorefinery nor in the tenth depot) versus pellets (where densification is present- in the 9 depots) for an average transportation radius of anywhere between 20 and 100 km for both processing systems as found in literature [33].

Table 2.2: Unit processes in the LCA and their energy inputs and emission outputs

System module	Input	Energy input and Emissions output per kg dry feedstock[a]. E= Energy (MJ), C = Emissions (kg CO_2 eq.)		
Feedstock production and harvest, animals	Energy for cultivation and harvest.	Cropping system[b]	E	C[d]
		Corn System[c]	4.274	-0.854
		Switchgrass	0.235	-0.916
		Miscanthus	0.176	-0.551
RBPD network	Processing energy	Process	E	C
		Single RBPD (excluding pelletization)	0.74	0.0001
		Pelletization	0.05	Negligible
Densified and non densified biomass transport	Transport energy		E	C
		Densified	0.2954	0.0233
		Non- densified	1.0434	0.06
Biorefinery	Processing energy	E =13.24, C =0.0018		

a. All values are based on kg dry feedstock and represent biomass derived only from the landscape area under consideration.
b. The values for cropping systems are entered as an average of all three configurations and for the perennial grasses as an average of high and low grass yields over all three configurations.
c. All values for combined cropping system of corn grain, stover and rye.
d. All emissions from crops are in terms of sequestered kg CO_2 equivalent and hence have a negative sign.

For the distributed processing network it is assumed that the transport distance between the farms and the depots is negligible compared to the transport distance of pellets from depots to the biorefinery. In the case of the centralized biorefinery it is assumed that all biomass is directly transported from the farms to the refinery in the form of conventional bales.

2.3. Results

2.3.1. Base case scenario

According to this analysis, Configuration 1, where 65% of the acreage was allotted to the corn system, with high grass yields (HG) has the greatest NEY because it exhibits the greatest total biomass production from all sources (grain, stover, rye and perennial grasses). Where the corn system dominates the acreage (for both low and high grass yields) the centralized processing system has a greater NEY than the distributed system (in Configuration 1). Rye and grain, which make up approximately 40% of total biomass in this configuration, are not densified prior to transport, thereby eliminating a primary advantage of the depots. As the acreage dedicated to the corn system gradually decreases and the total amount of densified biomass increases in Configurations 2 and 3 (with 85% and 100% of the entire acreage dedicated to perennial grasses respectively), the NEY of the distributed processing system surpasses that of the centralized system. On average, miscanthus has 15% and 56% greater NEY than the corn system and switchgrass respectively because of its greater biomass yield. The corn system on the other hand has 48% greater NEY than switchgrass since the combined biomass from the corn system is greater than that from switchgrass alone. Figure 2.4 shows the NEY of the two processing systems in different landscape configurations per unit land area.

Perennial grasses can contribute large quantities of soil organic matter over time because of their thick root masses and since they do not need to be replanted each year [36]. Moreover, no-till agricultural systems for corn also increase the amount of carbon stored in soil [37]. According to this analysis, switchgrass has the greatest potential for carbon sequestration among all the cropping systems. The corn system has a comparable carbon sequestration potential to switchgrass.

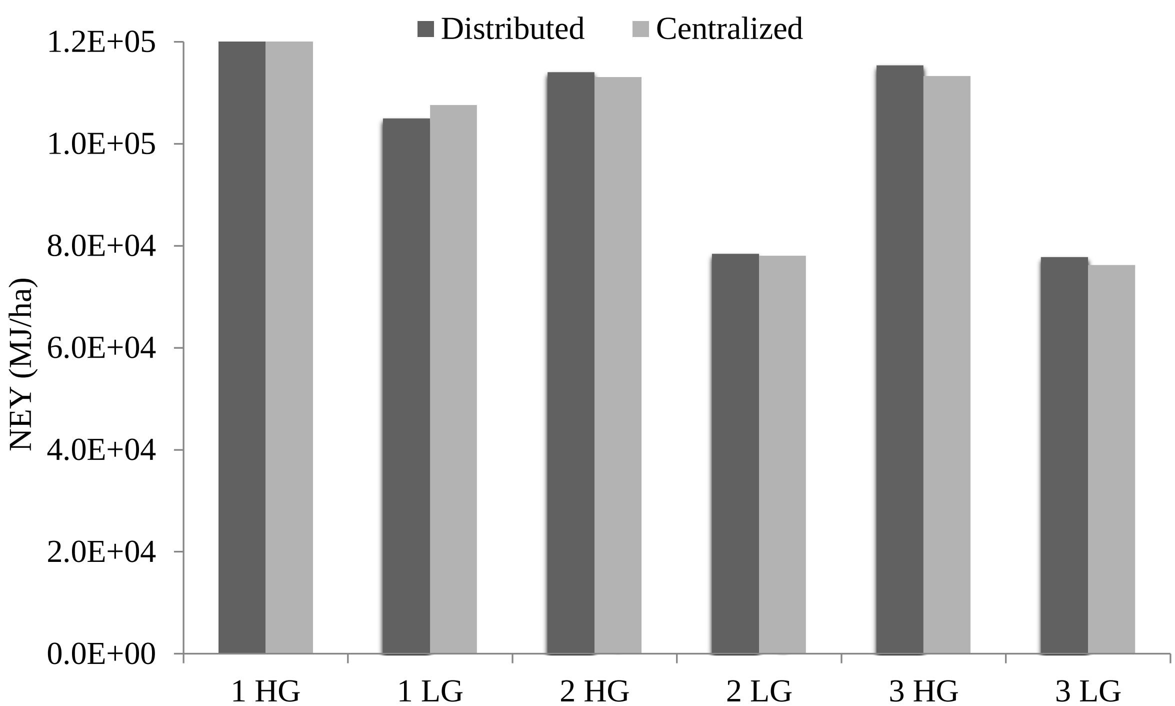


Figure 2.4: Net Energy Yield (NEY) per hectare of the collective system (landscape, transport, processing) in different configurations. The NEY (MJ) of the collective system comprises differences in energy inputs and outputs of each processing system (distributed or centralized) combined with crops and transport. HG represents high yields and LG represents low yields of the two perennial grasses

Switchgrass and the corn system both have about 30% greater sequestration potential than miscanthus on average for all configurations. Although both switchgrass and miscanthus are perennial grasses, their different sequestration potential is due to the differences in inputs and planting practices. Switchgrass and the corn-system are assumed to be cultivated using no-till whereas miscanthus is planted conventionally since it is a rhizome and must be propagated asexually [38]. Moreover, the carbon sequestration potential is related to yields because the total above-ground residue declines with decreasing yields. Consequently, the total residue contributing to soil organic matter increase decreases, thereby reducing carbon sequestration potential. This is the reason for differences in sequestration potential between low and high yielding grasses. It is to be noted that to calculate NCER due to gasoline displaced by ethanol for individual processing systems, a reasonable evaluation would be based on equivalent service provided by the two fuels; however this is a case of relative comparison between sequestration potentials of different cropping systems. Therefore as stated previously this “closed-system” assumption is valid because the land area remains constant in all configurations and a comparison is made within this land area between different cropping systems.

The NCER results for each configuration correspond to the sequestration potentials of each cropping system. The highest NCER occurs when the entire acreage is allotted to high yielding grasses (Configuration 3 HG) mainly because high yielding switchgrass is dominant in this configuration. In contrast, the lowest emission reduction occurs with all acreage allotted to low yielding grasses (in Configuration 3 LG). This is because the sequestration potential of the combined corn system is comparable to that of the grasses and at low yields the sequestration due to grasses does not exceed that of the corn system. Figure 2.5 shows the NCER of combined landscape and processing systems in different configurations per unit land area.

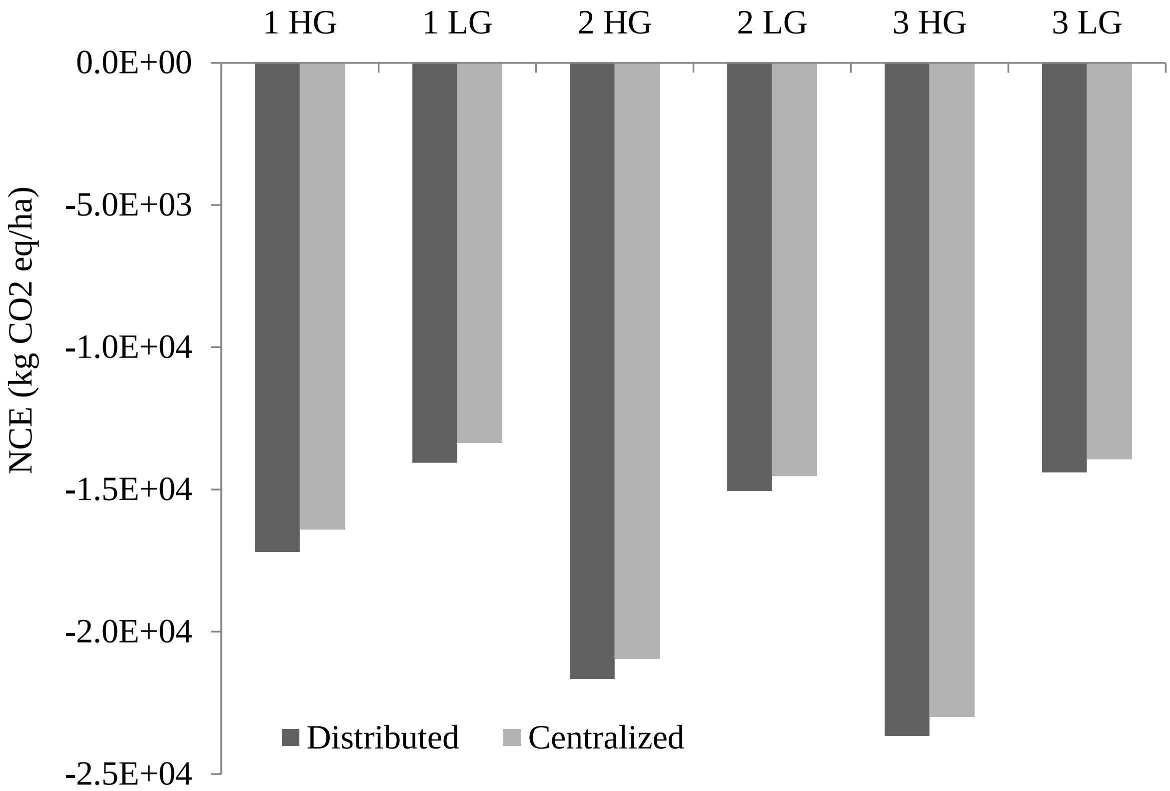


Figure 2.5: Net Carbon Emission Reductions (NCER) per hectare of the collective system (landscape, transport, processing) in different configurations. The NCER (kg CO_2 eq.) of the collective system comprises differences in GHG emissions generated by processing system (distributed or centralized) combined with transport, and animal operations and carbon sequestered by feedstocks. HG represents high yields and LG represents low yields of the two perennial grasses

2.3.2 Sensitivity Analysis

Sensitivity analyses were performed to identify significant system variables. Table 2.3 summarizes the results of variations in NEY and NCER between the two processing systems.

2.3.2.1 Densification

The base case scenario established the fact that pretreated perennial grass densification is a key contributor to the distributed processing network. Densification reduces both the environmental impacts and economic costs of transportation. Hence choosing the right densification method is essential. Three separate densification processes were considered in this sensitivity: briquettes**,** (“PAKs”) as produced by Federal Machine (Fargo, ND), pelletizing as performed as part of the Pro-Xan process on dehydrated alfalfa pellets and a ring-die densification process (see Table 2.3 for references). The energy requirements and emissions for these processes were incorporated into the distributed processing system calculations. The energy requirements for densification in these methods differ by 25, -67 and 78% respectively compared to base-case energy requirements for pelletization. The emissions generated are not significantly different compared to base-case.

The densification method can be a considerable source of variation in NEY as seen in Table 2.3 and causes small deviations in the NCER differences between the two processing systems. Selection of a densification method will depend largely on process economics.

2.3.2.2. Transport

The base-case scenario incorporated pelletized biomass transport energy and emission information obtained from the IBSAL model (Integrated Biomass Supply Analysis and Logistics) [41]. In this sensitivity analysis, we used transportation emissions and energy inputs for non-densified biomass from the GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) model for comparison. As seen in Sensitivity 1, using different methods of densification alters the NEY values of depots. Similarly, this sensitivity indirectly illustrates the variations in NEY and NCER when densification is not used in distributed processing networks.

Table 2.3: Data sources and results of sensitivity analyses

Parameter	References	%Δ NEY[a]	%Δ NCER[b]
S0- Base case	[33]	0.09	-3.7
S1,1- PAKs process	(DJ Marshall, 2010, Personal Communication)	2	-4.5
S1,2- Pelletization from Pro-Xan process	[9]	-5	-4.5
S1,3-Ring/Die process	[39]	34	-4.5
S2- Transport	[40]	10	0
S3- Credits for conversion to perennial grasses	-	0.05	-2.4
S4- Absence of double-crop	-	0.14	-3.6

a. Percentage difference in NEY (%Δ NEY) = $[((NEY_{cent} – NEY_{dist})/NEY_{cent})*100]$.
b. Percentage difference in NCER (%Δ NCER) = $[((NCER_{cent} – NCER_{dist})/NCER_{cent})*100]$

2.3.2.3. Credit for conversion to perennial grasses

Growing perennial grasses instead of annual crops on the same land area can result in environmental improvements. For example, eliminating annual cultivation and monocultures can benefit farmland biodiversity. Perennials can increase soil organic matter content thereby improving carbon sequestration and soil quality [23]. Moreover, energy inputs and maintenance costs of annual crops are higher than for perennial crops .The base-case scenario was based on the assumption of a “clean-slate land area” i.e. there were no crops present on the landscape prior to this analysis. It is also necessary to analyze possible changes resulting from land area conversions from existing agricultural system to perennial grasses [42]. Savings in energy inputs and carbon sequestration due to growing each perennial grass instead of the corn system were calculated. The corn system has greater energy inputs than both perennial grasses (Table 2.1, section 2.2); therefore an energy gain on an average of 2.7 MJ/ kg dry biomass and 2.3 MJ/ kg dry biomass is predicted for switchgrass and miscanthus respectively. In Configuration 3 where no corn system was initially present the same energy inputs as corn system in Configuration 1 were assumed. Carbon sequestration increases for all configurations except for miscanthus in Configuration 1. As mentioned in section 2.2.2 miscanthus has lower carbon sequestration benefits than the corn system because of different tillage practices. Therefore in Configuration 1 growing miscanthus instead of the corn system on the allotted acreage is unfavorable for sequestration. On average, carbon sequestration gains of 0.75 kg CO_2 eq / kg dry biomass and 0.36 kg CO_2 eq/ kg dry biomass are observed for switchgrass and miscanthus, respectively. The relative differences in NEY and NCER between the two processing systems are nearly the same (Table 2.3).

2.3.2.4. Absence of double crop

Double crops are attracting interest as a method to maintain or increase soil carbon content after harvesting agricultural residues, mainly corn stover [43, 44]. This is the primary reason for including the winter rye double crop in the base-case scenario. In this sensitivity, the double crop was removed from the corn system and this cropping system was reduced to only corn grain and stover production. Removing the double crop from the system, which undergoes densified transportation, has its primary negative effect on the NEY of the distributed processing system. The NCER values are practically unaltered.

Both sensitivity analyses 3 and 4 involve varying major components of the cropping system. These components are integral to emission reductions and contribute significantly to system energy consumption. Therefore it is important to assess individual variations in NEY and NCER compared to the base case (further discussed in Section 2.4) because the effects of these changes are not apparent in the relative differences between the two processing systems.

2.4. Conclusion

Based on this analysis, to achieve NEY and NCER objectives, the entire acreage should be dedicated to perennial grasses only when their yields are high. But when perennial grass yields are low, it is more advantageous to adopt a landscape configuration containing mostly perennial grasses but including some corn system acreage. The distributed processing system has consistently greater NEY and NCER than the centralized system when combined with perennial grasses. Additionally, different perennial grass yields change NEY values by 15 to 50% and NCER values by 20 to 65% in each configuration for both processing systems. On average, the distributed processing system has practically the same NEY as and a 3.7 % greater NCER than the centralized processing system.

This study also highlights the fact that distributed processing networks when combined with densified high yielding perennial grasses have consistently greater energy yields as well as larger emission reductions than centralized processing systems. Therefore dedicated energy feedstock landscapes (using perennial grasses) work best where grass yields are high and some form of densification is involved. However, if most feedstock is trucked as bales and if grass yields are low it is unlikely that the NEY of distributed processing systems will exceed that of centralized processing systems. Evaluating the impacts of landscape conversion from high-maintenance annuals to low-maintenance perennials is also important because of the reduced energy inputs and carbon sequestration benefits of the latter systems. For sensitivity analysis cases 3 and 4 it is more effective to look at the individual differences compared to the base case for NEY and NCER rather than examining relative differences in the two processing systems. The third sensitivity analyses (credit for conversion to perennial grasses) better highlights energy inputs and emission reductions due to growing perennial grasses instead of annuals if each processing system were evaluated individually. It emphasizes the importance of a detailed analysis to assess the energy and carbon sequestration characteristics of each cropping system. Evaluations compared to the base case showed increased NEY values ranging between 13 to 33% and increased NCER values ranging between 8 and 53% for the different configurations averaged over the two processing systems and low and high grass yield cases. Similarly, although in the fourth sensitivity analysis (absence of double crop) the relative differences in emissions and energy yields of the overall systems are nearly the same, individual evaluations averaged over the two processing systems and low and high grass yields shows decreased NEY values ranging from 8 to 22% and decreased NCER figures ranging between 5 and 21%. Analyses such as these can help determine the most sustainable land configurations within mixed feedstock landscapes in the RBPD context.

The economic performance of these depots is an important factor but is outside the scope of this analysis, nor do the data and tools used in this analysis permit the evaluation of other environmental impacts such as water quality or biodiversity. The conclusions from this study probably apply to systems containing similar combinations of crops and land areas. Landscapes with different soil conditions, cropping systems and yields will almost certainly require similar analyses. Hence further research using more advanced tools such as ArcGIS for landscape studies is underway. There is a necessity for the development of flexible models for sustainable landscape configurations combined with distributed processing based on varying yields, soil conditions, landscape sizes and processing technologies. Distributed processing networks using densified biomass may be able to catalyze the formation of commodity cellulosic biomass markets, thereby providing grower incentives and advancing biofuel production. Modeling the logistics and conversion technologies and performing integrated systems investigations is a stepping stone in the successful establishment of large-scale sustainable lignocellulosic biofuel industries.

APPENDIX A

2.5. Appendix A

A1. Crop inputs used in agricultural budget spreadsheets

Table A1. Corn grain and stover –inputs (all inputs for stover are same as that for corn)

Corn grain and stover	Quantity	Unit
% SOM	1.70	% SOM
SOM per Acre	3.E+04	lbs/ac
SOM Lost per year	1020	lbs/ac/yr
Corn Grain	106.64	bu
Biofuel Energy Component	298.592	gal/ac
Weight of Crop	5971.84	lbs/ac
Harvest Efficiency	0.50	
Shoot-to-Root Ratio	8.5	
Total Aboveground Biomass	11944	lbs/ac
Aboveground Residue	5972	lbs/ac
Belowground Residue	1405	lbs/ac
Total Residue	7377	lbs/ac
Residue Contribution to SOM	1475	lbs/ac
No-till or perennial crop SOM credit	15.00%	% SOM increase
Seed	0.24	units
	12	lbs/ac
N - NH3	31	lbs
Insecticides		

Table A1 (Cont'd)

Imidacloprid	0.32	oz
Herbicides		
Atrazine	0.5	qt
Glyphosate	12	oz
Drying	106.64	bu
Fuel, oil, lube	3.15	gal

Table A2. Winter rye inputs

Winter rye	**Quantity**	**Unit**
% SOM	1.70%	% SOM
SOM per Acre	3.E+04	lbs/ac
SOM Lost per year	1020	lbs/ac/yr
Biomass	2.5	ton
Biofuel Energy Component	180	gal/ac
Weight of Crop	5000	lbs/ac
Harvest Efficiency	0.95	
Shoot-to-Root Ratio	11.6	
Total Aboveground Biomass	5263	lbs/ac
Aboveground Residue	263	
Belowground Residue	454	lbs/ac
Total Residue	717	lbs/ac
Residue Contribution to SOM	143	lbs/ac

Table A2 (Cont'd)

No-till or perennial crop SOM credit	15.00%	SOM increase
Seed	2	bu
	90	lbs/ac
N - urea	60	lbs
Drying	89.3	bu
Fuel, oil, lube	1.63	gal

Table A3. Switchgrass inputs

Switchgrass	Quantity	Unit
% SOM	1.70%	% SOM
SOM per Acre	3.E+04	lbs/ac
SOM Lost per year	680	lbs/ac/yr
Biomass	10	ton
Biofuel Energy Component	720	gal/ac
Weight of Crop	20000	lbs/ac
Harvest Efficiency	0.80	
Shoot-to-Root Ratio	0.5	
Total Aboveground Biomass	25000	lbs/ac
Aboveground Residue	5000	
Belowground Residue	50000	lbs/ac
Total Residue	55000	lbs/ac
Residue Contribution to SOM	11000	lbs/ac
No-till or perennial crop SOM credit	15.00%	SOM increase

Table A3 (Cont'd)

Seed (1^{st} year only)	7	lbs
N - NH3	88	lbs
Atrazine	1.5	qt
Drying	333.33	bu
Fuel, oil, lube	9.1	gal

Table A4: Miscanthus inputs

Miscanthus	**Quantity**	**Unit**
% SOM	1.70%	% SOM
SOM per Acre	3.E+04	lbs/ac
SOM Lost per year	1020	lbs/ac/yr
Biomass	12	ton
Biofuel Energy Component	864	gal/ac
Weight of Crop	24000	lbs/ac
Harvest Efficiency	0.75	
Shoot-to-Root Ratio	1.2	
Total Aboveground Biomass	32000	lbs/ac
Aboveground Residue	8000	
Belowground Residue	27350	lbs/ac
Total Residue	35350	lbs/ac
Residue Contribution to SOM	7070	lbs/ac
No-till or perennial crop SOM credit	0.00%	SOM increase

Table A4 (Cont'd)

Root	4000	root
	40	lbs/ac
N - NH3	63	lbs
P_2O_5	41.2	lbs
K_2O	17.352	lbs
Drying	399.96	bu
Fuel, oil, lube	2.25	gal

A2. Densification

A typical pelleting operation of un-pretreated biomass consists of drying, size-reduction and compaction. In the case of pre-treated biomass, the feedstock will already have undergone preliminary size reduction and drying before pretreatment. The ground material is treated with super-heated steam at temperatures above 100°C before compaction. The superheated steam increases moisture and temperature of the mash causing the release and activation of the natural binders present in the biomass .In this study this is achieved by the use of AFEX™ pretreatment. The following table summarizes densification conditions and energy requirements [33, 34]:

Table A5: Values of parameters used in densification

Parameter	Values
Moisture content of incoming biomass	~10%
Energy requirement of processes (GJ/t)	
Drying Hammer mill (size reduction) Pellet mill Pellet cooler	0.35 0.1 0.268 0.013
Temperature of outgoing pellets before cooling	70-90 ^{o}C
Temperature of final pellets after cooling	Within 5 ^{o}C of ambient

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2.6. REFERENCES

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CHAPTER 3: ADVANCED REGIONAL BIOMASS PROCESSING DEPOTS - A KEY TO THE LOGISTICAL CHALLENGES OF THE CELLULOSIC BIOFUEL INDUSTRY

3.1. Introduction

3.1.1. Current biomass supply system: Problems and some prospective solutions

Biofuels are a near-term opportunity for the United States and the rest of the world to reduce or eliminate our reliance on petroleum for transportation. Currently, grain ethanol and oilseed biodiesel represent only a small fraction of United States transportation use, but the addition of cellulosic biofuels could greatly increase this fraction. The Energy Independence and Security Act of 2007, for example, mandates the production of 16 billion gallons of cellulosic ethanol by 2022. A shift from petroleum-based fuels to biofuels would be a tremendous undertaking, requiring hundreds of billions in investment and large shifts in land use. However, such a shift would produce substantial benefits in terms of economic stability, environmental sustainability, and national security.

Unfortunately, a paradigm shift to cellulosic biofuels is unlikely to occur unless several challenges can be met, including reconciling biofuels with food production, avoiding harmful land use changes, and assembling the supply chains. Some desirable characteristics of both feedstocks and feedstock supply chains are listed in Table 3.1.

In particular, the local economic and environmental sustainability of the supply system is vital in order to advance the farmers' interests. Appropriately priced, low supply risk feedstocks are needed to insure the growth of the nascent biofuel industry, as is the ability to inexpensively transport and store the biomass. Local economic and environmental concerns must be resolved in the feedstock supply chain, and diversifying the market for cellulosic feedstocks via valuable co-products would be advantageous as well. Unfortunately, not all of these properties are currently demonstrated by cellulosic feedstocks. A major purpose of this chapter is to demonstrate how low cost processing at the regional level can help cellulosic feedstocks more fully achieve these characteristics.

Table 3.1: List of desirable properties for both cellulosic feedstocks and supply chains

Desirable Cellulosic Feedstock Properties	Desirable Supply Chain Properties
Low cost	Low transportation cost
Price stability	Multiple markets available
Consistent composition	Uniform, consistent (commodity) feedstock
Easily stored	Provides local economic opportunities
Dense or easily densified	Satisfies local and global environmental criteria
Not competitive with food crops	
Potential for co-product generation	

The current paradigm for cellulosic biofuel production envisions large biorefineries (approximately 2000-5000 dry tons of feedstock per day) which are fully integrated, centralized facilities containing all biofuel conversion unit operations in a single location. Such facilities may be impractical from a logistical standpoint, as seen in Table 3.2. For example, a large scale biorefinery would require that one truck filled with biomass arrive every three minutes (for a full 24 hours per day), contract with thousands of farmers, and raise hundreds of millions of dollars to begin operations. The difficulties with this system are exacerbated by a short harvest season, requiring herbaceous biomass to be stored for months to insure a year-round biofuel production. In contrast, a much smaller facility might require relatively little investment and would be a simpler, more easily manageable operation. While there is substantial interest and investment to improve conversion technologies, supply chain challenges, which are further exacerbated by the low bulk density of feedstock, its compositional variability, and tendency to decompose, are largely unaddressed and unresolved.

Table 3.2: Comparison of logistics for a typical 5000 ton/day corn stover biorefinery vs. a 100 ton/day regional biomass processing depot (RBPD) in Iowa

	5000 t/d refinery	**100 t/d RBPD**
Collection radius	48.2 miles	6.8 miles
Frequency of trucks	1 truck/3 minutes	10 trucks per day
Farmers to contract with	3900	78
Storage footprint[a]	380 ha	7.6 ha
Capital cost[b]	$347 million	$3 million

The RBPD calculation was performed using US Census of Agriculture to assume average farm size of 276 acres, 38% of total land is in corn, and 4.6 tons/acre of corn stover are produced. Also assumes 35% corn stover removal and 60% of farmers participating.

a. Assumes 180 tons require 195 m^2 storage space for bales, and area open for access and machinery storage is equal to total storage space. A one year supply of corn stover must be stored in each location.
b. Cost of refinery determined from Laser et al. [1]. Cost of RBPD is an internal estimation.

One approach to help resolve these problems is to create satellite storage locations, satellite storage facilities, or satellite depots. These facilities are currently envisioned as transitory storage locations for square or round bales typically using standard farm equipment [2, 3] and sometimes including moderate processing, usually densification of biomass, before delivering biomass to the biorefinery [4]. As mentioned in Chapter 1, such depots are currently being used by the Tennessee Biomass Supply Co-operative (part of the University of Tennessee Biofuels Initiative) where these facilities perform functions such as aggregation, storage, pre-processing (size-reduction) and intermediate processing (densification) of switchgrass and corn cobs [5]. The preprocessed biomass is then sent to a cellulosic ethanol biorefinery operated by DuPont-Danisco Cellulosic Ethanol (DDCE) which can produce 250,000 gallons per year of ethanol. The Idaho National Laboratory (INL) bioenergy program is also focusing on developing an “advanced uniform format feedstock supply system” that attempts to imitate the current grain commodity supply system. The INL design proposes to locate specialized depots in regions to collect biomass with similar characteristics which is subsequently sent to and blended at a common shipping terminal to create a homogenized, consistent and stable commodity [6].

3.2. Regional Biomass Processing Depots

3.2.1. Decoupling pretreatment from biofuel production

While distributed storage and intermediate facilities in the biomass supply chain have been somewhat explored, this concept is explored further in this chapter by using distributed biomass pre-processing and pretreatment to bridge the gap between feedstock suppliers and biorefineries. These Regional Biomass Processing Depots (RBPDs) are in essence isolated preprocessing and pretreatment centers which, in their simplest configuration, produce pretreated and densified biomass. The biomass is then shipped directly to a local biorefinery or, alternatively, transported to a shipping terminal and sold to the global market.

A major objective of the RBPD network is to process and pretreat low density and often unstable biomass into stable, dense intermediate products compatible with current established commodity logistics systems, allowing the densified biomass to be transported economically over much longer distances. Various densification methods are available, such as pelletizing, briquetting, or cubing, which all have different capital and energy requirements. In general, a high bulk density (pelletization) requires higher energy costs, more unit operations, and more finely ground material than low bulk density material (cubing) [7]. Because biomass is naturally heterogeneous, different harvests of a particular species may have different physical properties that can impact biofuel production. Grinding, densifying, mixing, and storing the biomass produces a consistent product that can be supplied to biorefineries or other markets while standardizing the supply system schedule and logistics. RBPDs should provide relatively low capital cost processing to densify and stabilize heterogeneous feedstocks into more uniform, useful commodities. RBPDs would interact with local farmers and contract with them individually within certain regions, perhaps using the well-established mechanism of farmer cooperatives ("co-ops"). This co-op ownership model, in which the owners are the biomass suppliers themselves, including perhaps the local community, would help bolster rural job creation and income.

The RBPD concept can also be expanded to advanced configurations in which they provide intermediates and products beyond those required for biochemical and thermochemical biofuel production, such as higher value animal feeds, nutraceuticals, biocomposite materials, etc., thereby leveraging the capital and expertise of these well-established industries. Adopting RBPD systems that generate several products can potentially lead to greater per acre productivity and diminish concerns about direct and indirect land use change. Alfalfa, for example, can produce more protein per acre than soybeans, and extracted protein concentrates are similar in feed quality to soybean meal. Thus, alfalfa can conceptually replace soybean land, generating similar levels of protein while simultaneously producing fiber for biofuel production [8]. These advanced configurations could allocate biomass resources to their optimal final products. For example, in the "Biofuels Done Right" study [9] enhanced forage feeds for ruminant animals and leaf protein concentrate (LPC, an animal feed protein) production were combined with aggressive double cropping (planting a winter cover crop after corn or soybean harvest that can be harvested prior to the next year's planting) to maximize productivity on United States farmland. In this study, U.S. farmland was sufficient to displace 50% of current gasoline use while maintaining current food production, reducing U.S. annual carbon emissions by 10%, increasing soil fertility, and promoting biodiversity [9]. An RBPD could effectively produce the animal feed co-products while providing incentives to integrate unconventional cropping systems such as double cropping and dedicated energy crops into traditional corn/soybean production systems.

Figure 3.1 illustrates the advantages of the RBPD supply chain compared to more conventional supply chains. This figure shows three potential landscapes (A, B, and C) and the difference between a centralized refinery (bottom) and an RBPD network (top). By densifying the biomass close to the farm, the practical collection radius for bulky biomass decreases, decreasing transportation costs. This allows a refinery to collect biomass from a larger radius (landscape A), increasing the size of the refinery and thereby improving its ability to exploit economies of scale. Likewise, the ability to densify biomass near the feedstock source and to transport this densified biomass cheaply over long distances may allow biorefineries to be constructed in landscapes with limited biomass productivity (landscape B), where biomass transportation costs to a centralized biorefinery would otherwise be prohibitive. Finally, landscapes will likely contain a mixture of different feedstocks that would optimally be used for different products (landscape C). With a centralized system, it may not be economically feasible to allocate resources to different outputs, but instead allocate all biomass to a single product. However, flexible RBPDs might be able to upgrade the biomass into different intermediate commodity-like products, thereby allowing the optimal use of different feedstocks.

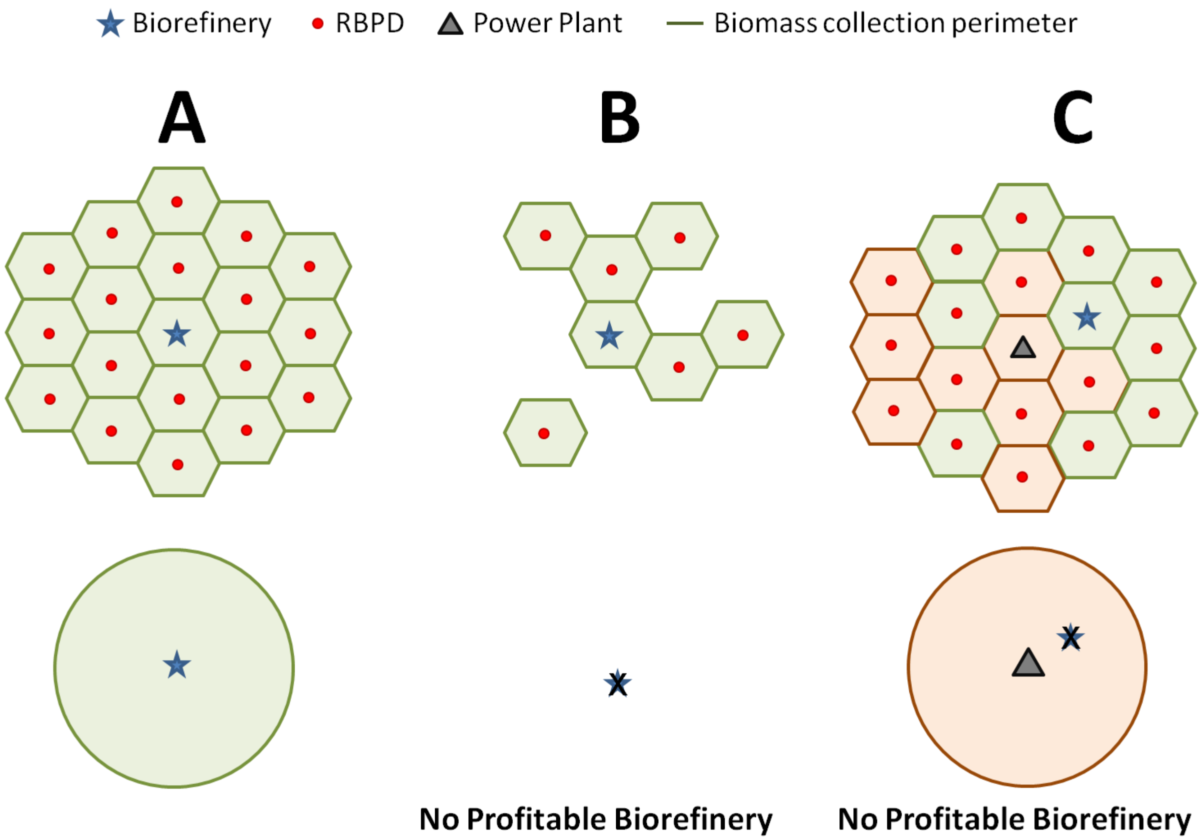

Figure 3.1: Comparison of potential RBPD systems (top) vs. no RBPDs (bottom). Advantages of RBPDs include **(A)** smaller collection radius for individual RBPDs combined with a larger total collection radius for the refinery, **(B)** individual RBPDs collecting enough biomass in marginal cropland areas in locations where a single biorefinery may not be profitable, and **(C)** allowing flexibility in feedstock allocation to multiple final locations, such as woody materials (brown) to a co-fired power plant while grass (green) is sent to a refinery.

3.2.2. Potential pretreatments for RBPDs

While traditional approaches to intermediate supply facilities may include densification, a key element of RBPDs as envisioned in this chapter is to include a chemical pretreatment as well. Pretreatment significantly alters the morphological structure of biomass while increasing the susceptibility of carbohydrate polymers to enzymatic attack. These changes can also be synergistic with the primary purposes of the RBPD, namely densifying and storing the biomass while producing valuable co-products. Ideally, a pretreatment operation at an RBPD would have a low capital cost, simple catalyst recovery, create few if any harmful degradation products, and produce a stable intermediate that could be upgraded to multiple products. Some potential pretreatments for herbaceous and woody materials include dilute acid, hot water [10], ammonia recycle percolation (ARP) [11], steam explosion, lime [12] and SPORL pretreatment [13].

Of particular interest is ammonia fiber expansion (AFEX™) pretreatment [14, 15]. In the AFEX™ process, hot concentrated anhydrous ammonia (temperatures of 70-200°C) is mixed with biomass under pressure (20-30 bar) for residence times of 15-30 minutes. Both ammonia and water loading range from 0.4-2.0 g/g dry feedstock. The pressure is then rapidly released causing the system to cool and the ammonia is recovered. During this reaction, recalcitrant lignin is depolymerized and some is relocated to the surface of the biomass, hemicellulose is hydrolyzed and cellulose is partially decrystallized, thereby making the sugars in the biomass more accessible to enzymatic breakdown. This reaction is performed under high solids loading (30-75% solids on a total weight basis) and produces no separate liquid phase while causing very little biomass degradation due to moderate conditions of temperature and pH.

AFEX™ pretreatment has several features that may make it almost uniquely suitable for RBPDs [16]. Since it is a relatively "dry" pretreatment, the resulting substrate is inert and stable. Some lignin, a natural adhesive, is removed to the surface of the biomass during AFEX™ and improves the binding properties of the biomass. This increases the ease of densification, eliminating the need to purchase binders or operate at high temperatures/pressures, thereby significantly reducing densification costs while simultaneously improving the transportation characteristics of pretreated biomass. AFEX™ can also add value to pretreated biomass as an animal feed by increasing the digestibility of fiber while simultaneously adding non-protein nitrogen in the form of acetamide. AFEX^{TM} treated corn stover and late-harvest switchgrass showed improved rumen digestibility by 52% and 128%, respectively over untreated material [17]. Also, preliminary analysis suggests that a very large fraction of both beef cattle and dairy cattle nutritional requirements can be met with AFEX^{TM} treated animal feed depending on the age of the cattle [18]. Thus, AFEX^{TM}-treated feedstocks might be viable alternatives to traditional forages and could help convert diverse biomass feedstocks into more uniform, salable commodities. The AFEX^{TM}-treated biomass could also be used for thermochemical conversion as a third potential market, although the additional cost might be problematic.

3.3. Discussion

3.3.1. Overcoming the challenges of an RBPD network

Despite the potential advantages of an RBPD network, several challenges to acceptance and eventual commercialization remain. These include compounded dry matter losses due to multiple storage locations and transport, potentially high energy costs of operations such as size reduction and densification, possible under-usage of equipment in each depot leading to capital cost intensification, and low total capacity leading to disadvantageous economies of scale.

Shrinkage, defined as dry matter losses between harvest and end use of the raw material, is a detriment to biomass refining and should be minimized. Shrinkage can occur through damaged bales, microbial contamination during wet storage conditions, or losses in pre-processing and transport. A stable, dry storage facility for bales can reduce losses due to moisture effects, but grinding biomass for densification can also cause shrinkage. Jannasch et al.

[19] reported losses up to 57% of dry matter during a test of grinding equipment, but noted that a system with the ability to recycle fines would expect only 5-10% losses. When combined with shrinkage from storage, a total of 10-15% of dry matter could be lost during the process, representing a significant loss of revenue.

In addition, grinding and densification can be costly steps in the process, both in terms of economics and energy requirements [20]. The cost of densification can be up to $25/Mg biomass, a cost which likely eliminates any savings in transportation costs. Such costs would probably not occur in an RBPD using AFEX™ due to the synergism between AFEX™ pretreatment and densification. Evidence suggests that particle size reduction is not beneficial to the effectiveness of AFEX™ treatment, and thus small particles are not required for downstream processing [21]. Furthermore, large particle sizes (>5 cm) are important for animal feed purposes, as large fibers are more effective at providing a rumen mat. Cattle feeding guides suggest that 75% of the fiber in the diet should be long pieces rather than ground particles [22]. Because of the improved binding characteristics of AFEX™ treated biomass, these larger particles can be easily compacted. Federal Machine (Fargo, ND) has successfully densified switchgrass and corn stover of up to 8 mm particle size into briquettes (called PAKs) with a bulk density of 330 kg/m [4]. Preliminary estimates suggest this process can be performed for approximately $5-10/Mg biomass (D Marshall, 2008, Personal Communication).

The added cost of densification is acceptable if it can abate both storage and transportation costs. Densifying biomass allows for more weight per truck, thereby decreasing the number of trucks required. Alternatively, RBPDs can be placed along rail lines, replacing road transportation from the RBPD to the refinery with cheaper rail transportation. Furthermore, storage of pellets or briquettes is simpler than storing bales. Vertical structures similar to grain storage tanks or silos can be used instead of horizontal bale storage options. A single storage tank (with a surface area of ~600 m^2) may hold over 5000 Mg of biomass briquettes, reducing the total storage footprint for a full size refinery by a factor of 20 (see Table 3.2), assuming a year's supply of biomass in reserve.

In order for an RBPD to be feasible, the overall capital cost must be low and the technologies used must be scalable to smaller capacities (e.g., 100-1000 Mg/day). AFEX™ pretreatment is generally considered to be cost competitive compared to other pretreatments [23] and the core processes are readily scalable. Much of the cost in AFEX™ pretreatment is due to the ammonia recycle system, and efforts are currently underway to design and validate ammonia recycling operations suitable for an RBPD setting.

Finally, the seasonality of feedstocks is another challenge involved in RBPD systems. Biomass harvesting is performed during a short window, forcing processing to be performed for only a few months out of the year while leaving the equipment idle for the rest of the year. For example, in an economic study of leaf protein production, the length of the processing season was a primary driver of profitability [24]. By creating a flexible RBPD network that can incorporate numerous feedstocks and processing technologies, the seasonality issue can perhaps be abated. Capital and overhead costs can be spread among multiple processes, and processing different feedstocks expands the available growing season. For example, double crops could be harvested and processed in the spring and summer, corn stover in autumn, switchgrasss in late autum and miscanthus in late winter.

By minimizing the challenges and potential costs associated with RBPDs, the added processes, energy costs, and complexity required by pretreatments might provide benefits beyond improved logistics. If densification can be performed cheaply and with low energy requirements, the transportation costs can be greatly reduced. As seen in the Chapter 2, a comparative life cycle assessment of an RBPD network (employing pretreatment and densification in all depots located away from biorefinery) vs. a centralized biorefinery showed that the RBPD network yields practically the same net energy while generating significantly lower greenhouse gas emissions compared to the centralized biorefinery in which all processing operations occur in one location [25]

3.3.2. Enhanced Depots: Multiple technologies

To further enhance the functionality and efficiency of the depots, the concept of "tailor-made" or enhanced depots is proposed: facilities that employ specific technologies that depend primarily on regional feedstock availability and biomass characteristics as well on synergies among these technologies. Figure 3.2 illustrates feedstocks and technologies that might be included in a depot and the various products and co-products that might be generated. It is unlikely that all depots will contain all technologies. The choice of appropriate technologies should be based on detailed system wide analyses starting at the landscape producing the feedstocks and going on through the exit of the biorefinery producing liquid biofuels and electricity.

The enhanced depots would likely process between 100 to 1000 dry tons per day of feedstock and should require a fairly low capital investment so that local ownership is facilitated. Feedstocks include agricultural residues (such as corn stover), grain/fiber mixes (such as corn silage), dedicated energy crops (mixed prairie grasses, switchgrass, and miscanthus), forages (alfalfa), and woody material (forestry waste, poplar). Utilizing many feedstocks can reduce risks for the depot network. Just as product diversification is important for the economic viability of the biorefinery, so is feedstock diversity in the upstream logistics systems.

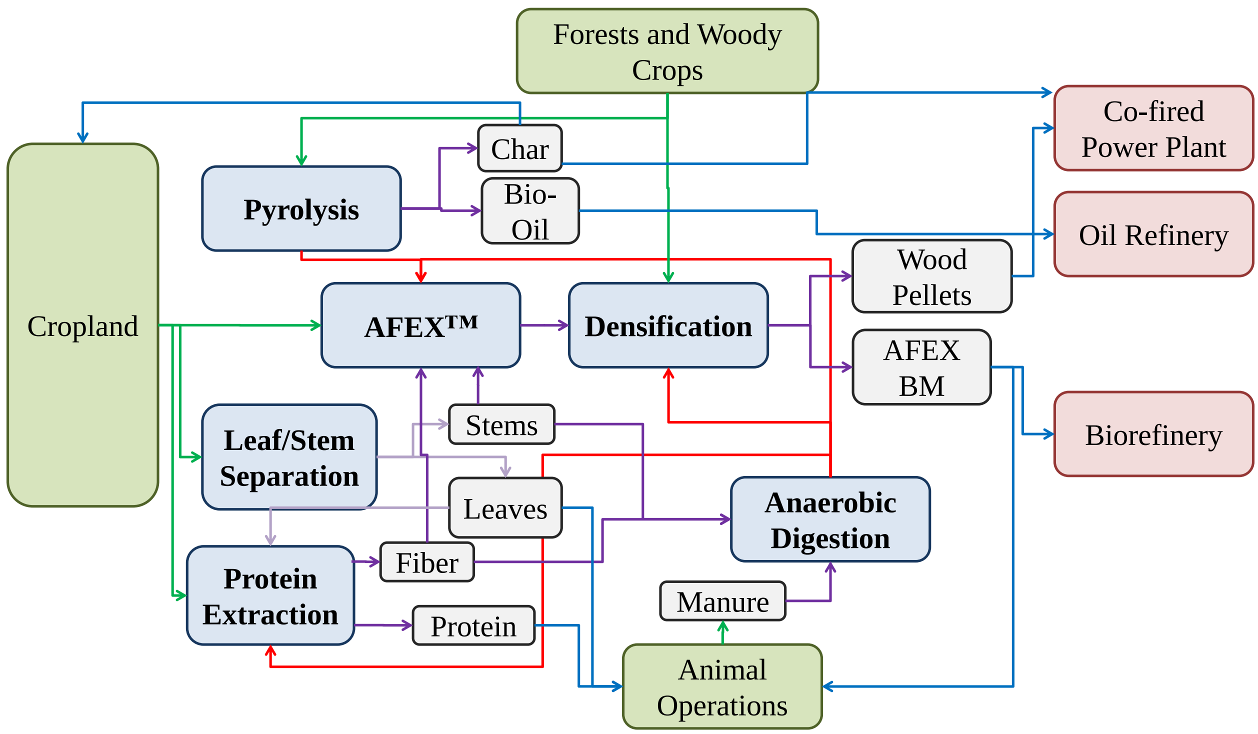

Figure 3.2: Process Flow Diagram of an RBPD with all technologies. Green squares represent the landscape, blue squares represent operations within the RBPD, gray squares represent products/intermediates, and red squares represent outside operations. Red arrows are energy flows, green arrows are feedstock flows, purple arrows are material flows within the refinery, and blue arrows are final products.

Two important technologies - AFEX^{TM} pretreatment and densification - were discussed in the previous sections in this chapter. Other relatively low capital cost technologies that might be included in the depots are as follows:

3.3.2.1. Leaf Protein Concentrate (LPC)

Forages such as alfalfa have the potential to produce more protein per hectare than soybeans, the primary source of protein meal in the United States. Unfortunately, the high fiber content of these forages make them unsuitable to swine and poultry diets unless the protein is separated to produce LPC. The industrial processes to manufacture LPC have been studied for decades but have not been widely adopted due to a short operating season and low value of the remaining fiber. By integrating this LPC process with other operations at an RBPD, both of these limitations might be significantly reduced. Alfalfa has been the usual feedstock for LPC technology, but the process can be applied to any high protein cellulosic biomass such as double crops and early season perennial grasses or grass/legume mixtures. The process involves pulping and pressing wet biomass to squeeze out a protein rich juice which is subsequently coagulated and dried to obtain a high protein powder [24]. The LPC extract is estimated to produce a profit of $27/Mg feedstock [26], potentially providing a valuable co-product to fiber processing.

3.3.2.2. Leaf/stem separation

This technology includes using simple gravity separation methods such as air-separation of heavier fractions (stem portions) from the lighter fractions (leaves). Techniques similar to “green leaf threshing” (GLT) in the tobacco industry will most likely be adopted [27]. The processed raw-material conditions in GLT are similar to those of feedstocks arriving from the farms to the depots, thereby making this technique potentially useful for leaf stem separation. Leaf stem separation can precede LPC extraction while the stems can be sent directly to pretreatment or other processing. Alternatively, the leaves can be fed directly to nonruminants, given that the leaves of forages tend to have 2-3 times greater protein content and 50% less fiber than the forage as a whole [28]. While the protein content remains low (28%), this could be a low capital cost alternative to LPC production. Feedstocks that might undergo this process include high protein forages such as alfalfa mixes, native prairie grasses and double crops.

3.3.3.3. Pyrolysis

This thermochemical conversion technique wherein biomass is broken down under anaerobic conditions can be applied to woody biomass and other highly recalcitrant feedstocks. Fast pyrolysis involves moderate temperatures (in the range of 500°C) and short residence times (in the order of seconds), producing 60-75% bio-oil, 12-20% biochar and 13-20% producer gas. Low process temperatures and long residence times (slow-pyrolysis) direct the reaction toward the production of biochar, whereas on the other extreme high temperatures coupled with long residence (gasification) times push the product distribution toward producer gas generation [29]. Producer gas can be used for process heat in the RBPD. Biochar (with its associated mineral content) can be sent back to farms as a soil-amendment, improving soil quality and decreasing overall carbon emissions. Field research and historical observations show that applying biochar to soil augments plant growth and reduces water runoff, soil erosion, and gaseous emissions from soil. Biochar can enhance the delivery of nutrients to crops and also improve physical and organic properties of soil. Even with high-input agriculture, application of biochar has shown to enhance fertilizer efficiency [30]. These features might make biochar an important co-product in the RBPD network. Biochar is a very stable compound with a high intrinsic energy value, and thus could also be combusted in a power plant or at the biorefinery to provide heat and power.

The liquid component of fast-pyrolysis, bio-oil, is a relatively unstable, viscous, and corrosive component that does not exist in thermodynamic equilibrium at storage temperatures.

It has high water and oxygen content leading to a low energy density. Bio-oil must be upgraded or "reformed" before it can be used as a blended additive in petroleum products or processed into valuable chemicals. Various hydro-deoxygenation, catalytic, emulsification and steam reforming processes can be applied to improve the properties of bio-oil [31]. The petroleum industry already possesses the expertise and equipment required to perform the upgrading process. Therefore bio-oil will in all likelihood be shipped to a petroleum refinery. A central question that might arise in the implementation of the pyrolysis technology in the RBPDs is whether it would be more favorable to optimize pyrolysis for bio-char production (slow-pyrolysis) vs. optimizing it for the bio-oil (fast pyrolysis). Furthermore, bio-oil would probably need to be stabilized at the facility, likely through the addition of hydrogen. Regardless, including pyrolysis in the depot network will probably benefit the system by helping to satisfy RBPD energy requirements, by providing valuable co-products, and by increasing feedstock flexibility.

3.3.3.4. Anaerobic digestion

Since the RBPD network is already coupled with agricultural and animal feeding operations, it is logical to maximize the raw materials available as feedstocks to the RBPDs and also to produce profitable co-products whenever possible. While RBPDs can send animal feed and biochar to the farms, they can also obtain manure from animal operations along with cellulosic biomass feedstocks. In an anaerobic digester, the manure is liquefied by bacteria and subsequently undergoes acidogenesis and methanogenesis to produce biogas which can be sold or used on-site at the RBPDs for heat [32]. The end product can be relatively easily separated after anaerobic digestion into solid and liquid fractions. The solid fraction may be used as recycled bedding for animals or applied to farm-lands to enhance soil properties. Since the animal feed is generated internally in the RBPD network, using manure in anaerobic digestion from the same animals tends to create a “closed-loop”, more sustainable system of industrial ecology in which wastes from one sub-system are used as raw-material for others.

3.4. Designing and implementing RBPDs

The technologies mentioned above are not meant to represent an exhaustive list. New technologies that are easily scaled to 100-1000 tons/day and are relatively low capital cost can also be included as these are developed. This includes further fractionating the biomass for higher value products (biochemicals, nutraceuticals, etc) as they become commercially viable. Likewise, the potential synergies and tradeoffs among all technologies must be determined in order to successfully establish these RBPDs. For example, lignin is relocated to the surface of the biomass during AFEX™ pretreatment, and a low cost lignin extraction might be performed to generate higher value products. If the lignin is removed, however, then it cannot be used as a binder during densification, thus requiring a redesign of the densification process. Alternatively, the anaerobic digester can also take in waste streams (for example, excess water from the leaf pulping process) as well as excess biomass that may not be suitable for other technologies to increase biogas production. Heat integration between technologies should reduce the heat demand for the overall process, and excess energy from pyrolysis and anaerobic digestion might also support the remaining technologies.

It is necessary to design these RBPDs at the correct scale and suite of technologies to adapt to the landscape surrounding it. Not all depots may operate at the same scale, nor will they all contain the same technologies. For example, if a certain region has a concentration of animal operations along with substantial land in forage, then a depot situated in this area might consist of LPC extraction, AFEX™ pretreatment, and densification, but not use fast pyrolysis. On the other hand, in regions containing only forest residues and marginal lands (where it is possible to grow low-maintenance perennial grasses), a depot consisting only of pretreatment, fast pyrolysis, and densification might be preferred. Proper locations for these RBPDs also must be considered. The sites would preferentially be located in or near rural communities, along a rail line if possible and potentially close to other industries to share heat needs. If a large animal feed operation is already present in the community, it may be advantageous to co-locate the RBPD there to share resources from manure or the sale of animal feed.

Implementing an RBPD network can also help solve the "chicken and egg" problem of establishing biomass production systems for a dedicated biorefinery. Early RBPDs can be focused primarily on providing animal feed or biomass for power production in a co-fired coal plant. Output would be scaled up as biorefineries are built. Because the biomass is densified, it can be transported long distances at relatively low cost. Thus, biorefineries will not necessarily need to secure all of their feedstock from the local area, and RBPDs do not necessarily need to be built around planned biorefineries. If so, this would allow the RBPD network to grow organically as the demand for lignocellulosic biomass increases. Alternatively, the RBPDs could be developed by the biorefinery owners as part of their supply chain. Such an approach would likely reduce the input from farmers and possibly reduce the economic value to the local community, it would ensure that RBPDs are built in the surrounding area and improve the supply chain for specific refineries. While this approach may be preferable in some instances, it would probably be more difficult to grow a commodity supply chain of pretreated lignocellulosic biomass from RBPDs controlled by the biofuel producers.

3.5. Conclusion

As cellulosic biofuel technologies improve, there will be increasing emphasis on commercial deployment of these technologies. Logistical and socio-economic challenges will then become increasingly important. Regional Biomass Processing Depots can help bridge the gap between rural concerns (rural economics, food security, environmental quality) and biorefinery supply concerns (steady supply, uniform feedstock properties, stable feedstock costs, and low transportation costs). By producing valuable co-products such as animal feed close to the farm level, the RBPDs can help satisfy local interests while simultaneously increasing the value and utility of cellulosic biomass feedstocks. Furthermore, RBPDs can also homogenize feedstocks and simplify the supply chain while reducing the overall risk to the biorefinery and spreading the capital costs of biofuel production over a greater number of interested participants. Developing flexible RBPDs into viable industries will help society achieve greater economic and environmental benefits from the nascent cellulosic biofuel industry.

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CHAPTER 4: LIFE CYCLE ASSESSMENT OF WATERSHED-SCALE CELLULOSIC FEEDSTOCK LANDSCAPES INTEGRATED WITH DISTRIBUTED PROCESSING

4.1. Introduction

The use of petroleum-derived fuels has created much wealth and societal progress over the past hundred plus years since these fuels became widely available. However, in recent decades petroleum use is increasingly problematic is terms of price and price volatility, national security and environmental issues. In order to mitigate these problems and diversify transportation fuels, alternatives to petroleum are being sought worldwide. Liquid fuel production from lignocellulosic feedstocks, an abundant and renewable resource, is one of the most attractive alternatives to continuing our near exclusive reliance on petroleum fuels for transportation.

However, the dominant existing conceptual model for cellulosic biofuel envisions large biorefineries processing thousands of tons of biomass a day. These fully integrated, centralized facilities contain all biofuel conversion unit operations in a single location. This model has severe logistical constraints as discussed in the previous chapters [1, 2]. As a possible solution to these logistical challenges, an alternative model is proposed in the form of advanced Local Biomass Processing Depots [LBPDs] (previously referred to as "Regional Biomass Processing Depots [2, 3]). These depots are decoupled pretreatment (for biochemical conversion of biomass to ethanol), storage and formatting facilities containing other potentially advantageous technologies to produce valuable end-products and co-products. A network of depots supplying large biorefineries will have much smaller biomass collection radii, simplified logistical arrangements, smaller biomass storage footprints and more tractable business arrangements (e.g. contracting with farmers) compared to fully integrated, centralized biorefineries. For example, a single small scale depot (100 dry tons per day (TPD)) will reduce the collection radius for biomass by a factor of 7 and will also reduce by a factor of 50 the number of farmers with whom contracts must be developed [2]. Furthermore, such a network of local depots also lends itself to local ownership and therefore increased potential for local economic benefits.

As discussed in Chapter 3, the "base-technologies" included in all depots are pretreatment and densification, including all pre-processing steps such as biomass handling, size-reduction, grinding, etc. The use of other technologies in the depots is dictated by the characteristics of the landscape generating the biomass. To summarize the potential technologies that may be included in depots: The Ammonia Fiber Expansion (AFEX™) process is a pretreatment method where hot concentrated ammonia is mixed with moistened herbaceous biomass under pressure. After the desired treatment time is complete, the pressure is then rapidly released causing the system to cool and the ammonia is recovered[4]. AFEX™ is used as the pretreatment method in all processing facilities because of its apparently unique suitability within the depot arrangement. AFEX™ adds value to biomass as a highly-digestible fiber-based animal feed, which is economically the most important co-product from the depots, and also improves the efficiency of the densification process following pretreatment [1, 2]. Mechanical compaction or densification of biomass into pellets or briquettes post-pretreatment can increase the bulk density of cellulosic feedstocks from as low as 60 kg/m^3 to as high as 800 kg/m^3, significantly reducing transport, handling and storage burdens associated with the depots [3, 5]. Coupling densification with AFEX™ pretreatment may also reduce the cost of densification because lignin brought to the surface during AFEX™ eliminates the need for added binders (e.g., starch or protein) to promote binding [1, 5, 6]. The Leaf Protein Concentrate (LPC) extraction process involves pulping and pressing wet biomass to squeeze out a protein rich juice which is subsequently coagulated and dried to obtain a high protein powder [7, 8]. LPC can be applied to any high protein cellulosic biomass such as double crops and forage[2] to obtain a high protein animal feed supplement. Pyrolysis is the thermochemical conversion of woody residues into biochar, producer gas and bio-oil. Producer gas can be combusted for process heat in the LBPD and bio-char is an important co-product that aids in soil amendment in the landscape[9]. Alternately, biochar can be used as a boiler fuel to substitute for coal[10]. Bio-oil however is an unstable compound that must be further processed for use as transport fuel[11]. In anaerobic digestion (AD) biogas is produced from manure and aqueous waste streams resulting from LPC production. Solids produced by AD are sent back to farms to use as animal bedding or as a soil amendment [12].

Not all depots necessarily contain all the other technologies in addition to the base-technologies of AFEX$^{\mathbf{TM}}$ pretreatment and densification. The depots can be imagined as "custom-made" facilities varying in capacity and operational characteristics as well as in the feedstocks processed and co-products produced, as dictated by the characteristics of the landscapes (e.g., largely agricultural landscapes vs. heavily forested ones).

In chapter 2, an LCA study was conducted to compare the current paradigm of a centralized biorefinery with the new concept of distributed biomass processing via depots [3]. This comparative LCA study was based on a small farm-scale landscape analysis but in more relevant scenarios, biomass for processing is procured from an aggregation of local farms. Therefore, the present study is based on seven digit watershed-scale landscapes. A group of 9 counties (Allegan, Barry, Branch, Calhoun, Cass, Eaton, Kalamazoo, St.Joseph and Van Buren) in South-west Michigan termed the "Regional Intensive Modeling Area" (RIMA-MI) was identified as a region of interest for modeling by in the Great Lakes Bioenergy Research Center [GLBRC [13]]. The total area of this RIMA is 1.38 million ha (2010 estimate) and it has a population of 0.89 million people (2010 estimate) [14]. The total harvested farmland area of the RIMA amounts to 0.54 million ha (2007 estimate) [15].The RIMA was divided into five 7-digit hydrologic unit code (HUC) watersheds (Upper Grand, Black-Macatawa, Kalamzoo, St.Joseph and Thornapple) encompassing all counties contained within the RIMA. Cellulosic feedstocks i.e. corn stover, forage (hay), switchgrass, miscanthus, native prairie and woody residues (woody residues are only available in limited areas) are assumed to be cultivated in this RIMA in four scenarios.

4.2. Structure and methods

The previous comparative LCA established that simple depots when combined with high yielding perennial grasses and densification return comparable or sometimes greater energy and environmental benefits compared to centralized systems. To better understand and assist the development of this novel logistical system, a comprehensive LCA is required. Hence, in this study the LCA of advanced depot configurations is combined with watershed scale landscapes (7-digit hydrologic unit code [HUC]).

4.2.1. Technologies in the processing system

For the distributed processing system module in this analysis, an in-house technical model [16] was developed to determine the processing energy required based on technologies included in each scenario. This model uses a combination of literature values and experimental results to form a basic material and energy balance around each unit operation. These balances determine the fossil fuel and raw material input required. Pyrolysis was included in only one advanced depot scenario and only in areas with relatively large forest cover. All processing energy inputs and emission outputs for reforming bio-oil into gasoline and diesel [17] and fossil fuel emissions displaced by bio-oil were included in the system boundary. As mentioned previously, bio-oil is an unstable compound that has to be reformed before it can be further converted into fuels. Just as distributed processing systems are being evaluated for bioethanol production so it is likely that supply chains be put in place for distributed bio-oil reforming [18] and that these facilities may be located in the vicinity of the biorefinery.

In the AD process, manure is procured from the animal operations within the landscape. Using manure as a raw material within the depots enhances system sustainability. Animal operations are already coupled with the depot network since animal feed is a principal co-product. One definition of an industrial ecology system states that it is: "a change from linear (open) processes to cyclical (closed) processes, so the waste from one industry is used as an input for another" [19]. Therefore, providing feed to and using wastes from animal operations creates a "closed-loop" or industrial ecology system in these distributed biofuel networks, potentially enhancing the overall system sustainability[2]. For the biorefinery module the processing energy for operation and energy gains due to electricity and ethanol produced were determined using the NREL/Dartmouth biorefinery model [20, 21].

4.2.2. Feedstocks

The RIMA-MI is principally agricultural with forested areas present in some portions of the more northern watersheds. The cellulosic feedstocks included in the study are agricultural residues (corn stover), perennial grasses (switchgrass and miscanthus), forage (alfalfa and grass hay), native prairie biomass and forest residue The agricultural residues and perennial grasses were chosen because of their relevance as primary feedstocks of interest in lignocellulosic biofuel production. Although low input high diversity (LIHD) native prairies do not yield large quantities of biomass, they are have attracted interest as potential lignocellulosic feedstocks because of their positive environmental effects and ability to generate biomass on abandoned/degraded land [22-24]. A recent study connected simplified landscapes with heightened pest infestations and insecticide use and concluded that perennial bioenergy crops such as switchgrass and mixed prairie can counterbalance these effects [25]. In a related study, it was found that diverse landscapes can promote better bio-control services, an important and beneficial ecological provision [26]. Hence the use of complex landscapes containing a mix of cellulosic feedstocks may have positive environmental benefits in areas such as biodiversity, habitat preservation and reduced chemical use. Non-cellulosic feedstocks (e.g. corn grain) are excluded from this analysis which focuses on lignocellulosic ethanol production. All associated burdens (crop energy input and environmental output) were split between corn and stover on a mass basis. Only the burdens of stover harvested were included in the system boundary. For example, for 40% stover harvest, only the energy inputs/emission outputs to generate this mass of stover were included in the system boundary.

4.2.3. Landscape system

Given the emerging importance of water use for bioenergy production [27, 28] and the centrality of watersheds in a plant based ecosystem; this analysis is based on watershed scales. The analysis is also structured in this way for other reasons a) Data availability- accessibility of data for land use, feedstock yields, transport network, etc. for real regions of interest from watershed-scale models, b) Ease of modeling- the data from these watershed models can be connected with other map manipulation and data analysis software to create a flexible analytical framework, c) Model validation [29]- an analysis on the similar scale provides an opportunity for comparison and data exchange between various ongoing biogeochemical studies involving the same region of interest, d) Impact assessment- environmental impacts such as nitrogen leaching and soil nitrogen losses and impact assessment. The U.S. EPA Better Assessment Science Integrating Point and Non-point Sources (BASINS) model [30], a multi-function open-source GIS based environmental assessment model was chosen as the tool to obtain data such as land availability and for identifying watersheds within the RIMA. This model contains 7-digit HUC watershed data required by our analysis, including as land-use categories and their respective areas (National Land Cover database), road network lengths, etc. BASINS is also easily adaptable to other geospatial reference software such as ArcGIS. Data for all five watersheds were obtained from BASINS and mapping projections and operations were performed in ArcGIS. Maps of different land uses in the watersheds thus obtained are shown in Appendix B. A watershed weightage factor method was developed to identify only watershed regions encompassing the nine counties in RIMA-MI and a geometric factor method (discussed in Appendix B) was established to apportion land areas to individual depots. Yields for available feedstocks were determined using National Agricultural Statistics Service (NASS) data (Table B1 in Appendix B). Yields of currently unavailable feedstocks (Table B2 in Appendix B) and energy inputs for all feedstock operations were determined from extensive literature review.

4.2.4. Life Cycle Assessment

The functional unit in this analysis is one hectare of the RIMA-MI land area. LBPD-biorefinery distances were determined by combining the road network map in the US EPA Basins model with the Arc GIS software to calculate the shortest routes from each LBPD to the central biorefinery. Using this method the processing depots and central refinery were located within the RIMA-MI. Distances of transport (collection areas and radii) of raw materials (herbaceous feedstocks, animal manure and forest slash where applicable) to LBPDs and co-products (pretreated animal feed, LPC solids, AD sludge and biochar where applicable) from LBPDs back to farms were determined using formulae from the literature (Appendix B). Transport distances for finished products (pretreated biomass to biorefinery and bio-oil where applicable) were determined using the US EPA BASINS and Arc GIS softwares. Using these distances (as seen in Table 4.2) and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model [31] for both densified and non-densified transport where applicable, transport emissions were calculated. It was assumed that animal farming operations were located conjointly with feedstock cultivation operations and therefore the same distances were used for transport of all relevant co-products back to these animal farms.

The amount of animal feed returned and number of animals in the system were determined based on forage displaced from the original land area in each scenario. The amount of pretreated animal feed sent back is determined based on its nutritional value (total digestible nutrients [TDN] and protein content) compared to the nutritional value of alfalfa [3]. Only animals that consume this pretreated animal feed are considered to be within system boundary of the LCA and only the manure generated by these animals is considered to be sent to the depots for biogas production.

Methane emissions (converted to CO_2 equivalent emissions) from only the animals within the system boundary are included in the net greenhouse gas emission calculations. Co-product credits for all animal related co-products based on nutritional values were calculated using the displacement method and the general formula [3]:

Co-product credit (for y displacing x) = [animal feed production (kg feed/kg y)*(Kg x displaced/kg animal feed)]* [x production energy] (MJ/kg x)

Where y is the new animal feed product namely pretreated stover, perennial grasses or LPC extract from double crop and x is the original animal feed product being displaced (corn grain and soybean protein and forage). For biochar in scenario 3, the environmental co-product credits were calculated based on the avoided emissions from fertilizers [9, 32]. The heat and electricity burdens of the biorefinery were allocated to each LBPD based on the amount of pretreated biomass sent to the biorefinery from that particular LBPD. Similarly, the energy output from the biorefinery was allocated to each LBPD based on the pretreated biomass it provided to the biorefinery. The data from various system modules were consolidated and a life cycle assessment was conducted for the combined landscape-transport-processing system to determine NEG and NCER for the overall system.

Table 4.1: Scenario description- Reconfiguration of RIMA-MI land area and technologies used in each scenario

Scenario Number (S)	**1**	**2a**	**2b**	**3**
Technology suite	*Base*[a]*+AD*[b]	*Base+AD+LPC*[c]	*Base+AD+LPC*	*Base+AD+LPC+ pyrolysis (in forested region depots)*
Corn stover	40% harvested[d]	40% harvested	40% harvested	50% land converted to perennial grasses, 60% of remaining stover harvest
Forage	25% harvested	50% land converted to perennial grasses	50% land converted to perennial grasses, 25% of remaining forage harvested	100% land converted to perennial grasses
Perennial grasses (switchgrass & miscanthus)	-	Grown on 50% of converted forage land and on all marginal land	Grown on 50% of converted forage land and on all marginal land	Grown on 100% of converted forage land and on 50% of marginal land

Table 4.1 (Cont'd)

Winter rye (double crop)	-	Grown on 30% of corn land	Grown on 30% of corn land	Grown on 75% of corn land not converted to perennial grasses
Native prairie	-	-	-	Grown on 50% of marginal land
Woody residue	-	-	-	Obtained from major forested watersheds

a. Base stands for AFEX^{TM} and densification technologies
b. AD stands for Anaerobic digestion
c. LPC stands for leaf protein concentrate extraction
d. In the corn stover row, % indicates percent of total corn land considered in RIMA-MI. ^ In the forage row, % indicates percent of total forage land considered in RIMA-MI
e. Marginal lands are defined as land not being used to grow commercial or conventional crops that may be capable of growing low-maintenance, low-input biomass feedstocks such as perennial grasses [3] as determined from BASINS as "transitional lands"

Table 4.2: Transportation distances of feedstocks, raw-material and co-products

LBPD no.	Distance from feedstock and animal farms to LBPD and vice-versa (mi)				Distance from LBPD to biorefinery (mi)
	S1	**S2a**	**S2b**	**S3**	**S1, S2a, S2b, S3**
1	21.53	13.78	13.24	20.09	51
2	25.58	15.88	15.17	23.19	36
3	25.58	15.88	15.17	23.19	37
4	25.58	15.88	15.17	23.19	68
5	12.83	8.88	8.58	12.66	48

Table 4.2 (Cont'd)

6	12.83	8.88	8.58	12.66	34
7[a]	21.53	13.78	13.24	20.09	-

a. LBPD 7 does not generate animal feed nor does it use manure or generate AD solids as it is co-located with the central biorefinery.

4.3. Results and discussion

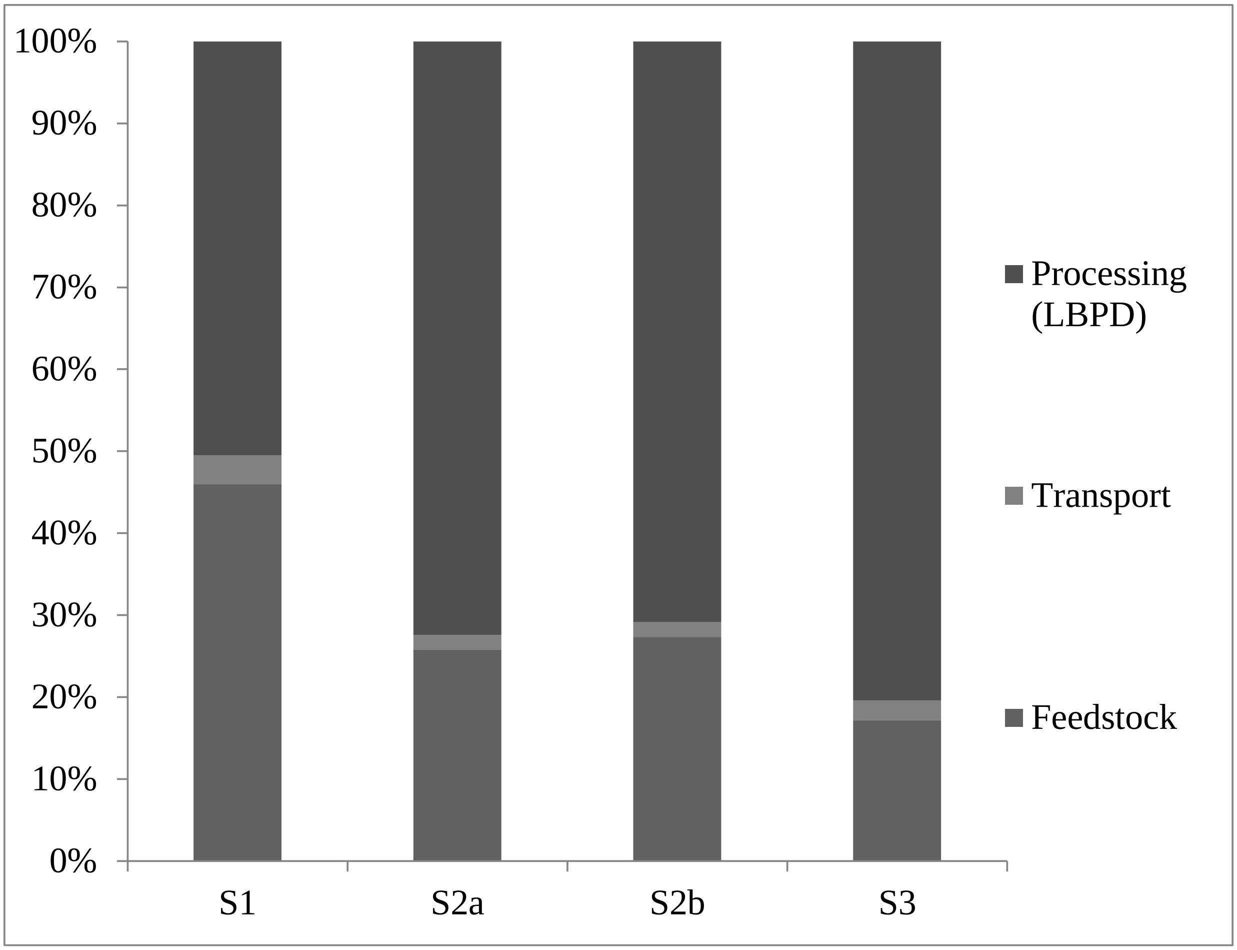
4.3.1. Base case

The current situation (or base case) was assumed to produce no cellulosic biofuels. Then the land use was repurposed or reconfigured to produce feedstocks for cellulosic biofuel production. Scenarios were formulated starting from a base reconfiguration in scenario 1 (or S1) which utilizes some corn stover and forage; to intermediate configurations in scenarios 2a and 2b (or S2a, S2b) which make use of perennial grasses and marginal lands; to an advanced configuration in scenario 3 (or S3) which employs the most land efficient techniques and new biomass feedstocks. Table 4.1 summarizes these scenarios, land area reconfigurations and also shows that the technologies included are directly dependent on the RIMA configuration, starting from the base technologies and subsequently incorporating other technologies previously discussed. Varying amounts of alfalfa hay, an important dairy cattle feed [33], are taken out of the landscape and sent to processing instead of being used as animal feed in each scenario. Twenty five percent of current-situation (or base-line) forage in S1, 50% in S2a, 75% in S2b and 100% in S3 is sent to processing in the LBPDs and is replaced with an equivalent amount of pretreated biomass based on its nutritional value[3]. Henceforth any reference to the landscape implies that animal operations are included within the landscape. Forage land was converted to higher yielding perennial grasses in S2 and S3 in increasing amounts. Among perennial grasses there was a 50%-50% distribution of land area between switchgrass and miscanthus. Restored prairies were grown only on marginal lands in scenario 3 since they have low yields but also low inputs.

More land is brought into production and used more efficiently in S3 by using more forage land (after converting it to perennial grasses), more double cropping, use of marginal lands and woodlands. Energy and emission inputs and outputs from all modules namely landscape, processing and transport were consolidated in a life cycle assessment to determine energy and (some) environmental impacts of the overall system.

4.3.2. Base case results

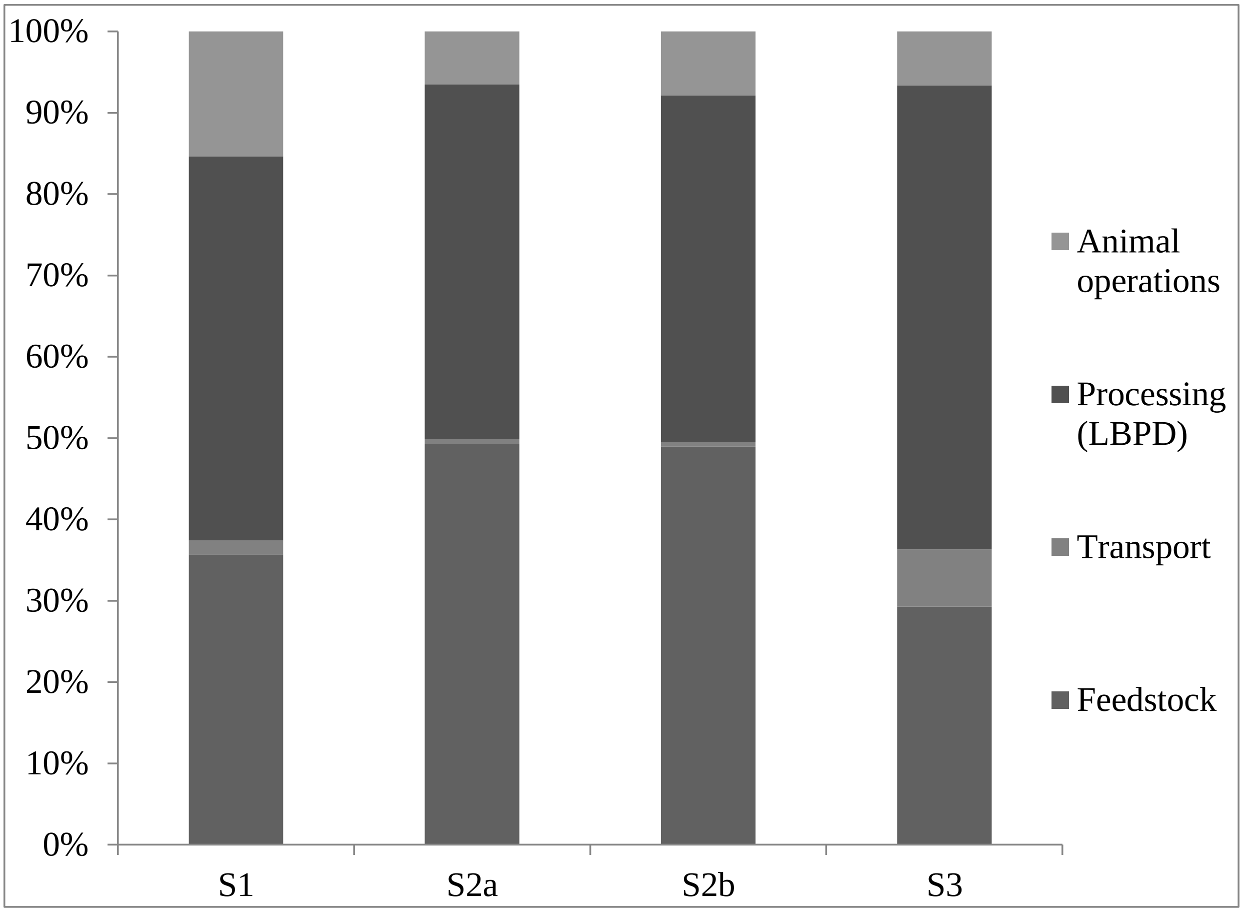
Figure 4.1 a, b shows the energy input and emission output burdens of the different system modules. Appendix B contains absolute energy and emission burdens. Feedstock production constitutes a large portion of overall energy burdens in scenario 1 due to the inclusion of more energy intensive and less energy dense feedstocks (corn stover and forage) with lower average yields. In scenario 3, including multiple processing technologies leads to greater processing energy burdens generated in the LBPDs. In the LBPD processing module, the AFEX™ process was found to have the largest energy requirement among all technologies in the LBPDs per ton of biomass processed since it has a substantial natural gas requirement for ammonia recovery.



(a)

Figure 4.1: (a) Energy burdens of system modules, percent of total **(b)** CO_2 eq. GHG emission burdens of system modules, percent of total

Figure 4.1 (Cont'd)



(b)

Biorefinery processing inputs and emissions amount to zero since all its requirements are covered by burning lignin to produce steam and electricity. The contribution of transport emissions to total emissions increases in S3 because of extra transport burdens due to woody residues and multiple co-products.

The total production of biomass per acre of the RIMA-MI increases substantially in the more complex scenarios (S2, S3) by utilizing previously unused or under-used land areas and by implementing land management techniques such as the use of double crops (e.g.; winter rye). In this analysis the "biomass multiplier" is defined as the ratio of total cellulosic biomass used in each scenario to the cellulosic biomass currently generated in the RIMA (i.e. total forage land yield). The denominator in the biomass multiplier ratio includes only forage (which is currently used as animal feed), since no stover is currently harvested in RIMA-MI for the purposes of either biofuel production or as a co-product (animal feed) and advanced cellulosic feedstocks do not yet exist in the RIMA. With each intensification in the RIMA-MI reconfiguration, biomass multipliers change from as low as 1.7 in scenario 1 to 11.7 in scenario 3. Potential usable land area in the RIMA-MI includes the sum of all corn and forage land, all forested areas and transitional lands. This amounts to only 21% in S1 and about 73% in S3. There is a 27% land area that is unused which can also potentially be used for biofuel production but was not considered in this study. Figure 4.2 a) shows the distribution of land area to different feedstocks and the biomass multiplier. Figure 4.3 a) shows LBPD profiles for net energy gain (NEG) and Figure 4.3 b shows carbon emission reductions (NCER) on a functional unit basis (one hectare of RIMA-MI land area). NEG is defined as the difference between all renewable energy outputs from ethanol and electricity produced by the system and the fossil energy inputs into agriculture, transport and processing. NCER is defined as the difference between carbon sequestration potential of the feedstock system and all emissions from harvest, transport and processing systems. Carbon "sequestration" potential includes gasoline displaced by ethanol, soil nitrous oxide emissions as well as gain or loss of soil organic matter. Because of the improved efficiency with which the RIMA land area is used, NEG is increased by 88% and NCER is increased by 68% in S3 relative to S1.

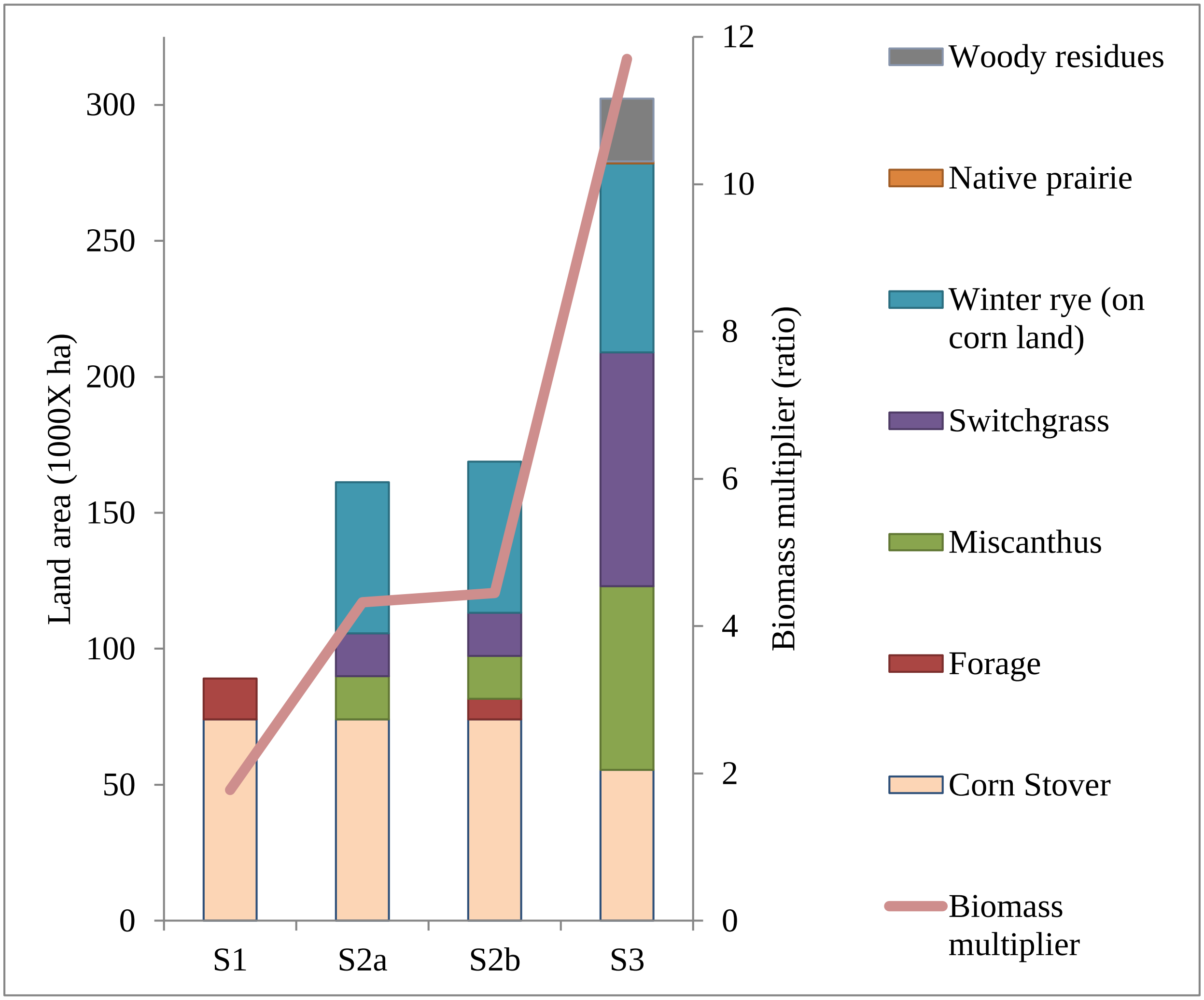
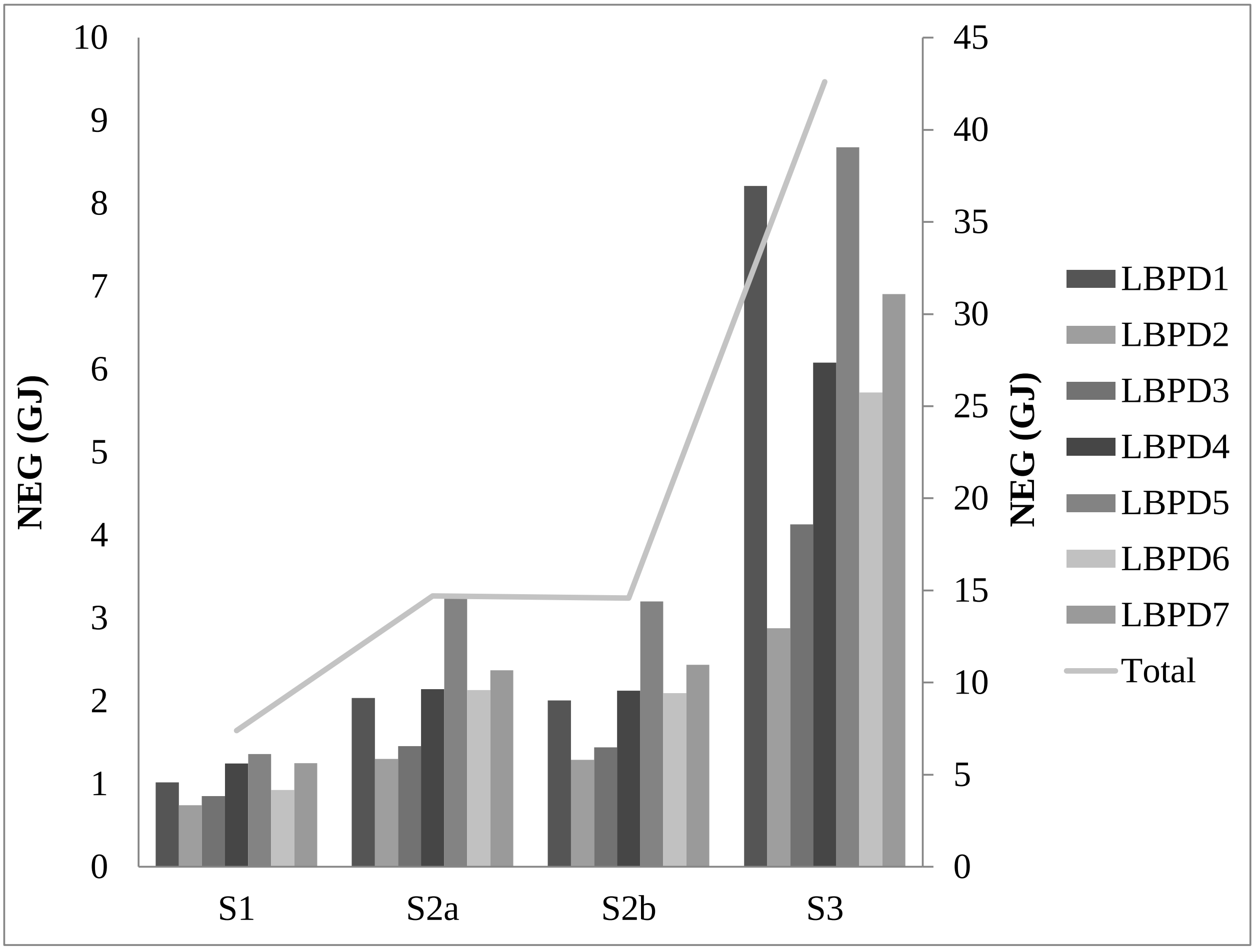


Figure 4.2: Land area distribution of different feedstocks and biomass multiplier.

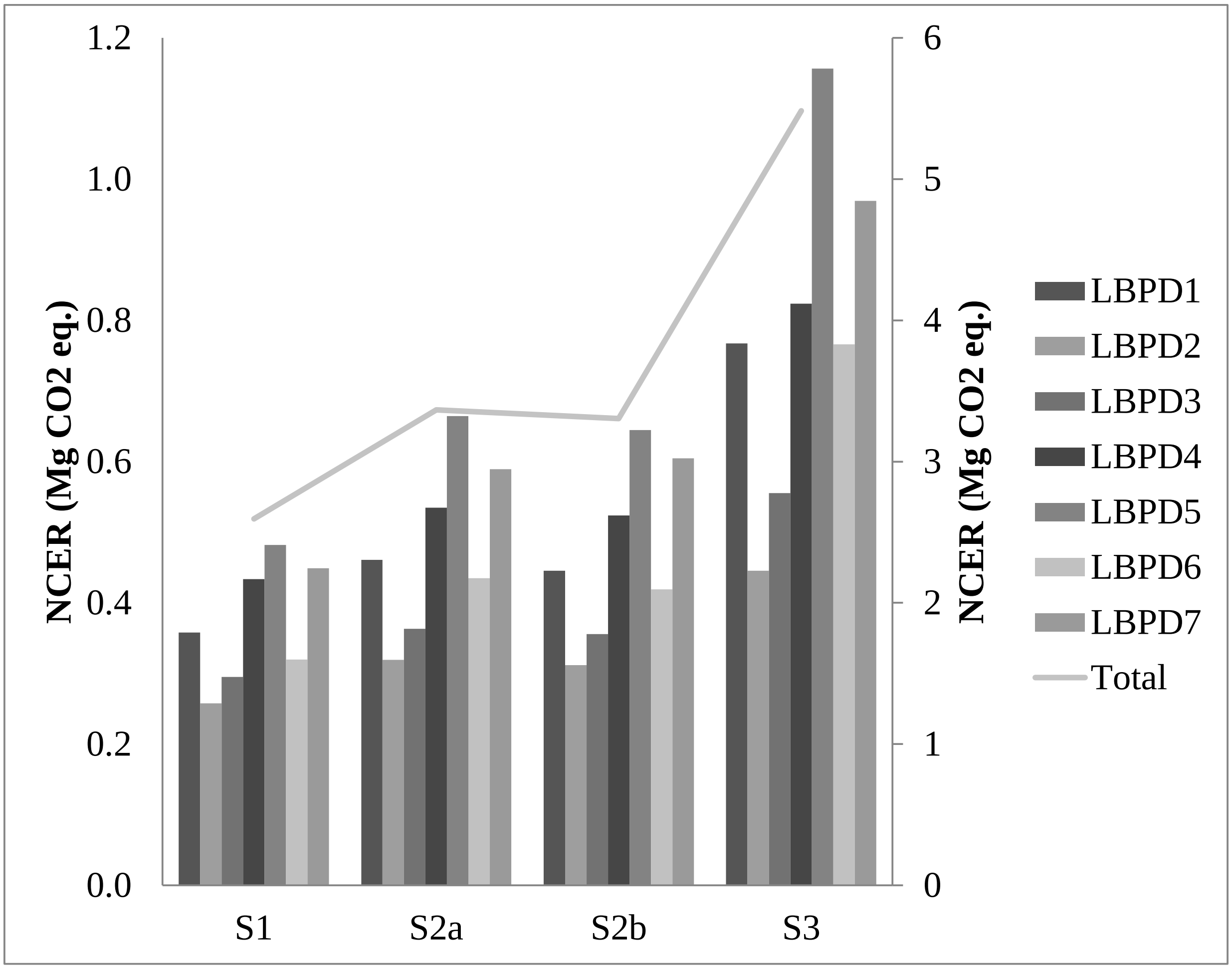
Figure 4.4 shows the watershed-profiles nitrate (NO_3-) leaching within the feedstock landscapes on both the functional unit basis and also on the amount of ethanol generated in each scenario. A 45% increase in nitrate leaching is observed on average from S1 to S3 on a RIMA land area basis due to large acreages of land being dedicated to grow (fertilized) perennial grasses (perennial grasses have nitrate leaching values comparable to a corn-cover crop system with no-tillage as simulated by the Daycent model [34]).



(a)

Figure 4.3: (a) Net energy gain [NEG]- LBPD profiles and averages **(b)** Net carbon emission reductions [NCER] - LBPD profiles and averages. The base-case for these values is set on the vertical line at zero.

Figure 4.3 (Cont'd)



(b)

However, based on per unit ethanol production, S3 has the least nitrate leaching impact due to greater amounts of ethanol produced in this scenario. Overall, NEG and NCER are both greatest in the scenario in which the land area is used most effectively and a large amount of perennial grasses and native prairies are cultivated (scenario 3). Various sensitivity analyses were performed on scenario 3 to determine the most significant parameters affecting NEG and NCER. The biofuel production rate from each scenario is 2037, 2676, 2555 and 3869 liters/ ha in S1, S2a, S2b and S3 respectively. These values are calculated based on the amount of ethanol produced from the biomass sent to the biorefinery in each scenario and on the total RIMA land area used in each scenario.

The Energy Independence and Security Act [EISA] of 2007 [35] mandates the production of 16 billion gallons of cellulosic biofuels by 2022. With the ethanol production rate of S3, it is possible to generate this amount of ethanol using about 16 million hectares of land. This amounts to approximately 14% of US cropland currently being used to produce animal feed, corn ethanol and exports [36], while still providing the same amount of animal feed. All displaced animal calorie and protein requirements are replaced and by producing animal feed in addition to renewable fuel from the same land area, indirect land use change (ILUC) effects are avoided[37, 38]. With 6 Mg/ha NCER predicted in scenario 3, 16 million hectares of land area can act as a sink for 96 Tg of CO_2 eq. emissions annually. This amounts to approximately 2% of the total annual GHG emissions of the U.S. [39] (this is the extrapolated total CO_2 eq. emissions sink after reconfiguring the land area of 16 million ha as in scenario 3. The base-line in this study is "no cellulosic biofuel production"; therefore the assumption is that currently this land does not act as a sink for CO_2 eq. emissions from a cellulosic biofuels production perspective). In addition the EISA regulates the use of feedstocks expected to have minimal land use change impacts and those that do not adversely affect food production such as residues, cover crops or perennial grasses. As mentioned previously, this constraint is thoroughly satisfied within the scenarios analyzed here.

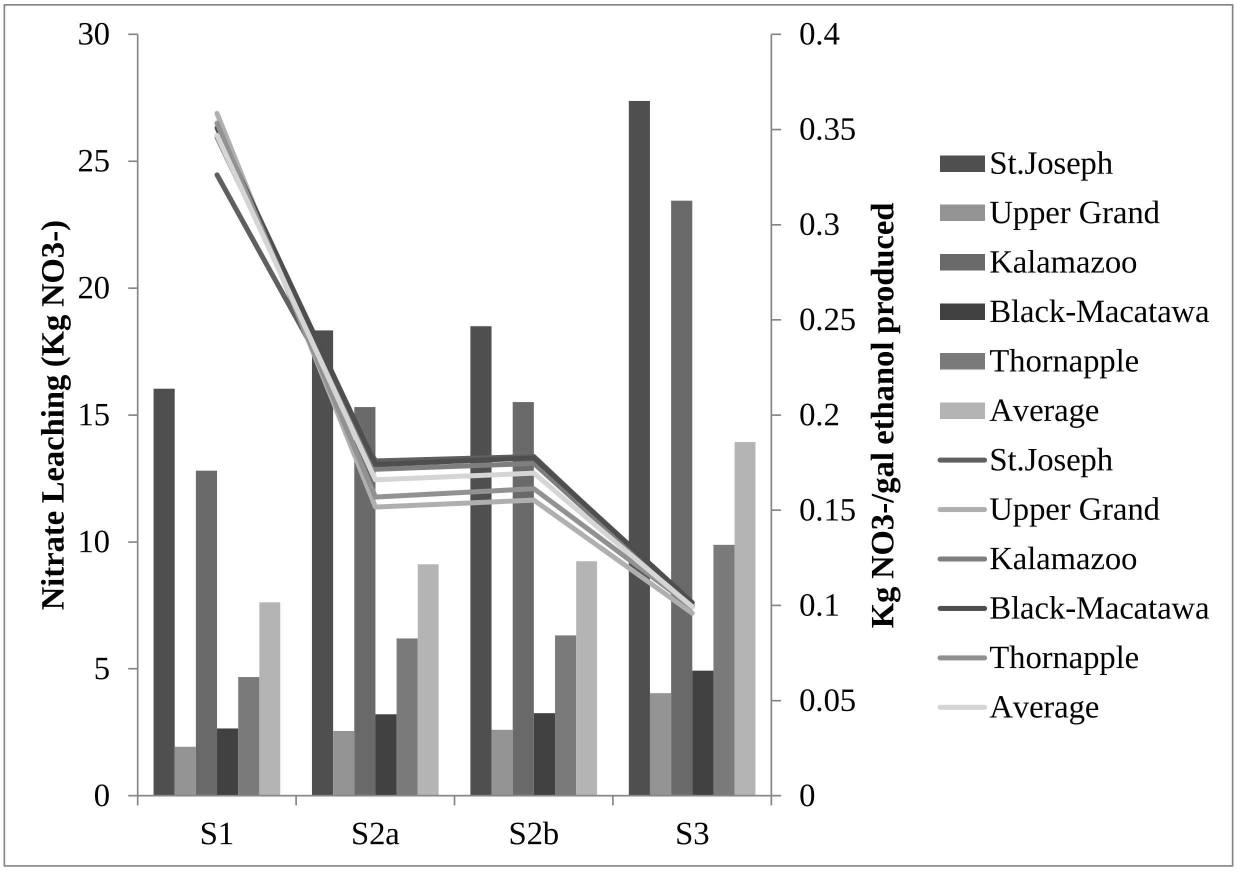


Figure 4.4: Soil N_2O loss and NO_3- leaching (based on functional unit [RIMA-MI land area] and on unit ethanol production) - watershed profiles and averages.

4.3.3. Sensitivity analyses

Scenario 3 offers the best results for energy gains as well as for emission reductions. Moreover, this scenario contains all representative technologies in a majority of the depots. Therefore S3 was chosen as the base case from which to perform several sensitivity analyses. The most important sensitivity analyses included: A) Varying feedstock cultivation and harvest energy inputs and emission outputs by +/- 25%. B) Varying feedstock yields by +/-25%. C) Varying AFEX^{TM} process energy by +/-25%. D) Using corn stover cultivation inputs from the GREET model to evaluate the effect of allocation (of inputs between corn grain and stover) on system results. E) Optimizing the pyrolysis process for bio-char production rather than bio-oil production. One question that arises during the development of the LBPD model employing the pyrolysis process was whether it would be more favorable to optimize pyrolysis for bio-char production vs. for bio-oil production. In the original scenario 3 the pyrolysis process in the LBPD technological model is optimized to produce more bio-oil in order to meet the renewable liquid biofuel goal.

Differences in results of sensitivity analyses compared to the base case were calculated as: $\Delta NEG = ((NEG_{sensitivity\ S3} - NEG_{base\text{-}case\ S3}) / NEG_{sensitivity\ S3})*100$,

$\Delta NCER = ((NCER_{sensitivity\ S3} - NCER_{base\text{-}case\ S3}) / NCER_{sensitivity\ S3})*100$

4.3.4. Sensitivity analyses results

Variations in feedstock yields have the largest effect on NEG (ΔNEG=-33 to +20 %) and NCER (ΔNCER= +/-9%) whereas the other parameters do not seem to significantly impact the system as seen in Figure 4.5. Feedstock yields affect all system modules including the amount of feedstock cultivated and harvested (thus changing feedstock production inputs), amount of feedstock transported (thus changing transport inputs) and amounts of feedstock processed to finished products (thus changing LBPD and biorefinery inputs). Increased feedstock yields also provide more energy production from raw material per unit area of the RIMA. This fact explains the increased NEG in case of higher feedstock yields and a decrease in NEG with lower feedstock yields. However, increased feedstock yields increase LBPD processing emissions thereby decreasing overall NCER and vice-versa.

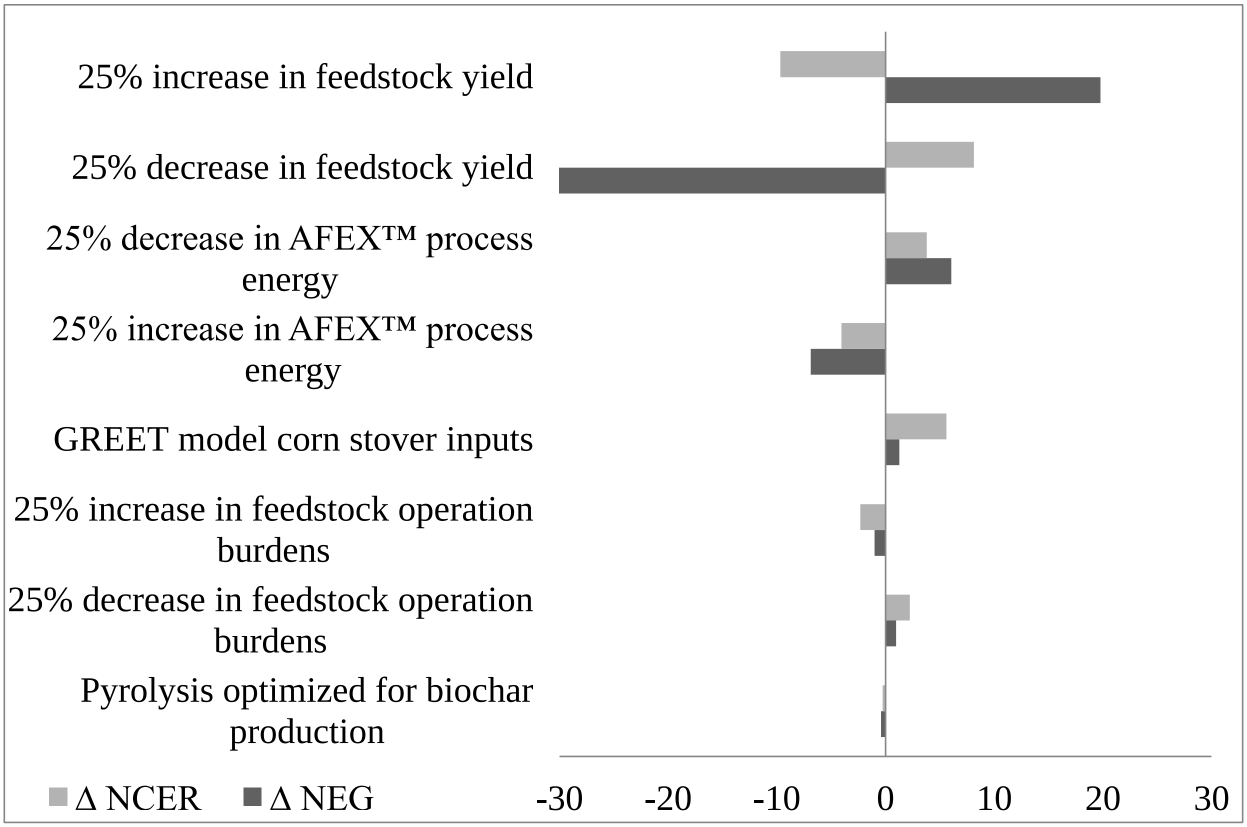


Figure 4.5: Results of the sensitivity analyses as a percentage increase or decrease from values of original scenario 3 (on which the sensitivity analyses were performed)

4.4 Conclusion

Large scale commercial cellulosic biofuel refineries are currently being built and many more are expected in the future as crop production and processing technologies improve. This study provides a foundation for a novel approach to cellulosic biomass logistics that may help resolve biomass supply chain constraints as biofuel demand increases. Using this comprehensive modeling approach, the most promising scenarios for cellulosic ethanol supply chains can be identified. The depot network can help bridge the gap to biofuel commercialization by providing valuable co-products for biofuels and thereby create more market demand to establish such systems.

Greater energy and environmental benefits accrue to the overall system beyond simply improved logistics when the challenges associated with biomass supply and processing are minimized. By implementing land efficient techniques (such as use of marginal lands to grow low input high diversity feedstocks, double-cropping, recycling wastes within the system) and by producing valuable co-products (such as animal feed) close to the feedstock operations depot networks can respond to local and global sustainability concerns while simultaneously increasing feedstock value. The methodology adopted in this analysis can be applied to a wide range of landscapes, feedstocks and flexible depots to evaluate the net energy returns and the environmental benefits of this new approach to developing supply chains for cellulosic biofuels. This analysis serves as a foundation to create the watershed-scale optimized and rearranged landscape design (WORLD) model that will be discussed in Chapter 5.

APPENDIX B

4.5. Appendix B

B.1. The "watershed weightage factor" method for division of RIMA-MI into watersheds

Seven digit HUC watersheds covering the counties belonging to RIMA-MI were identified using the BASINS model. The areas of these large watersheds were found to be greater than the combined 9 county area thereby exceeding the boundaries of the area of interest in this analysis, namely the RIMA-MI. Therefore, to allocate biomass yields and transport distances only to watershed areas belonging within the 9 counties of RIMA-MI, a weightage method was developed. The following calculations and map manipulations were done using the BASINS model and the ArcGIS software: The total area of each complete watershed was calculated. The land areas of each county were calculated. The percentages of county areas contributing to each watershed were determined. A "watershed weightage factor" (wwf) was then developed as the sum of all % county land areas belonging to each watershed. Actual land areas for different land uses (cropland, pasture, forest lands, marginal lands, etc) were determined using the geographic information retrieval and analysis system (GIRAS) database in BASINS. Land areas to be considered for analysis (i.e equivalent to RIMA-MI land area) were then calculated using wwfs on actual land areas.

B.2. The "geometric factor" method for assignment of watershed land area portions to depots

The RIMA-MI was divided equally into land-area portions covering each RBPD (based on a manual square grid division). The percentage of land area of each watershed dedicated to each LBPD was determined. For example 48.3% of the Thornapple watershed land area is apportioned to LBPD 5 and 51.7% of the Thornapple watershed land area is apportioned to LBPD 6. Similarly all five watershed areas were divided between the seven LBPDs. Using these percentages, different raw-materials and co-products (such as feedstocks and manure) from the watersheds were allotted to respective LPBDs.

Table B1: Yields of currently available feedstocks

Watershed	Corn stover (tons/ac)		Forage (tons/ac)
	40% harvest	60% harvest	
St.Joseph	1.32	1.98	2.50
Upper Grand	1.26	1.88	1.79
Kalamazoo	1.27	1.90	2.34
Black-Macatawa	1.26	1.89	2.66
Thornapple	1.29	1.93	2.30

Yields are calculated using NASS data [40] and wwf method (B1). Stover yields were estimated based on a 1:1 mass ratio from corn yields (converted from bushels to tons)

Table B2: Yields of currently unavailable feedstocks estimated from literature values

Feedstock	Yield (tons/ac)	Sources
Winter rye	2.4	[41, 42]
Switchgrass	7	[43, 44]
Miscanthus	10	[45-47]
Native prairie	0.97	[22, 23]
Woody biomass	2.7	[48-50]

B.3. Land uses in different watersheds

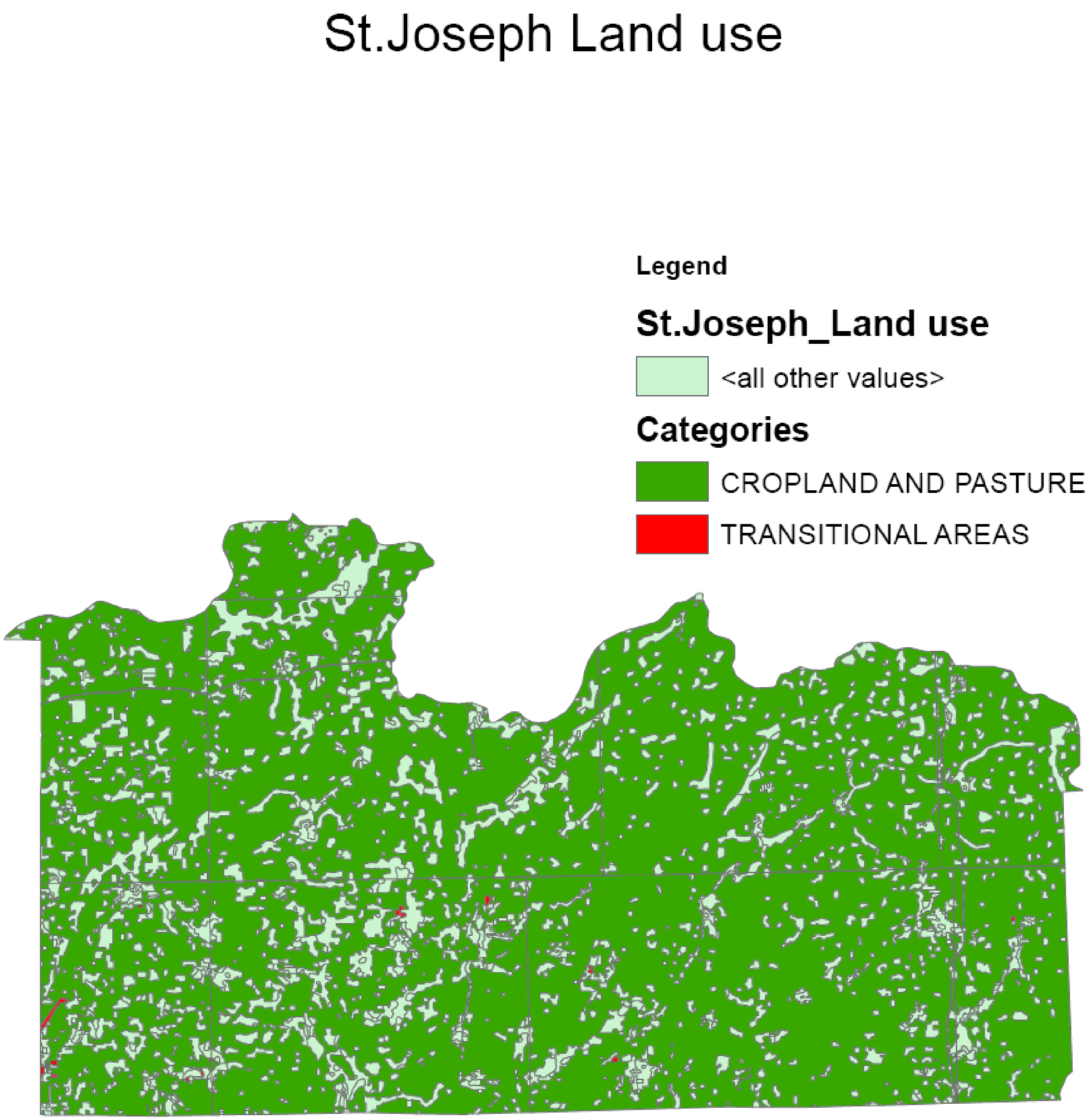


Figure B.1: Land use in the St. Joseph watershed in RIMA-MI

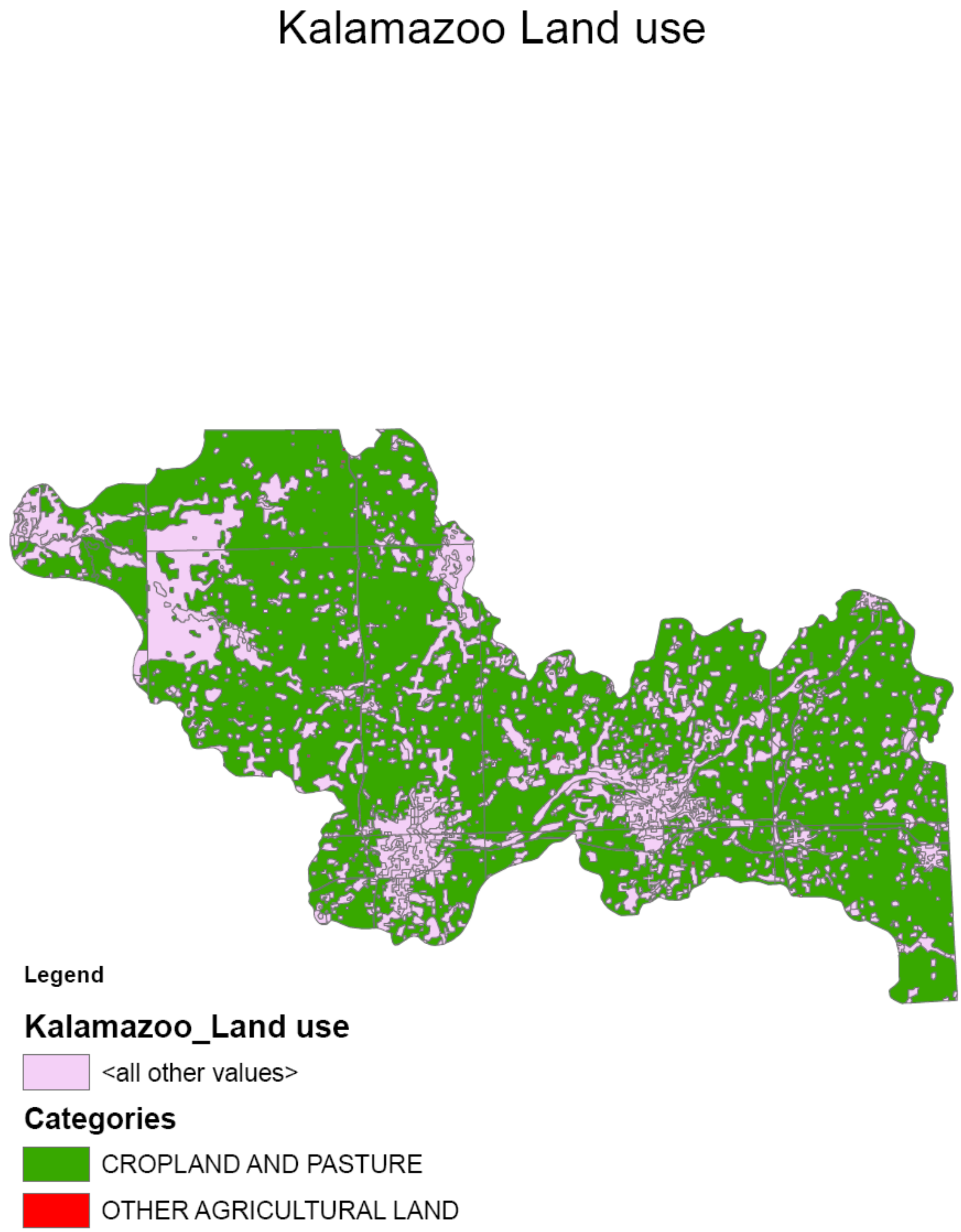


Figure B.2: Land use in the Kalamazoo watershed in RIMA-MI

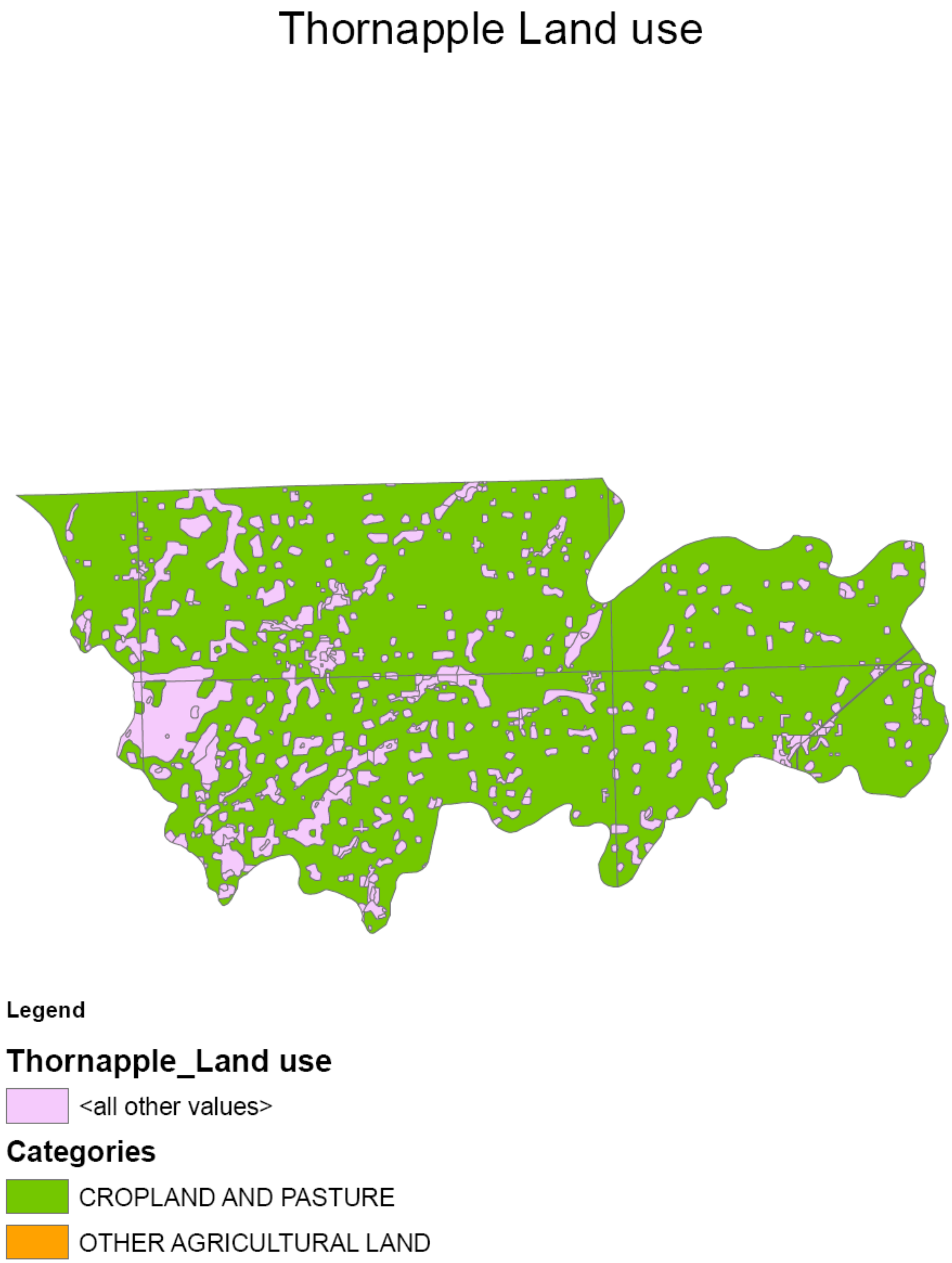


Figure B.3: Land use in the Thornapple watershed in RIMA-MI

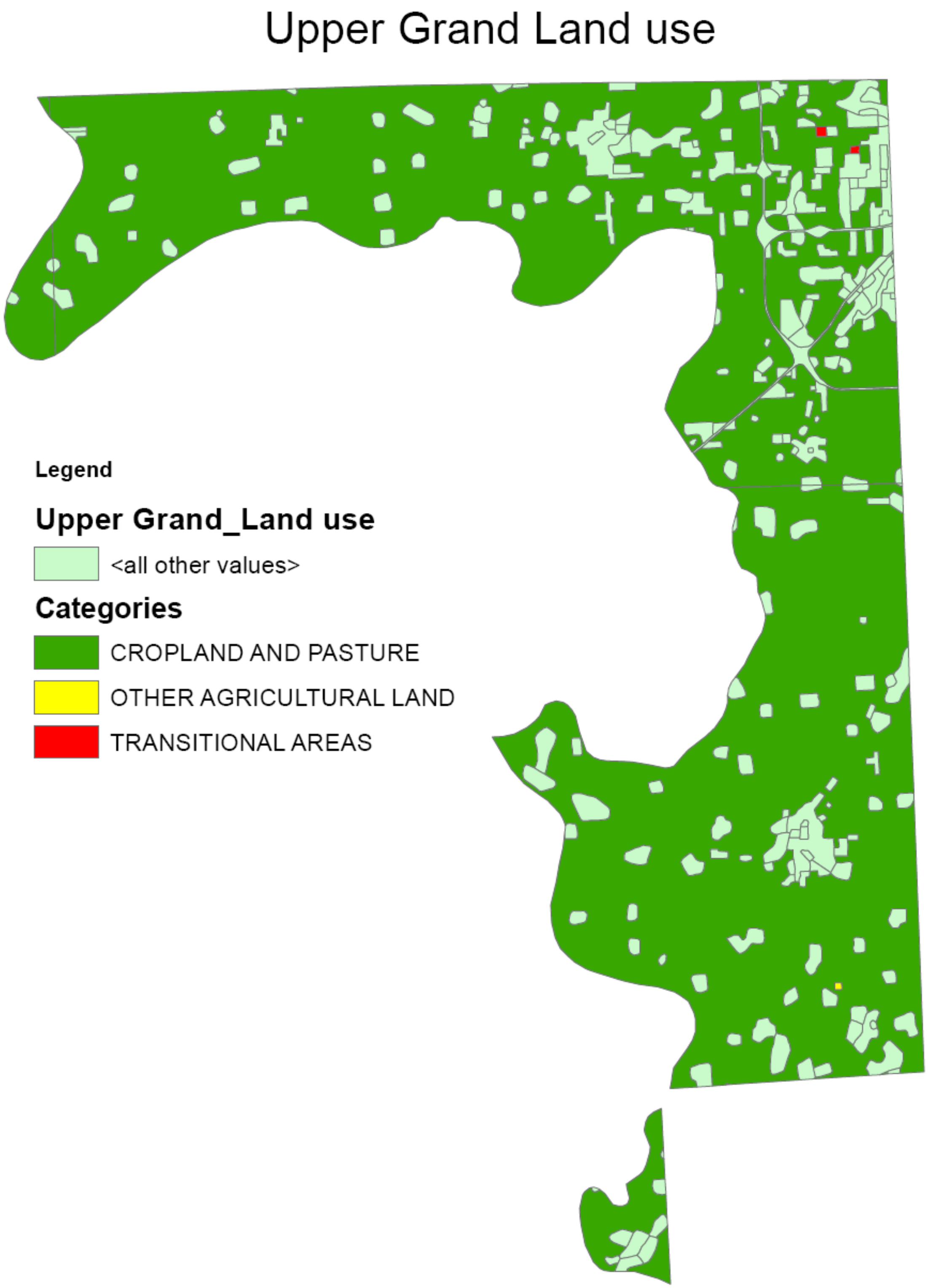


Figure B.4: Land use in the Upper Grand watershed in RIMA-MI

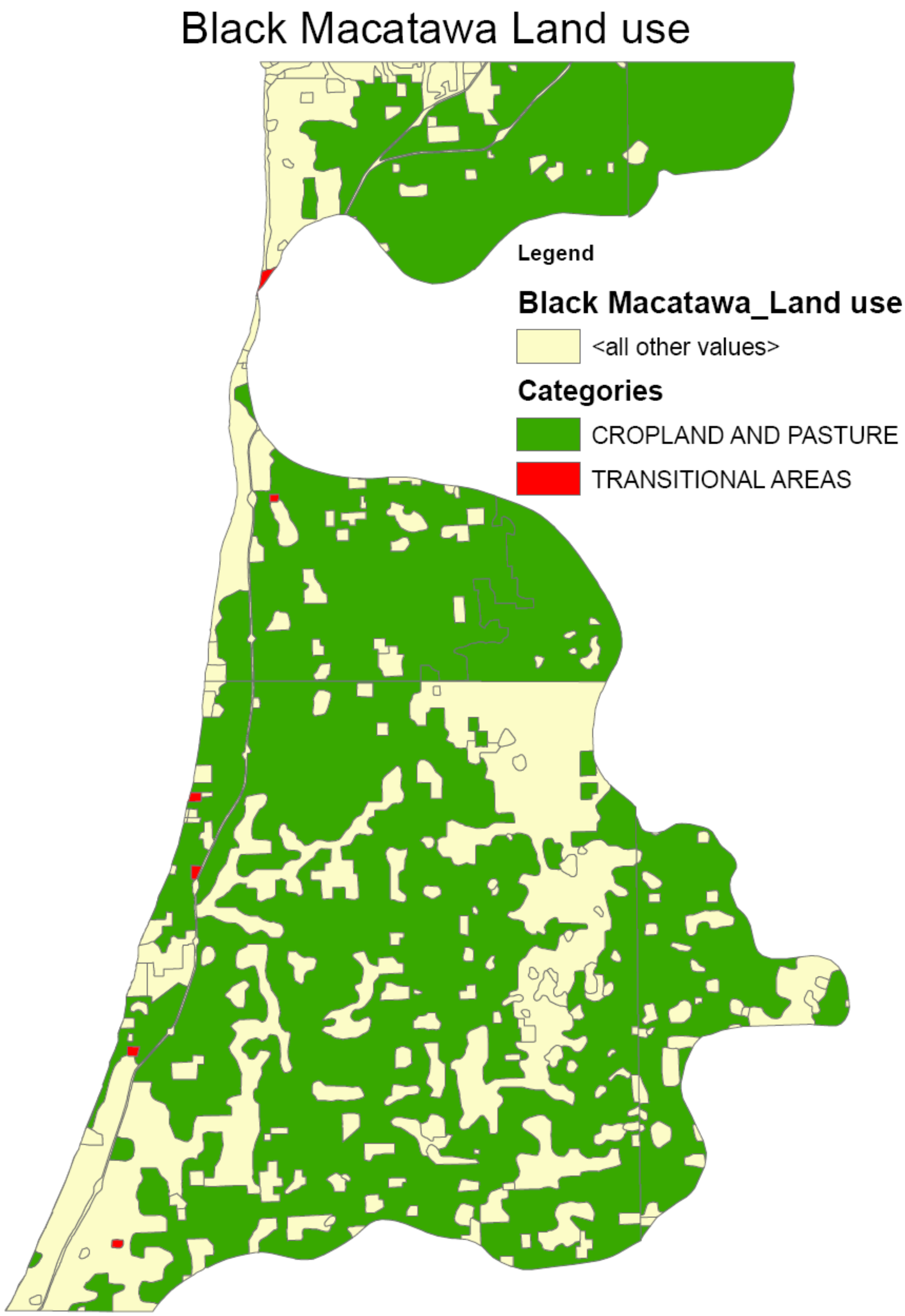


Figure B.5: Land use in the St. Joseph watershed in RIMA-MI

B.4. Transport calculations

A 20% road winding factor was applied to these calculated values to account for non-linear road networks. Densified and non densified transport were differentiated by modifying the cargo payload (or truck capacity) suitably (higher payload for densified material vs. lower for non-densified) in GREET 1.8b [31]. Formula for collection distances from farms[51]:

Collection area (mi^2) = $ß / [\delta * \rho * (1 - I) * \lambda * 640]$

Where ß= biomass collected (dry tons/ yr), δ= density of feedstock acreage, ρ= % of farmers selling feedstock, I = % of fields inaccessible, λ= biomass yield. Whereas δ, ρ and I remain constant (~0.2 on average, 0.5, and 0.1 respectively), ß and λ vary in different scenarios thus changing the collection area.

B.5. Nutritional values and co-product credit calculations

The following calculations are performed based on similar calculations in the comparative LCA study [3].

For stover

It is assumed that pretreated corn stover displaces corn grain animal feed. Displacement ratio = 0.653 (1 kg of stover can displace 0.653 kg of corn fed as animal feed based on TDN content), Animal feed production ratio = 1 (1 kg of stover produces 1 kg animal feed). Using the displacement method equation:

Co-product credit_corn = [animal feed production (kg feed/kg stover)*(Kg corn displaced/kg animal feed)]* [corn production energy] (MJ/kg grain)

For perennial grasses

It is assumed that pretreated perennial grasses displace soybean protein animal feed. Displacement ratio = 0.202 (1 kg of perennial grass (SG or miscanthus) displace 0.202 kg of soybean protein), Animal feed production ratio = 1 (1 kg of grass produces 1 kg animal feed)

Co-product credit_soy = [animal feed production (kg feed/kg grass)*(Kg soy displaced/kg animal feed)]*[soy production energy (MJ/kg)]

For rye forage

It is assumed that leaf protein concentrate produced from forage displaces soybean protein animal feed. Displacement ratio = 0.804 (1 kg of perennial grass (SG or miscanthus) displace 0.804 kg of soybean protein), LPC production ratio = 0.18 (1 kg of forage yields 0.18 kg LPC)

Co-product credit_soy = [LPC production (kg feed/kg forage)*(Kg soy displaced/kg LPC)]* [[(soy production energy-rye production energy) (MJ/kg)]

Carbon emission reduction co-product credits

Similar calculations for co-product credits of greenhouse gas emissions were performed. For perennial grasses extra emission reduction for any corn or forage land displaced was also included (in Scenarios 2a, 2b and 3)

Additional GHG emission sequestered (due to below ground root mass) = perennial grass acreage grown on originally corn or forage land *(sequestration by perennial grass- sequestration by corn or forage).

Soil nitrous oxide emissions were included in the feedstock emission output calculations by converting to CO_2 eq. using a factor of 298 for the global warming potential of N_2O.

B.6. Results of energy and emission burdens as absolute values

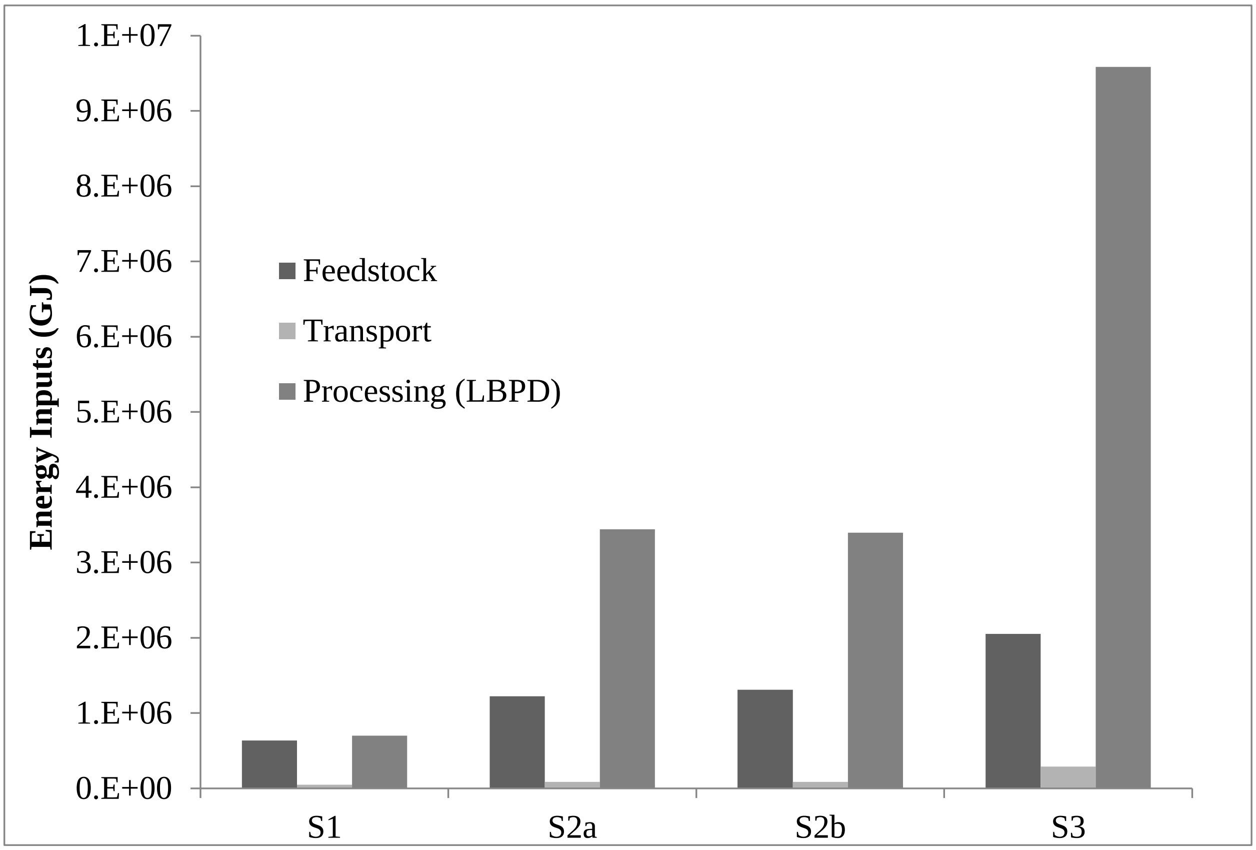


Figure B.6: Absolute energy inputs of the different system modules

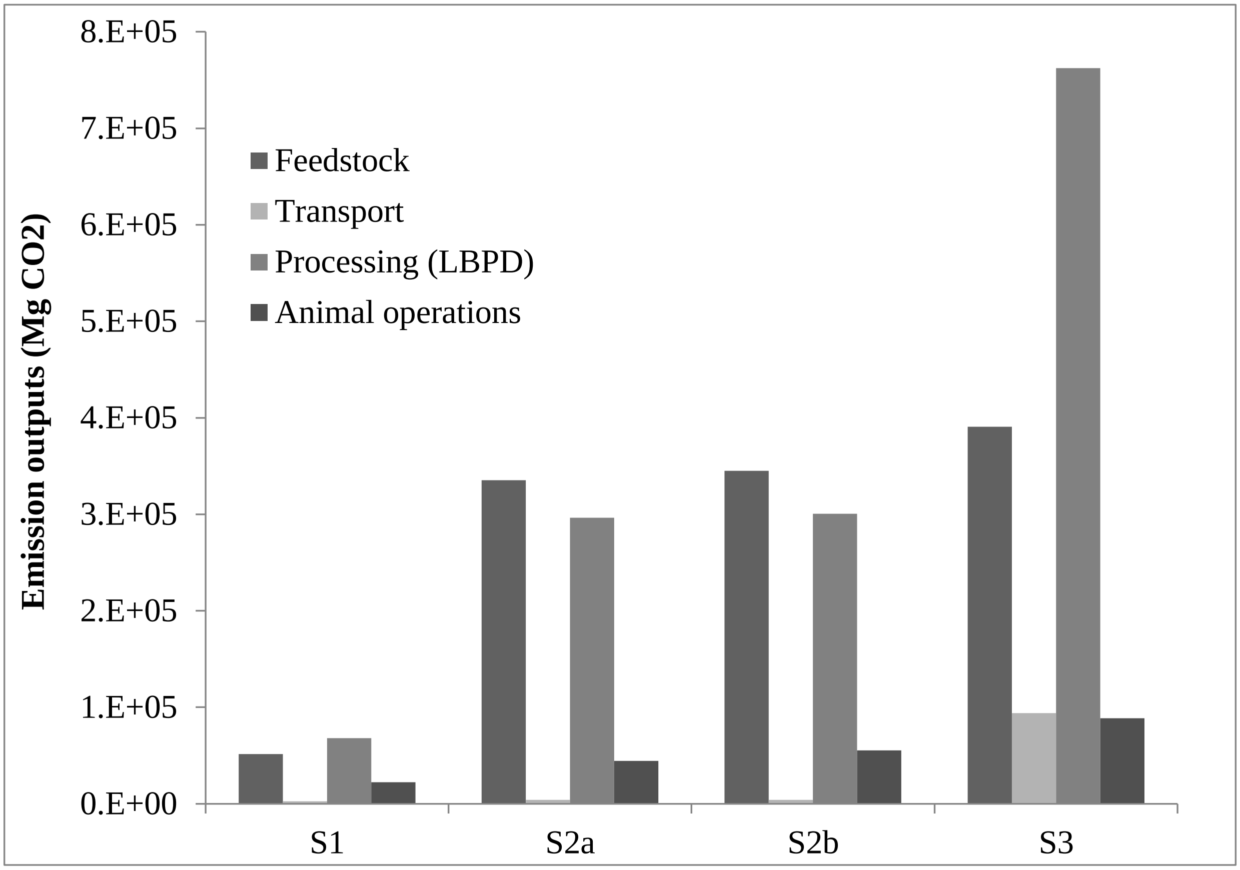


Figure B.7: Absolute emission outputs of the different system modules

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CHAPTER 5: THE WATERSHED-SCALE OPTIMIZED AND REARRANGED LANDSCAPE DESIGN (WORLD) MODEL AND LOCAL BIOMASS PROCESSING DEPOTS FOR SUSTAINABLE BIOFUEL PRODUCTION: AN INTEGRATED LIFE CYCLE ASSESSMENT

5.1. Introduction

Several plant biomass types such as those derived from corn (*Zea mays* L.) stover, switchgrass (*Panicum virgatum* L.), miscanthus (*Miscanthus x giganteus*), and native prairie grasses, are under evaluation as “best feedstocks” for cellulosic biofuel production. Further, management practices such as double-cropping or other practices tailored for marginal lands and riparian buffers may contribute to the design of sustainable biofuel production systems. However, since these feedstocks vary greatly in their net energy potential, co-product generation, and environmental impact characteristics, it may prove most beneficial to grow a combination of these feedstocks within specific landscapes. For example, a recent study connected low-diversity, annual crop landscapes with heightened pest infestations and insecticide use and concluded that perennial bioenergy crops such as switchgrass and mixed prairies may counterbalance these effects [1]. In a related study, diverse landscapes were found to promote better bio-control services, an important and beneficial ecological provision [2]. Moreover, since one of the key concerns about biofuels is the so-called “food vs. fuel” conflict, sustainable landscape designs that maintain the current food/feed production potential and also provide large amounts of biomass for fuel must be explored and understood [3].

Distributed processing in the form of depots that preprocess and pretreat local biomass form a solution to the logistical challenges of large- scale, centralized biorefineries. All depots contain the ammonia fiber expansion (AFEX$^{\mathbf{TM}}$) pretreatment and densification technologies, and may also contain additional processing technologies (e.g., leaf protein concentrate (LPC) extraction, anaerobic digestion, or pyrolysis (to produce a “bio-oil” plus a combustible gas and biochar) based on the landscape characteristics. The depots vary in capacity, operational characteristics, and in the feedstocks processed and co-products produced, as dictated by the characteristics of the landscapes in which they are embedded (e.g., largely agricultural landscapes vs. heavily forested ones). Appendix C summarizes the details of these technologies.

Watersheds constitute an ecologically-relevant scale at which to understand the potential for integrating food and biofuel production with enhanced environmental performance. From the results of all the previous analyses (Chapters 2, 4) where manual land allocations were made, there is a requirement for an accessible model to predict how land might be allocated within this area to provide cellulosic biofuel feedstocks while maintaining existing food/feed production levels and enhanced environmental performance. Therefore, the watershed-scale optimized and rearranged landscape design (WORLD) model was created.

The objective of this study is to describe and test the WORLD model for its ability to allocate land areas to different feedstocks and combine these landscapes with the processing technologies of LBPDs in a given region and thereby determine how this combination may impact energy yields and the environmental performance of such landscapes. Figure 5.1 gives a visual summary of the various modules, their inputs and outputs and the tools used in this analysis.

5.2. Structure and methods

5.2.1. The watershed-scale optimized and rearranged landscape design model

WORLD is a user-friendly and flexible linear optimization model created to determine optimal landscape configurations for a variety of feedstocks within real landscapes, for various sets of optimization criteria. Instructions on setting up and running the WORLD model and codes of macros used in the model are provided in Appendix D. The model is constrained by the primary requirement that all of the food/feed provisioning services currently provided by the landscape are provided by the new, rearranged landscape. Constraining the model in this way avoids the so-called “food vs. fuel” issue and the associated indirect land use change (iLUC) effect [4]. The analysis is structured for watershed-scale landscapes due to data availability, ease of modeling and model validation [5]. The present study focuses on nine counties (Allegan, Barry, Branch, Calhoun, Cass, Eaton, Kalamazoo, St.Joseph and Van Buren) in Southwest Michigan (the “Regional Intensive Modeling Area” (RIMA)) [5, 6] discussed in Chapter 4. This RIMA was divided into five 7-digit hydrologic unit code (HUC) watersheds (Upper Grand, Black-Macatawa, Kalamazoo, St.Joseph and Thornapple) for the purpose of this analysis.

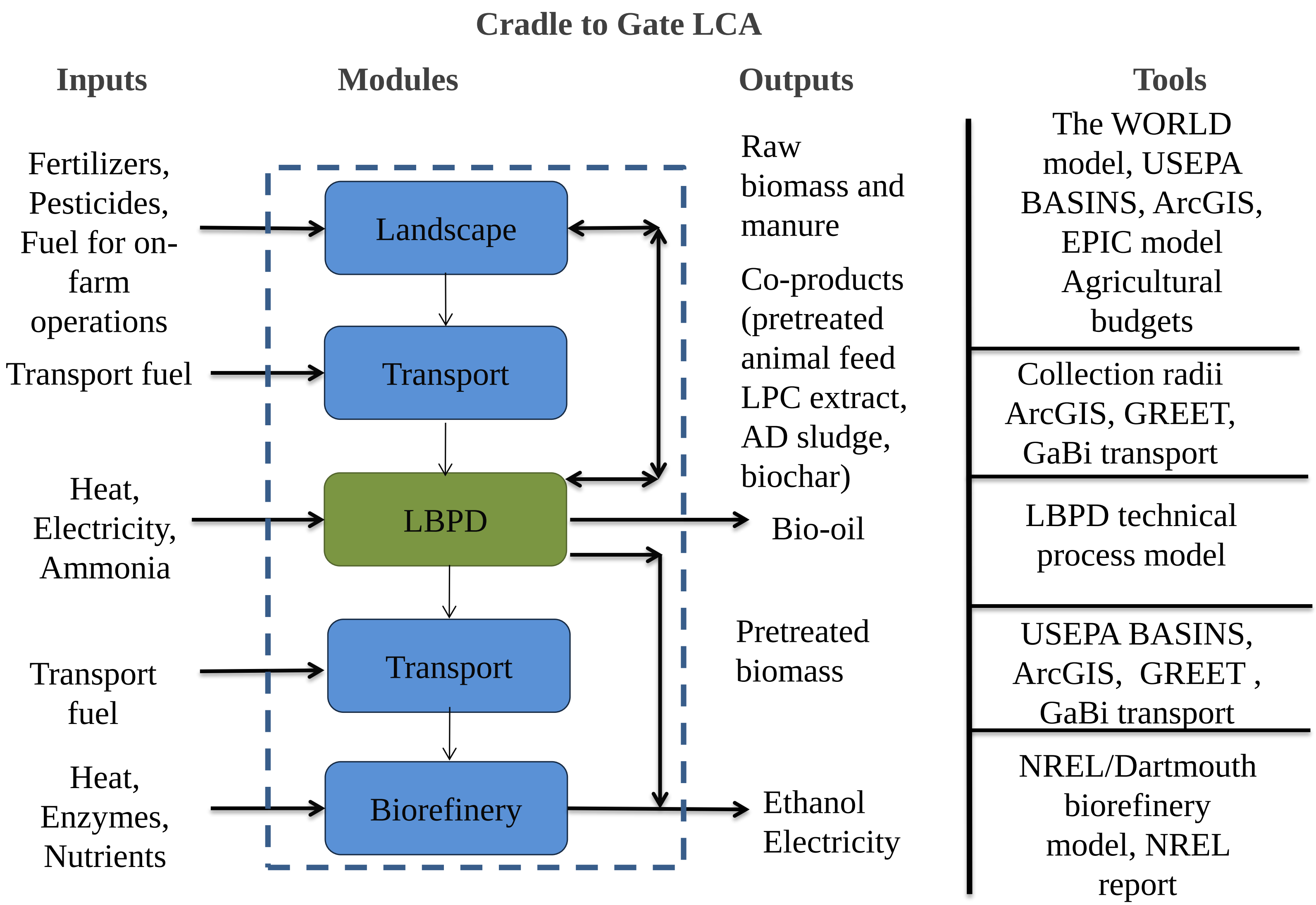


Figure 5.1: Modules, material flows and tools used in this analysis

The cellulosic feedstocks included in the study are agricultural residues (corn stover), perennial grasses (switchgrass and miscanthus), forage crops (alfalfa [*Medicago sativa* L.] and grass hay), native prairie grasses, winter wheat [*Triticum aestivum* L.] grown as a double crop with corn/soy production, forest residues and perennial grasses used as buffer strips or riparian buffers (a mix of switchgrass and miscanthus) along river banks and also canola (*Brassica* spp.). The agricultural residues and perennial grasses were chosen because of their relevance as primary feedstocks of interest in lignocellulosic biofuel production [7-10]. Native prairies have attracted interest as potential sources of lignocellulosic feedstocks because of their positive environmental effects and ability to generate biomass on abandoned/degraded land [11-13]. Canola is used to replace any displaced soybean oil in the reconfigured landscape.

The WORLD model obtains most of its inputs from GIS-based models such as the US EPA BASINS model and the Environmental Policy Integrated Climate (EPIC) biogeochemical model [14], as discussed in Chapter 4. EPIC is a field scale biofuel and crop simulation model combining soil and crop components such as erosion, crop growth, nutrient balance and nitrogen and carbon cycles [15]. These models provide data such as land availability and watersheds within the RIMA, land use categories(from the National Land Cover database [16]) and road network lengths, etc.

The primary inputs to the model are:

1. The type of land area in each watershed, namely marginal land (ML), pasture land (PL) and arable land (AL). In this analysis, arable land is the land area used to grow conventional crops such as corn and soy. Pasture land is defined as the land used to grow forage crops such as alfalfa and grass hay. Marginal land areas were determined from the national land cover database in GIS as “transitional lands” or those with land capability

class 7 within the National Resource Conservation Service definition [17]. Current cropland and pastureland areas were determined using GIS software and from NASS statistical surveys. Table C1, Appendix C contains details of current acreages of different land category used in the model. The total land area used in the RIMA is the sum of these three land categories. Forested lands and urban lands are not used in this analysis; only cropland, pasture and marginal lands.

2. Biomass yields on each type of land category (arable, pasture or marginal) for each watershed and the environmental impacts of each feedstock, as determined from the EPIC model. Environmental impacts include changes in soil organic carbon (ΔSOC), erosion, nitrogen (N) and phosphorus (P) losses, crop water use efficiency (CWUE) and farm greenhouse gas emissions (FGE). ΔSOC is the total change in soil carbon after growing a feedstock (positive ΔSOC indicates an environmental benefit as this indicates carbon sequestration in the soil). Erosion is the average soil eroded over the land area. Nitrogen and phosphorous losses are a result of surface runoff, sediment, lateral subsurface flow and percolation below the root zone. Crop water use efficiency as defined in this analysis is the ratio of biomass yield to evapotranspiration resulting from a particular feedstock. Farm greenhouse gas emissions are the carbon dioxide (CO_2) and nitrous oxide (N_2O) emissions (in CO_2 equivalents) from crop production due to inputs such as tillage, seed preparation, fertilizer production and use (including N_2O generated), and pesticide production. Improvements (decreases) in these environmental impacts represent progress toward a more sustainable system [18, 19]. Table C2, Appendix C shows the feedstocks used, their average yields over all watersheds and the management

practices assumed to produce these feedstocks in EPIC. Table C3, Appendix C shows the assumed nutritional values of different feedstocks.

3. The RIMA currently produces conventional animal feeds such as corn grain, soy protein and grasses. It is assumed that 41% of corn grain, 61% of soy and 100% of both alfalfa and grass hay produced in the landscape are used as animal feed [20, 21]. Required animal nutritional needs include total non-protein digestible nutrients (TNPDN), protein, and fiber [3, 22, 23]. Oil produced from soybean in the landscape is also provided as an input to the model so that any displaced oil due to growing new feedstocks instead of soybeans may be replaced with canola oil.

4. Ethanol and electricity yields of each of the different feedstocks are from literature[24]. Table C4, Appendix C shows environmental impact values from the EPIC model. Table C5, Appendix C shows the energy inputs for different feedstocks obtained from literature and agricultural budgets. Table C6, Appendix C shows the assumed ethanol and electricity yields of different feedstocks.

The following is a summary of the universal assumptions and constraints in the model:

- Corn grain ethanol is excluded from the system boundary.
- All marginal land (ML), pasture land (PL) and arable land (AL) used should be less than or equal to the original configurations respectively and the sum of all ML,AL and PL should equal the original
- All fractions of feedstock going to animal feed should be between 0 and 1
- Ratios of TNPDN, protein, fiber and oil coming from the new configuration to that of the from the original configuration should be between 1 and 2

- Stover and double crop land are excluded from the sum of arable land to avoid double counting as they are grown on the same land area as corn
- Early succession vegetation (ESV) or (cool season native prairie grasses simulated in EPIC) is always allowed to grow only on marginal lands
- Variable percentages of original feedstocks (corn, soy, grass hay, alfalfa) are assumed to be sent to animal feed from the original configuration based on literature values
- All biomass harvested from buffer strips is assumed to go to ethanol production (no animal feed generation)
- Original animal feed crops such as corn grain and soybean whenever displaced from the landscape are replaced with nutritionally equivalent pretreated cellulosic feedstocks

Land areas of existing crops are varied or new feedstocks are added to the landscape on different land categories- arable (AL), marginal (ML) or pasture (PL). The fraction of biomass going either to ethanol production or to animal feed is varied in the model based on the parameter being optimized in a particular scenario. The model also varies the amount of double cropping and the amount of stover harvested from corn land. The model is configured to vary these factors within a set of constraints. All marginal, pasture and arable land used in the new configuration is not allowed to exceed the original areas respectively. In all cases, ESV is allowed to grow only on ML but not on PL or AL. Conventional crops are never allowed to grow on ML, similarly forage crops are never allowed to grow on AL; this is done in order to keep the different types of land areas distinct. ESV is allowed to grow on ML only. In order to illustrate the capabilities of this model, two scenarios were created:

Scenario 1 (S1): *Technical biomass production potential of the landscape*- In this scenario there are no limitations set on the type of feedstocks grown on arable land. Double cropping is allowed to take place on a significant but conservative amount of corn land of between 20 and 30% [the upper limit for double cropping on corn land is around 50% of total agricultural land (Kurt Thelen, personal communication, Feb, 2012)]. Riparian buffers can be present in moderate amounts (up to 30% of available river bank areas) within the landscape.

Scenario 2 (S2): *Biomass production potential of landscape in case of opposition to conversion from conventional crops to novel bioenergy feedstocks*- In this scenario, perennial grasses are allowed to grow only on marginal lands and pasture lands while making no changes to arable land currently used to grow conventional crops. There is considerably lower double cropping (between 5 and 20%) and riparian buffers (10% of available river bank areas) used within the landscape. These two scenarios were run on the model in combination with the optimization categories (called tests) shown in Table 5.1,

The outputs from the model are the newly reconfigured land areas of different feedstocks on different land categories- AL, ML, and PL.

Table 5.1: Summary of optimization categories (tests)

Tests	**Description**
T1:Fuel	Maximize ethanol production
T2:Soil	Minimize erosion
	Maximize Δ Soil Organic Carbon (SOC)
T3:Water	Minimize Nitrogen losses
	Minimize Phosphorus losses
	Maximize Crop water Use Efficiency (CWUE)
T4:Emissions	Minimize CO_2 e. GHG emissions from feedstock production sector (FGE)

The original landscape contains corn, soybean, alfalfa and grass hay whereas the reconfigured landscape contains a combination of switchgrass, miscanthus, winter wheat, and ESV in addition to the original feedstocks.

The model also generates values of ethanol, electricity and animal feed produced and environmental impacts of growing the feedstocks within the landscape. Environmental impacts can be obtained either as absolute values for the new landscape or as percent changes compared to baseline (where the original landscape forms the baseline).

In this analysis, instead of a low-input high- diversity native prairie, a fertilized cool season native prairie also denoted here as ESV is simulated in EPIC and its resulting biomass is also assumed to be used for ethanol production along with other feedstocks. Unfertilized native prairie grasses may perhaps not generate substantial biomass yields but might nonetheless be included in landscapes for their environmental benefits. Double cropping can enhance the productivity of agricultural landscapes based on annual crops [3] and achieve some of the benefits of perennial systems. Winter wheat is assumed to be grown as a double crop in the analysis. Perennial grass buffer strips can minimize herbicide and sediment run-off and improve water quality [25]. However, the analysis does not estimate improvements in water quality versus systems without such buffers. Such buffers may minimize losses of sediment, nutrients and pesticides by 50-70% [26]. Finally, the use of complex landscapes containing a mix of cellulosic feedstocks will likely exhibit positive environmental benefits such as increased biodiversity, increased wildlife habitat and reduced chemical use.

5.2.2. Local Biomass Processing Depots and Biorefinery

In all scenarios in this analysis, the processing module is assumed to contain a network of depots providing pretreated biomass to the central biorefinery. For the distributed processing system an in-house technical model [27] was developed to determine the processing energy required based on technologies included in each scenario. This model uses a combination of literature values and experimental results to form a basic material and energy balance around each unit operation. These balances determine the fossil fuel and raw material input required. For the biorefinery module the processing energy for operation and energy gains due to electricity and ethanol produced were determined using the NREL/ Dartmouth biorefinery model [28, 29].

5.2.3. Life Cycle Assessment

The functional unit in this analysis is the land area generating cellulosic biomass in the RIMA and the reference flow is defined as one hectare of the RIMA land area. This is the functional unit of choice since one of the primary goals of the analysis is to illustrate the variations in land productivity with differences in types and amounts of feedstocks and the management practices used in the RIMA. The system boundary in this study includes the feedstock landscape (the only land area within the RIMA used to generate biomass), LBPDs, the biorefinery and all associated transport operations between the feedstock and processing modules. The production of only cellulosic ethanol (but not corn grain ethanol or soybean biodiesel) is included in the system boundary. The energy and emission factors associated with various feedstocks were obtained from agricultural budgets, extensive literature review[23] and EPIC model results. The EPIC model results set stover harvest to an average of 60% (in all cropping systems with stover removal). Conventional feedstocks such as corn and soy are only included to determine arable land area, current animal feed requirements and oil production (in the case of canola replacing soybeans).

Details of transportation distance estimation within the different watersheds are provided in Table C7, Appendix C. Using these distances and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model [30] for both densified and non-densified transport where applicable, transport energy requirements and emissions were calculated. Details of energy requirements and emissions of transportation of densified and non-densified material as well as those of bio-oil and biochar are provided in Table C8, Appendix C. Manure from animal operations that goes to anaerobic digestion is also included in the transportation calculations to depots. A 15% dry matter loss (DML) in transportation of raw biomass from farms to LBPDs and a 10% loss of all other material (such as densified biomass and solid co-products) is assumed in all scenarios.

As mentioned previously, one of the primary requirements in the WORLD model is to provide equal or greater animal nutritional services in the newly reconfigured landscape as in the original landscape. It is assumed that pretreated stover displaces TNPDN from corn grain, perennial grasses switchgrass and miscanthus displace fiber from grass hay, and the double crop and canola displace protein and oil from soy, respectively. Co-product credits for all animal feed related co-products were based on nutritional values and were calculated using the displacement method [23]. Details of co-product credit calculations (similar to those seen in Chapters 2 and 4) are provided in Appendix C.

The data from various system modules i.e. the WORLD model for feedstocks, the LBPD and biorefinery technological process models and transport modules are consolidated and an integrated life cycle assessment is conducted to determine net energy yields (NEY) and net greenhouse gas emission reductions (NGER) for the overall system. The absolute value of net energy yield (NEY) is defined as the difference between total energy outputs (in the form of ethanol, electricity and coproduct credits) and energy inputs of feedstock, transport and processing systems of new cellulosic biofuel producing acreages in the newly reconfigured RIMA. The absolute values of net greenhouse gas emission reduction (NGER) is defined as the difference between total CO_2-equivalent (CO_2 e) GHG emissions displaced and total CO_2 e GHG emissions from feedstock, transport and processing systems of cellulosic biofuel producing acreages in the newly reconfigured RIMA. GHG emissions displaced include emissions due to ethanol displacing gasoline, emissions displaced due to surplus electricity generated in biorefinery, and due to using new feedstocks (such as perennial grasses which increase soil organic carbon) as animal feed as well as raw material for biofuel production in place of conventional feedstocks. Fargione et al. [46] state that a "biofuel carbon-debt" may occur due to the release of CO_2 emissions as a result of converting native habitats into alternate forms such as croplands. They define the debt as CO_2 emissions released during the first 50 years of this land conversion. A question regarding incurring "carbon-debt" while bringing previously unused marginal lands into production may arise in the calculation of net carbon emissions. However, incurring a carbon-debt is unlikely in this analysis for the following reasons:

1. Firstly, in the study stated above [46] it is seen that the C-debt accumulated is greater if the marginal/abandoned land is converted to a conventional crop such as corn to generate corn-ethanol. However this debt is low or negligible while generating prairie ethanol on abandoned/marginal lands (about 6 Mg CO_2/ha when prairie ethanol is generated on abandoned cropland and 0 when prairie ethanol is generated on marginal land). The study however does not give values for marginal lands converted to perennial grasses but states that degraded and

abandoned agricultural lands when planted with perennials "incur little or no carbon debt and can offer immediate and sustained GHG advantages". Since in the present analysis, it is assumed that marginal lands (defined as lands that are already very low in carbon reserves) are only used to grow with perennials or native prairie/ ESV, the risk of incurring a carbon-debt is negligible.

2. Moreover, in this analysis less than 1% marginal land (based on total RIMA land area) is assumed to be used. This makes the C-debt negligible compared to overall C-sequestration of perennial grasses.

All values of both NEY and NGER are also calculated as a change versus the baseline i.e.

$(NEY)_{rel} = (NEY)_{abs}$ – Feedstock energy inputs of changing acreages of original landscape.

$(NGER)_{rel} = (NGER)_{abs}$ – Feedstock GHG emissions of changing acreages of original landscape,

where $(NEY)_{abs}$ and $(NGER)_{abs}$ represent the absolute NEY and NGER of the reconfigured landscape.

To obtain absolute values, only the energy inputs of cellulosic biomass generating land areas in the new configuration are considered. To obtain relative values, only the energy burdens of acreages that change from crop areas to cellulosic biomass generating land areas are subtracted from absolute values. This is done to ensure that the functional unit does not change and that the same types of areas (changing acreages) are included in both S1 and S2. However, the model constraints dictate the amount of changing acreages in S1 and S2. These values are normalized by considering the total RIMA land area as the reference flow in both scenarios.

5.3. Results and discussion

5.3.1. Reconfigured landscapes, animal feed and environmental impacts

Multiple runs were performed on each test and scenario combination in the WORLD model to verify that the model converges each time, to determine how consistent the results are and to find global maxima or minima. The model ran consistently each time with no significant errors. The results from various runs in each scenario are provided in Appendix C. Pretreated biomass can be used either to generate ethanol or animal feed but not both. Therefore, the ratio of animal nutritional services provided in the new reconfigured landscape vs. the old configuration is set to be between 1 and 2. This is done since no condition is set on ethanol production in these scenarios; the model would otherwise be driven to produce large amounts of animal feed which is contrary to our objective of generating large amounts of ethanol. Figure 5.2 shows the feed requirements met (in the new configuration vs. original) in the various categories of TNPDN, protein, fiber and oil and ethanol produced, as determined by the WORLD model. The new land configurations meet or exceed all animal feed requirements compared to that generated by the original landscape.

Figure 5.3 shows the land ratios allotted to different feedstocks in the two scenarios.

Table 5.2 contains details of various modifications to the original landscape. The model drives the landscape to grow more miscanthus than switchgrass especially on ML in all cases except T4 (minimizing farm GHG emissions). This is because there are differences in the characteristics of these grasses.

According to EPIC simulations, miscanthus has 36% greater biomass yields, 33% greater CWUE, and 14, 31 and 38% lower N and P losses and erosion, respectively.   Miscanthus also generates 92% greater accumulations of soil organic carbon compared to switchgrass in the EPIC simulations.

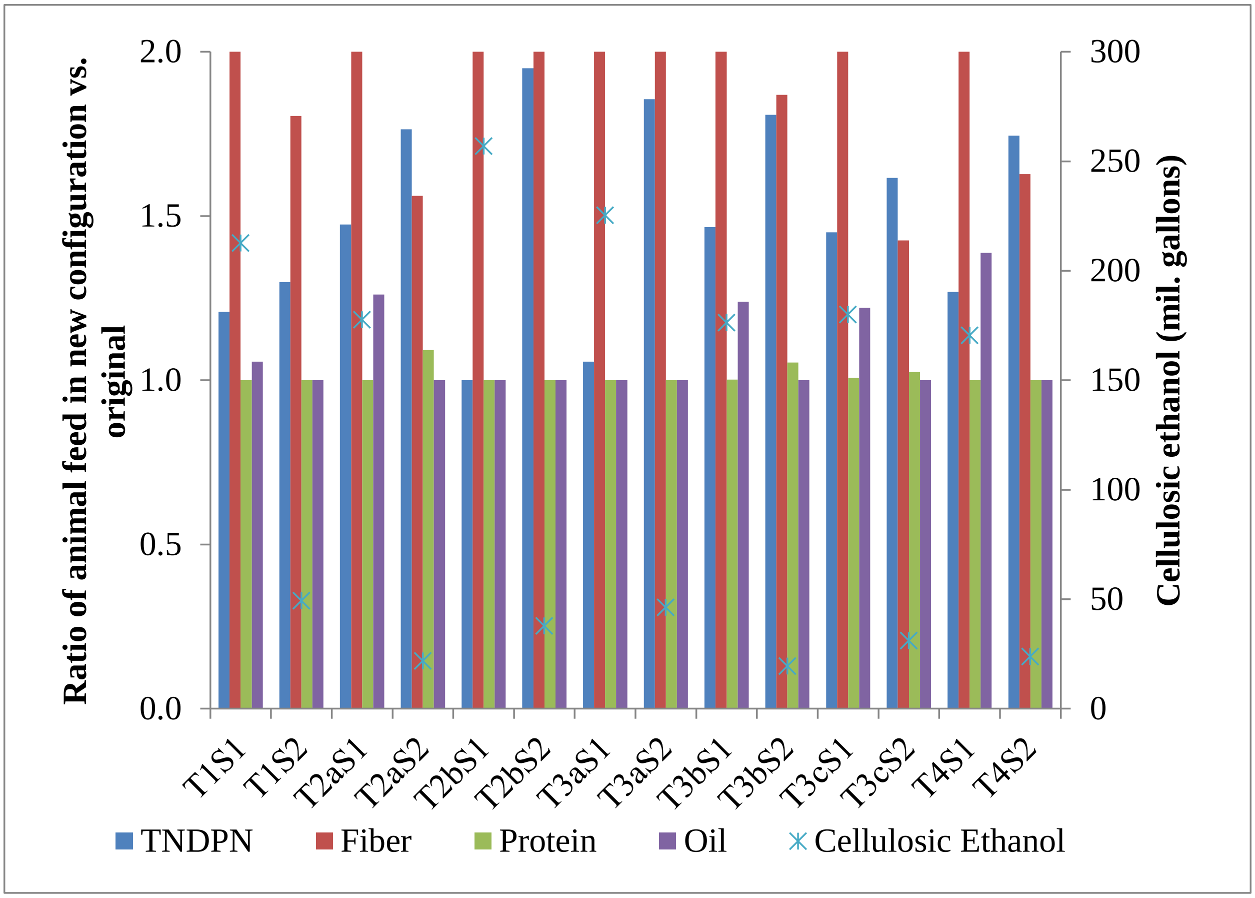
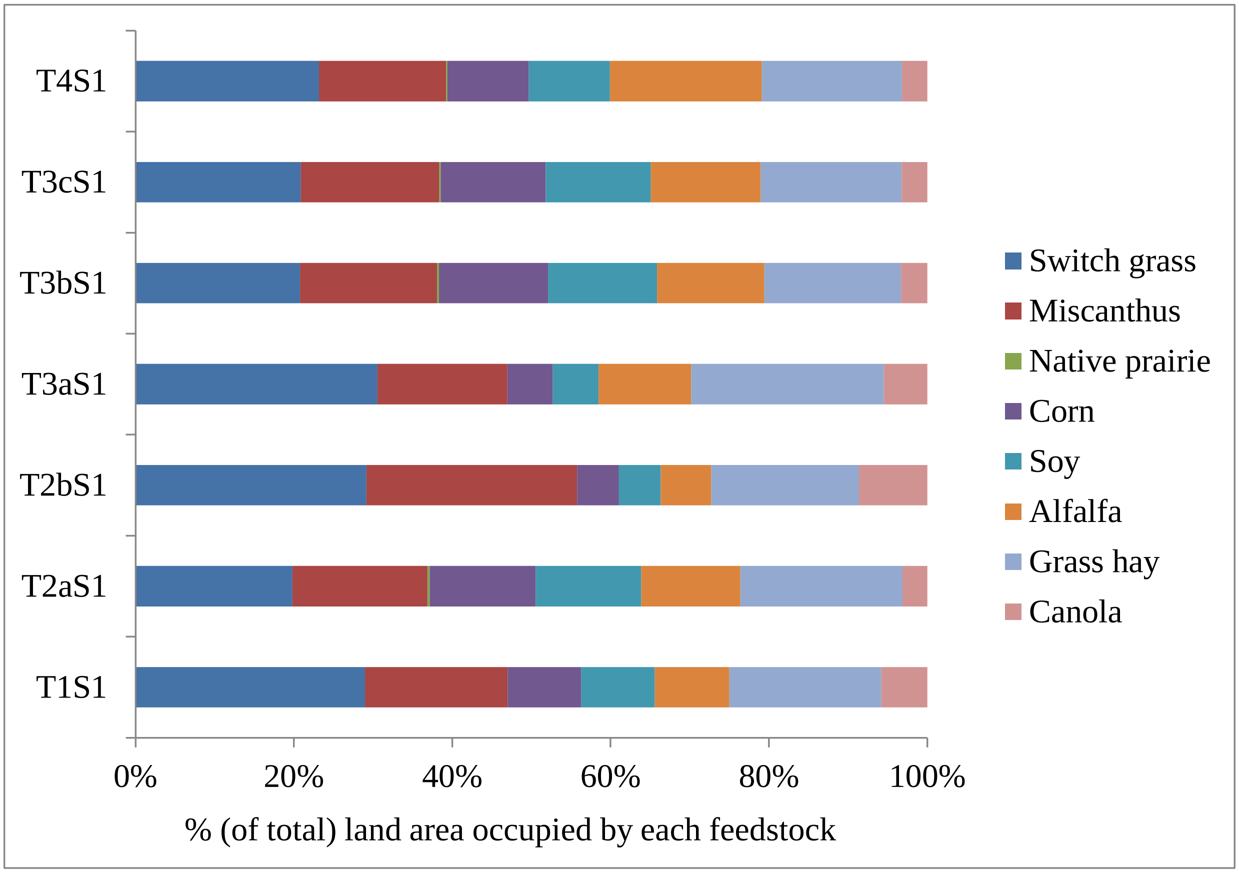


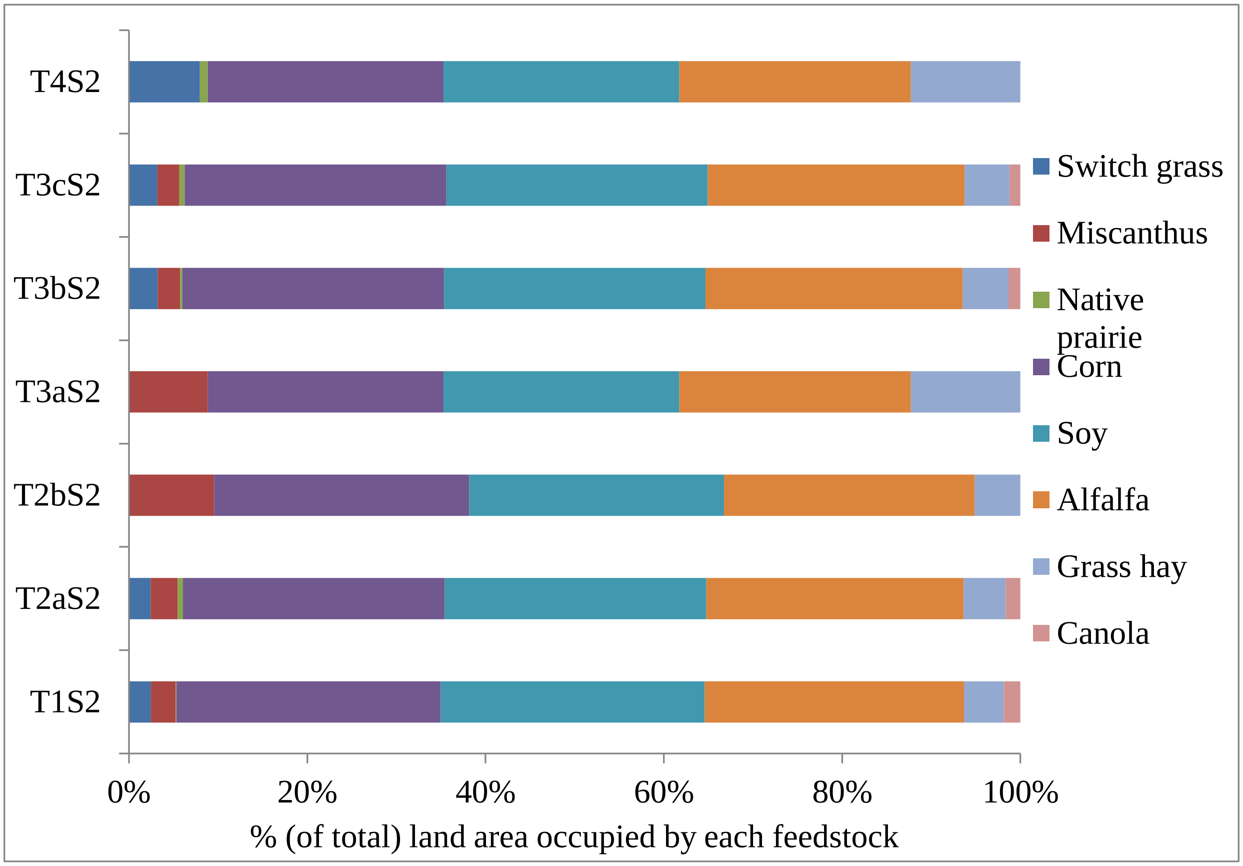
Figure 5.2: Animal feed nutrition provided in new configuration (vs. original) and cellulosic ethanol production



(a)

Figure 5.3: (a) Percentage of total land area occupied by each feedstock in the "technical potential of landscape" scenario (S1) **(b)** Percentage of total land area occupied by each feedstock in the "opposition to conversion from conventional landscape" scenario (S2)

Figure 5.3 (Cont'd)



(b)

Table 5.2: Details of perennial grasses in reconfigured landscape and changes in the original landscape

	Scenario 1							Scenario 2						
Test	**1**	**2a**	**2b**	**3a**	**3b**	**3c**	**4**	**1**	**2a**	**2b**	**3a**	**3b**	**3c**	**4**
S_ML[a]	0	0	0	0	0	1	46	47	15	0	0	8	1	0
S_PL[b]	4	21	0	16	18	20	40	25	25	0	0	33	33	92
S_AL[c]	38	0	38	41	25	25	24	-	-	-	-	-	-	-
M_ML[d]	100	0	100	100	24	34	0	10	28	100	100	8	1	0
M_PL[e]	22	28	30	23	28	27	22	26	31	100	100	26	26	0
M_AL[f]	20	19	29	19	19	19	18	-	-	-	-	-	-	-
NP_ML[g]	0	100	0	0	76	65	54	40	58	0	0	86	98	100
Cor_ch[h]	75	63	86	84	63	64	73	-	-	-	-	-	-	-
Soy_ch[i]	75	64	83	66	63	61	48	-	-	-	-	-	-	-
For_ch[j]	26	49	30	40	46	47	62	52	61	100	100	60	63	0
L_ch[k]	68	61	77	70	60	60	61	7	9	14	14	8	9	0
Cor_AF[l]	40	9	67	60	9	12	34	-	-	-	-	-	-	-
Soy_AF[m]	59	41	73	44	39	37	15	-	-	-	-	-	-	-

a. S_ML= % of ML acres used to grow switchgrass
b. S_PL= % of PL acres used to grow switchgrass
c. S_AL= % of AL acres used to grow switchgrass
d. M_ML= % of ML acres used to grow miscanthus

Table 5.2 (Cont'd)

e. M_PL= % of PL acres used to grow miscanthus
f. M_AL= % of AL acres used to grow miscanthus
g. NP_ML= % of ML acres used to grow switchgrass

Where; ML = marginal land
PL = pasture land
AL = arable land

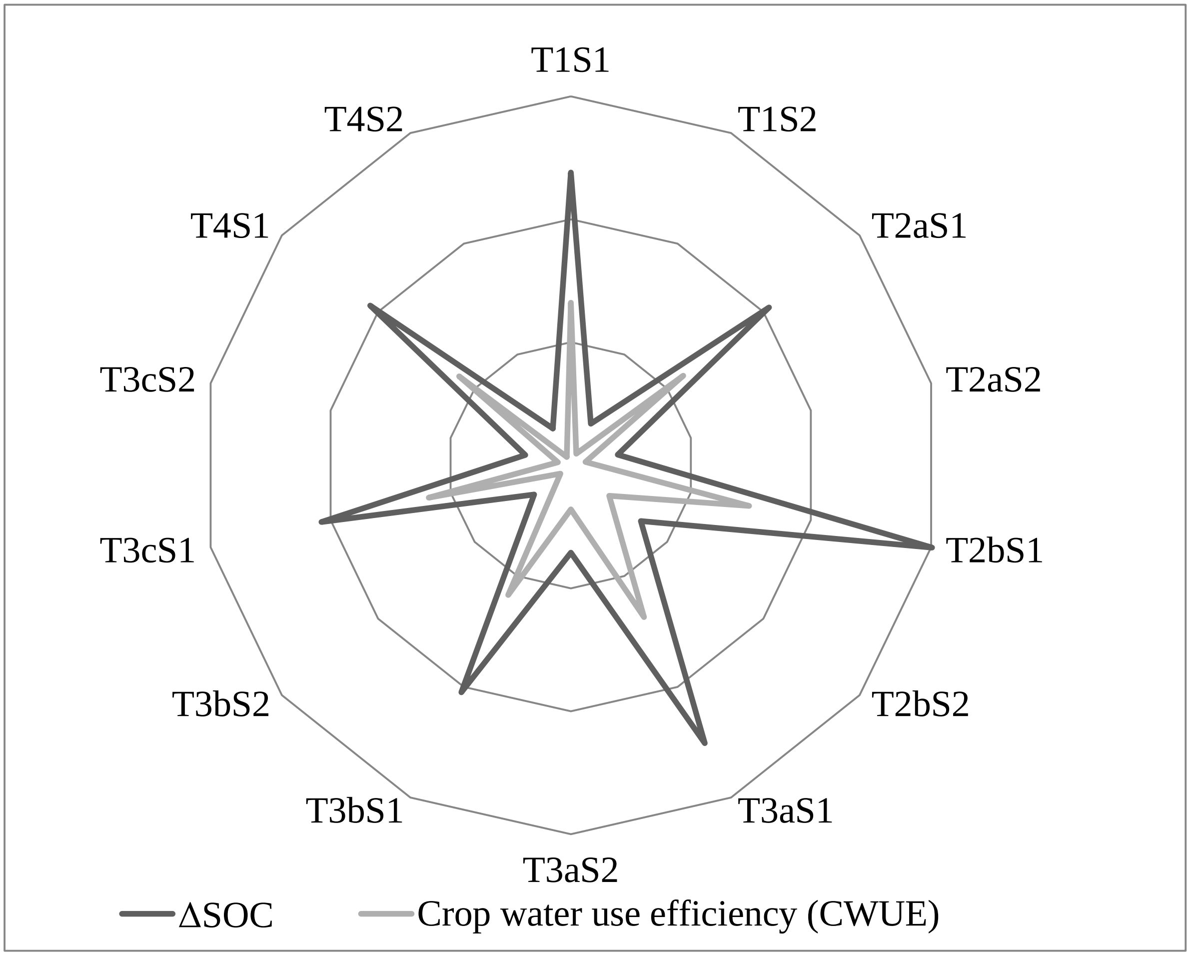
h. Cor_ch = % of corn land that changes into new feedstock (perennial grasses)
i. Soy_ch = % of soy land that changes into new feedstock (perennial grasses or canola)
j. For_ch= % of forage land that changes into new feedstock (perennial grasses)
k. L_ch = the total % of original land area that changes crops (i.e. from conventional to new feedstocks)
l. Cor_AF = % reduction in corn acreages used for animal feed (new vs. old landscape)
m. Soy_AF = % reduction in soy acreages used for animal feed (new vs. old landscape)

Miscanthus production also generates 10% greater N_2O emissions compared to switchgrass. Furthermore, the greatest changes in landscape (from conventional to new feedstocks) that are especially prominent in S1 translate to greater net energy yields and environmental benefits. In all tests in scenario 1, lower acreages of corn and soybean lands are used to grow animal feeds since a large part of animal nutrition requirements are supplied by the pretreated cellulosic feedstocks in this scenario. Figure 5.4 shows an increase and decrease, respectively in desirable (ΔSOC and crop water use efficiency (CWUE)) and undesirable (erosion, N and P losses, farm GHG emissions (FGE)) environmental factors compared to the original landscape. The Y axis in this figure represents percentage change (either increase or decrease) compared to baseline- the original landscape.

The FGE category is seen as more rounded than peaked in the figure since it is the only category with comparable changes from baseline in both scenarios 1 and 2. Because the EPIC results do not exhibit great differences in FGEs (combined CO_2 and N_2O e. emissions) between different feedstock systems, the FGE category does not vary much between scenarios, so it is seen as more rounded than sharp in the figure. Compared to scenario 2, scenario 1 shows between 9 -20 fold increases in ΔSOC and CWUE (positive environmental effects) and between 2-4 fold decreases in detrimental impact categories as percent change from baseline). The greatest gains in SOC are found not only in the test in which it is intended to be maximized (T2bS1) but also in another scenario T3aS1 (minimizing N losses).

A similar result is seen with CWUE where greater percentage increases in this factor are seen in T3aS1 and in T2bS1 (minimizing N losses and maximizing SOC respectively). Similarly, not only are the greatest reductions in impacts such as P loss, and erosion seen in tests in which this is the intended result, but great reductions are also seen when minimizing N losses and maximizing ΔSOC are the intended results.

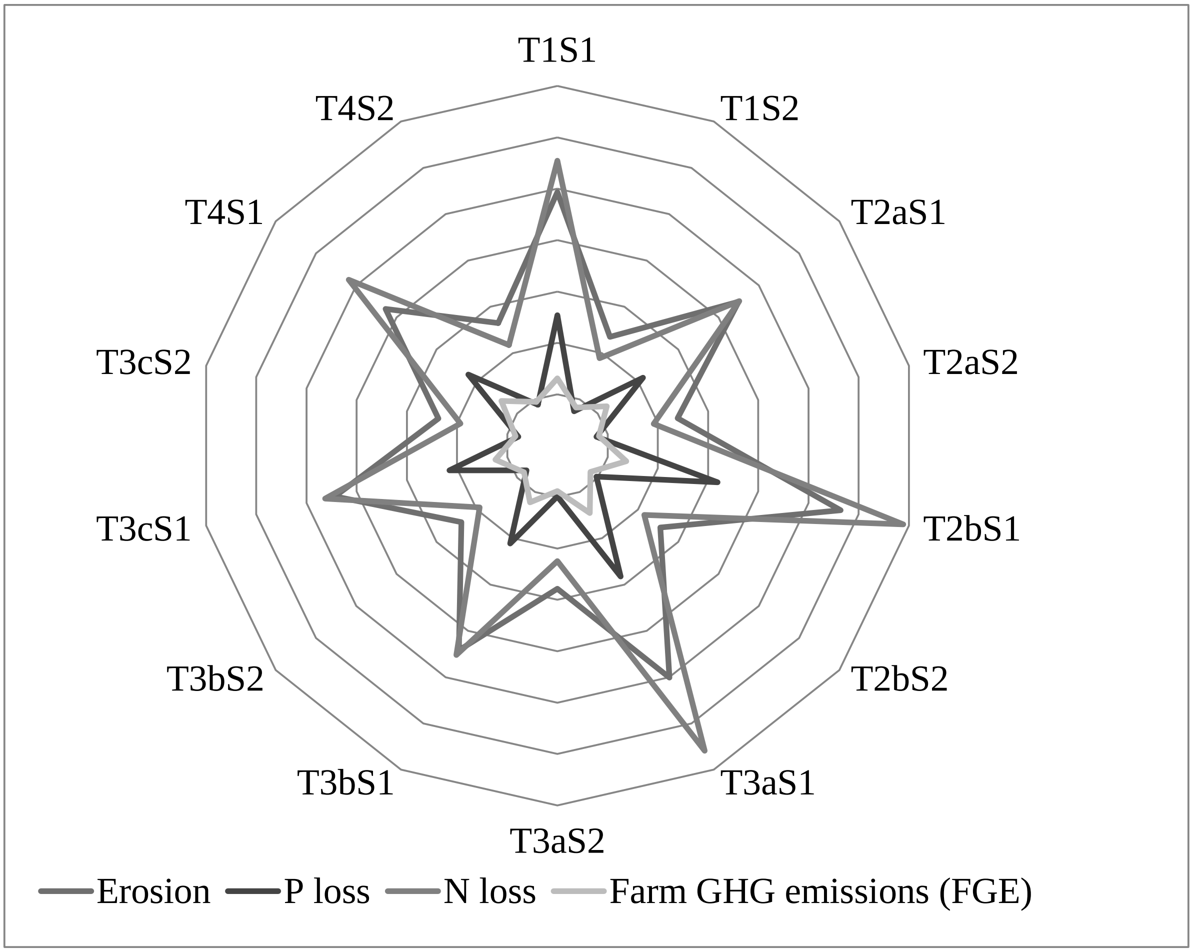
Also, significant improvements in environmental impact criteria are seen in the case where ethanol production is maximized (T1S1). A correlation is observed between greater changes in the original landscape (especially from corn and soybean land to perennial grasses) and increases and decreases in beneficial and detrimental environmental impacts, respectively, in the analysis.



(a)

Figure 5.4: (a) Percentage increases in beneficial environmental impact categories (Scale ranges from 0 to 120 % in the figure) **(b)** Percentage decreases in detrimental environmental impact categories under various scenarios in reference to the baseline (Scale ranges from 0 to 105% in the figure). Notation: T = test, S = scenario. The figure shows tests 1 (maximize ethanol), 2a (minimize erosion), 2b (maximize Δ SOC), 3a (minimize N loss), 3b (minimize P loss), 3c (maximize CWUE), 4 (minimize FGE) in combination with the two scenarios (S1- technical potential of landscape, S2- opposition to conversion of conventional landscapes)

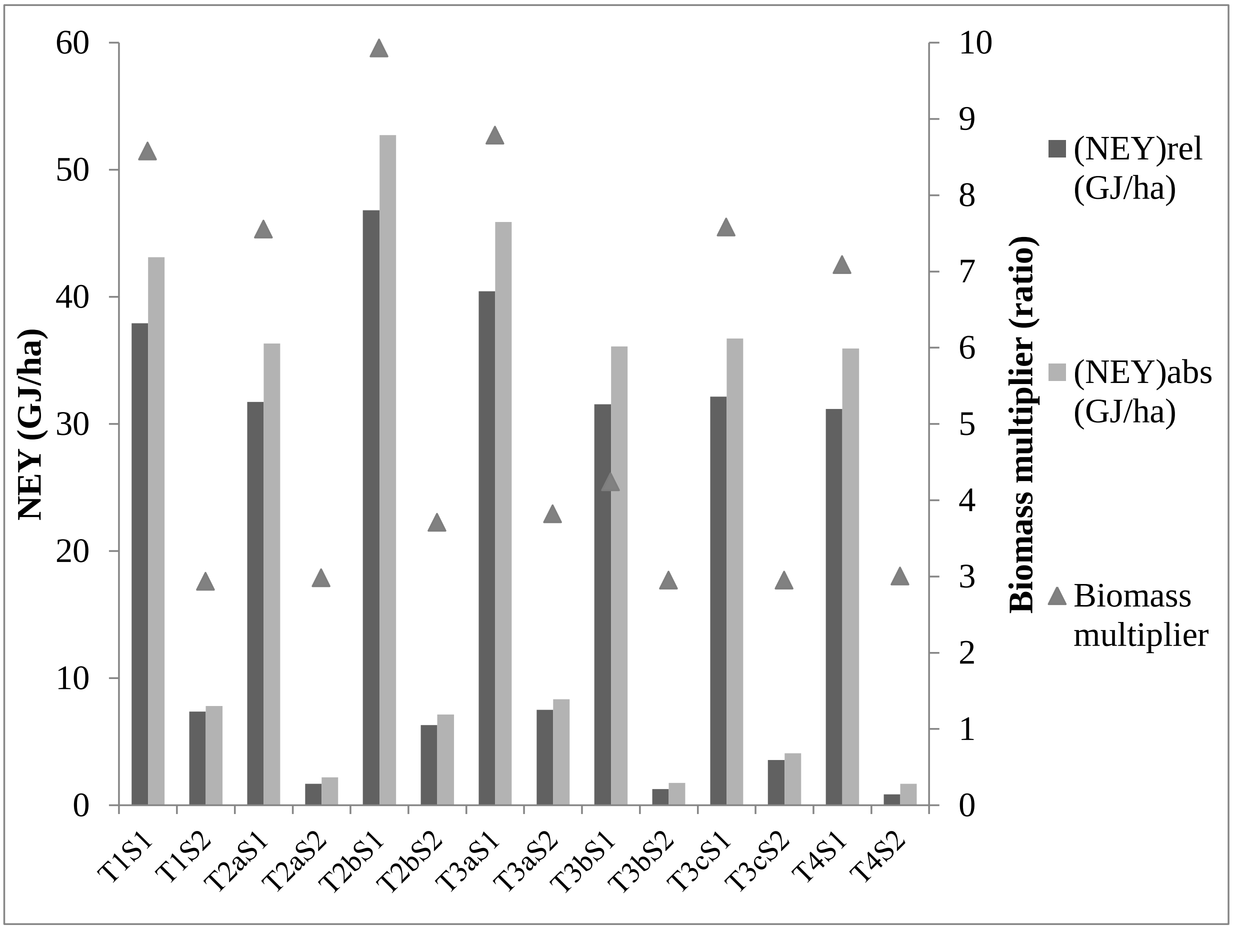
Figure 5.4 (Cont'd)



(b)

5.3.2. Net energy yields and net GHG emission reductions

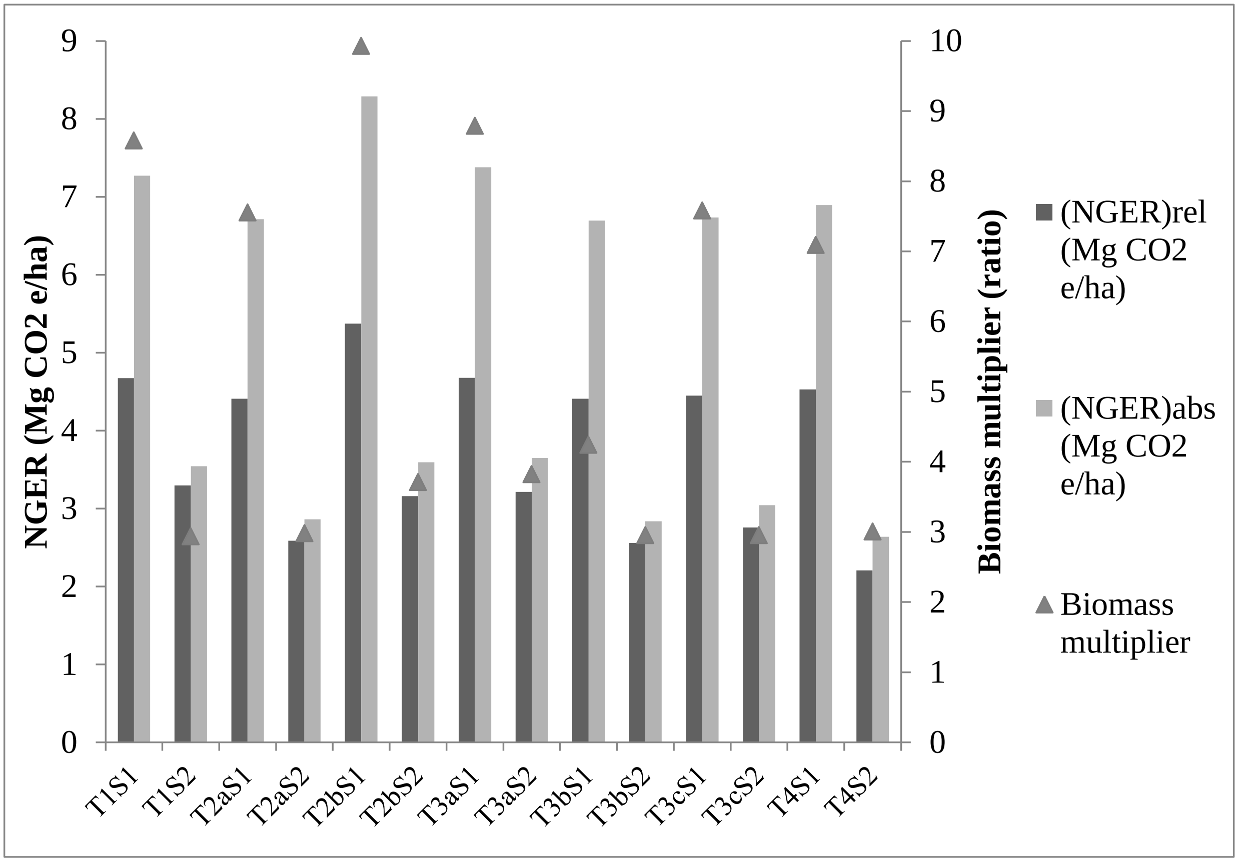
As defined in Chapter 4, the "biomass multiplier" (BM) is the ratio of total cellulosic biomass generated in each new reconfigured landscape to the cellulosic biomass currently generated in the RIMA. In the reconfigured landscape cellulosic biomass comes from switchgrass, miscanthus, native prairie grasses, stover, alfalfa, grass hay and buffer strips. The current cellulosic biomass (the denominator in the biomass multiplier ratio) includes only forage feedstocks grass hay and alfalfa since no stover is assumed to be currently harvested in RIMA for either biofuel production or as a co-product (animal feed).The biomass multiplier varies from as high as 9.9 in the greatest NEY case to 3.0 in the lowest NEY case. This implies that the new reconfigured landscape can provide nearly 10 times as much cellulosic biomass as the original landscape. Figure 5.5 shows the NEYs and NGERs in all cases both in absolute and relative values (compared to original landscape as defined in the *life cycle assessment* section) for the reference flow of one hectare of land area generating biomass in the RIMA. Figure 5.5 also relates the biomass multiplier and NEYs, NGERs. The value of BM remains approximately a constant in all tests in S2 because the landscape does not change significantly to generate substantially greater biomass. Overall, the greater the value of BM, the greater the NEYs and NGERs. A general trend consistent with all tests is that S2 (i.e.; opposition to conversion of landscapes from conventional feedstocks) has lower NEYs and NGERs compared to S1. In S2 relatively more stover and forages and less perennial grasses are used to generate ethanol while also meeting animal feed requirements.



(a)

Figure 5.5: (a) Relative and absolute net energy yields (NEY) and biomass multiplier (BM). NEY = Energy outputs of ethanol and electricity - energy inputs of feedstock, transport and processing modules **(b)** Relative and absolute net greenhouse gas emission reductions (NGER) and biomass multiplier (BM). NGER = CO_2 e. emissions displaced due to ethanol and electricity minus CO_2 e. emissions generated due to feedstock, processing and transport modules. BM is defined as the ratio of total cellulosic biomass generated in the reconfigured landscape to that generated in the original landscape.

Figure 5.5 (Cont'd)



(b)

The energy generated from such minor changes to the landscape is not sufficient to greatly exceed the energy inputs of producing, processing and transporting the feedstocks. This is due to 78% lower biomass yields of corn stover and 52% lower yields of forages on average compared to perennial grasses. Similarly, some NGERs in scenario 2 are low since emissions reductions are not substantial in the reconfigured landscapes compared to the original configuration. For example in T4S2, where the model does not generate any changes in landscape (Table 1), the lowest NEY as well as the lowest NGER is observed. Table 2 shows the ranges of relative and absolute NEYs and NGERs in the two scenarios.

Interestingly, in the ethanol production case (T1), maximizing the BM instead of directly maximizing ethanol production in the model generates a greater NEY and NGER. Specifically, 18% greater NEY and 8% greater NGER are seen in the case where BM is maximized compared to where ethanol production [i.e. biomass tonnage (ton) * ethanol yield (gal/ton)] is directly maximized in T1. This is probably because ethanol yields (per kg feedstock) are assumed to be similar in the model inputs for all feedstocks whereas there are significantly greater differences between biomass yields of perennial grasses, especially miscanthus, compared to other cellulosic ethanol feedstocks. Therefore, in the case where ethanol production is maximized, the model does not drive the landscape towards any one particular feedstock. However, where BM is maximized, the model drives the landscape towards generating larger amounts of perennial grasses. Similarly, in the scenarios that focus on environmental impacts (such as minimizing N losses or maximizing ΔSOC gains), the model drives the landscape towards growing more perennial grasses due to large differences in environmental impacts of perennial grasses compared to their conventional counterparts (such as corn).

Table 5.3 summarizes the range of NEY and NGER values observed in different scenarios. Since the processing and transport assumptions may vary in different analyses but the farm level assumptions remain constant for the given set of landscape configurations in this analysis, Table 5.3 also contains NEY and NGER ranges at the farm-gate level for the different scenarios.

Table 5.3: Ranges of NEY and NGER in different scenarios, ranges of NEY and NGER at the farm gate

	NEY		NGER	
	Relative	Absolute	Relative	Absolute
	--------- GJ/ha ---------		-------- Mg CO_2 e./ha --------	
Integrated LCA				
S1	31.1- 46.8	35.9-52.7	4.4-5.4	6.7-8.3
S2	0.9-7.5	1.7-7.8	2.0-3.2	2.6-3.7
Farm-gate				
S1	34.9-53.7	39.7-59.6	5.5-7.0	7.9-9.9
S2	3.4-10.3	4.3-11.2	2.7-3.9	3.2-4.2

The model also shows several significant correlations between various parameters, seen in Figure 5.6. First, the model shows a direct positive correlation between beneficial environmental impacts and the biomass multiplier, BM. This relationship is primarily driven by the percentage of perennial grass land present in the landscape. Increasing the amount of perennial grasses in the landscape leads to greater BM which in turn leads to increases in beneficial environmental impacts and decreases in detrimental environmental impacts. NEY increases parallel the increased biomass multiplier. This is because greater NEYs are generated in scenarios with more perennial grasses which in turn are linked to greater BMs. Similarly, a direct positive correlation is observed between increasing BM and increasing NGERs.

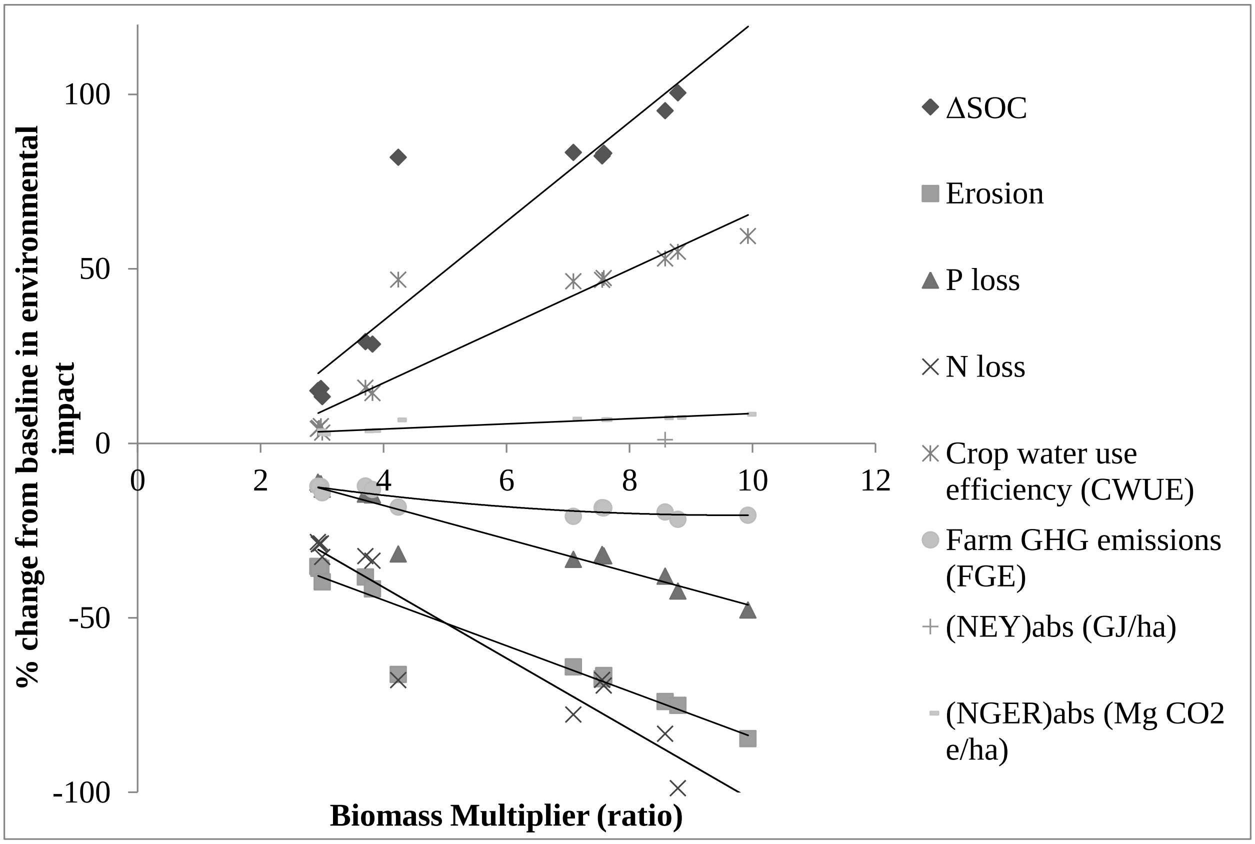
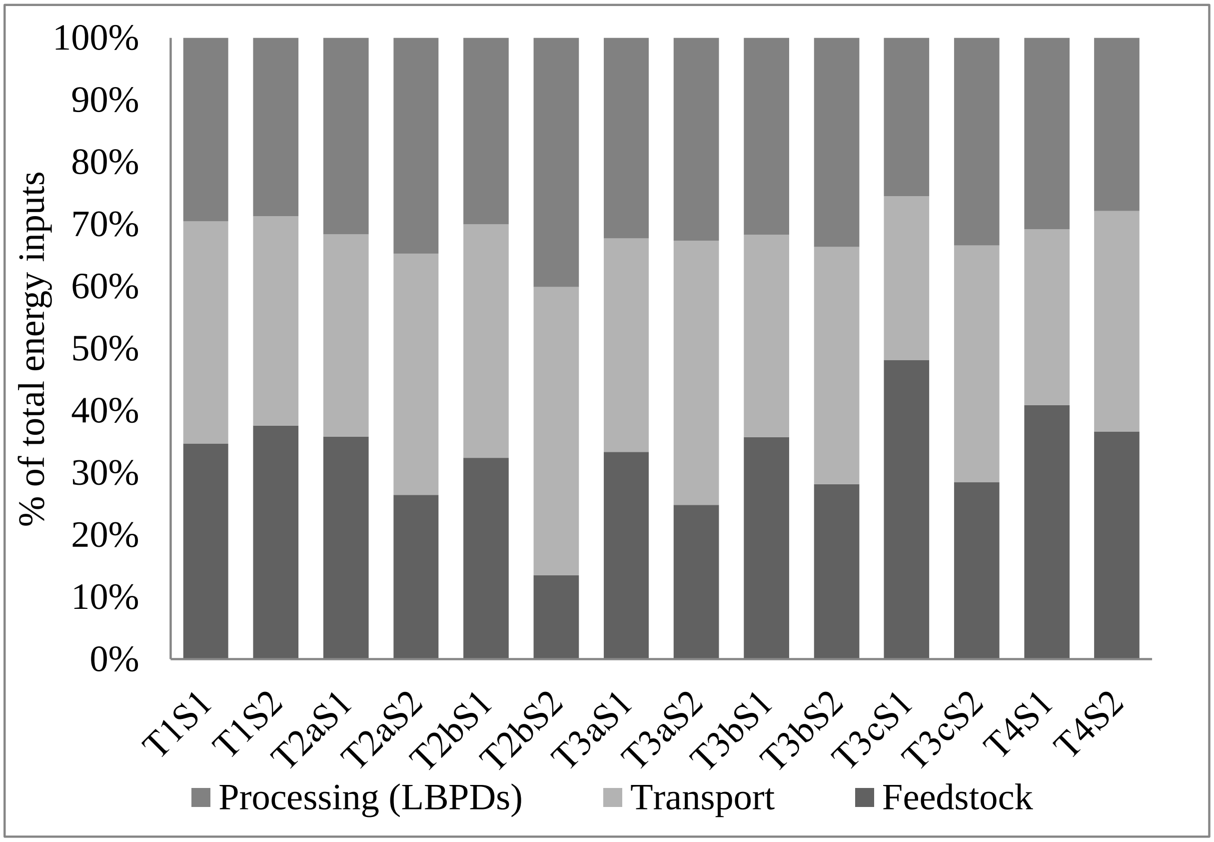


Figure 5.6: Correlations between the biomass multiplier and various system parameters. ΔSOC – change in soil organic carbon. P loss – Phosphorus loss. N loss – Nitrogen loss. $(NEY)_{abs}$ – absolute values of net energy yield. $(NGER)_{abs}$ – absolute values of net GHG emission reductions

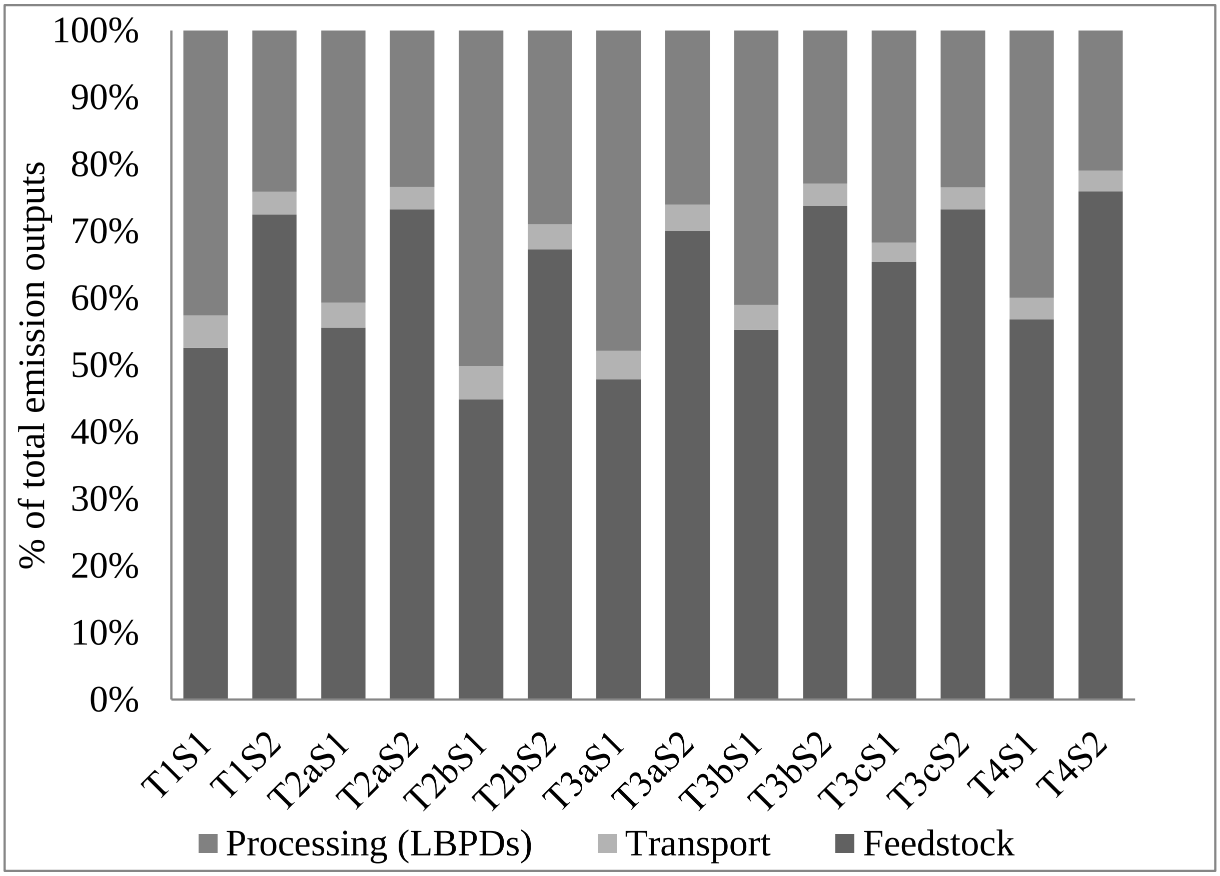
The contribution of the feedstock module to the total energy inputs includes only energy inputs of cultivating new cellulosic feedstocks grown on the landscape but not those of non-cellulosic conventional croplands (corn, soy). The transport module includes transport of all non-densified raw material and pretreated densified products as well as co-products to and from farms, LBPDs and the biorefinery. The processing module includes the energy inputs to the LBPDs. As seen in Figure 5.7 a, in scenario 1, feedstock, processing and transport contribute nearly equally (on average) to the total energy inputs of the overall system. In scenario 2, where lower amounts of cellulosic feedstocks are generated in the landscape, the contributions of feedstock and processing modules to the total energy inputs are lower compared to the transport module. However, the feedstock module has consistently higher emission output contributions in all cases as seen in Figure 5.7 b.



(a)

Figure 5.7: (a) Energy burdens of various modules- feedstock, processing and transport **(b)** Emission burdens of various modules- feedstock, processing and transport.

Figure 5.7 (Cont'd)



(b)

Increased double cropping lowers the total energy co-product credit in this analysis since the crop production energy inputs of the assumed double crop (winter wheat) management scenario is greater (per kg of dry feedstock) than that of soy production. Since double cropping can enhance both total biomass production and positive environmental impacts, it will be important to understand how its energy efficiency can be improved. The biochar co-product credit remains same in all cases since the amount of forest residue collected does not vary between scenarios.

The number of LBPDs varies in each scenario ranging from as low as 8 LBPDs in the low biomass production scenarios to as high as 18 in the high biomass production scenarios and the depots range in average processing capacities from 600 to 750 (short) tons/day (tpd). Biorefinery processing inputs and carbon dioxide emissions associated with processing in the biorefinery are assumed to be zero since these requirements are covered by burning lignin to produce steam and electricity.

5.3.3. Sensitivity analyses

Sensitivity analyses were performed on the scenario with the greatest NEY and NGER namely, T2bS1 (maximizing ΔSOC). This was done by increasing and decreasing by 25% parameters such as percentage of conventional animal feed (corn, soy, grass hay, alfalfa) currently used as animal feed, ethanol and biomass yields of perennial grasses and doubling and halving the constraint of ratio of new vs. old animal feed requirements in the categories of TNPDN, protein, fiber and oil. Percentage differences between NEYs and NGERs obtained in the sensitivity analyses vs. the original scenario, T2bS1 were calculated. Figure 5.8 shows all eight cases of sensitivity analyses. A 25% decrease in perennial grass ethanol yield causes the NEY to decrease by 58% and NGER to decrease by 27%. Since in T2aS1 perennial grasses dominate the new landscape, a decrease in their ethanol yield leads to decreases in NEY and NGER. For similar reasons, a 25% decrease in perennial grass biomass yields causes a 50% decrease in NEY and a 26% decrease in NGER. A 25% increase in the amount of conventional crops used as animal feed causes NEY to decrease by 54.5% and NGER to decrease by 32%. This is because more pretreated cellulosic biomass has to be diverted from ethanol production to compensate for increases in animal nutritional requirements, thereby decreasing NEY and NGER. For similar reasons, doubling the upper limit of new/old animal nutritional requirements (a constraint that diverts more pretreated biomass to animal feed instead of to ethanol production) causes a 54% decrease in NEY and a 30% decrease in NGER. However, a 25%

increase in perennial grass biomass and ethanol yields or decreasing the amount of animal feed requirements causes relatively less significant increases in NEY and NGER.

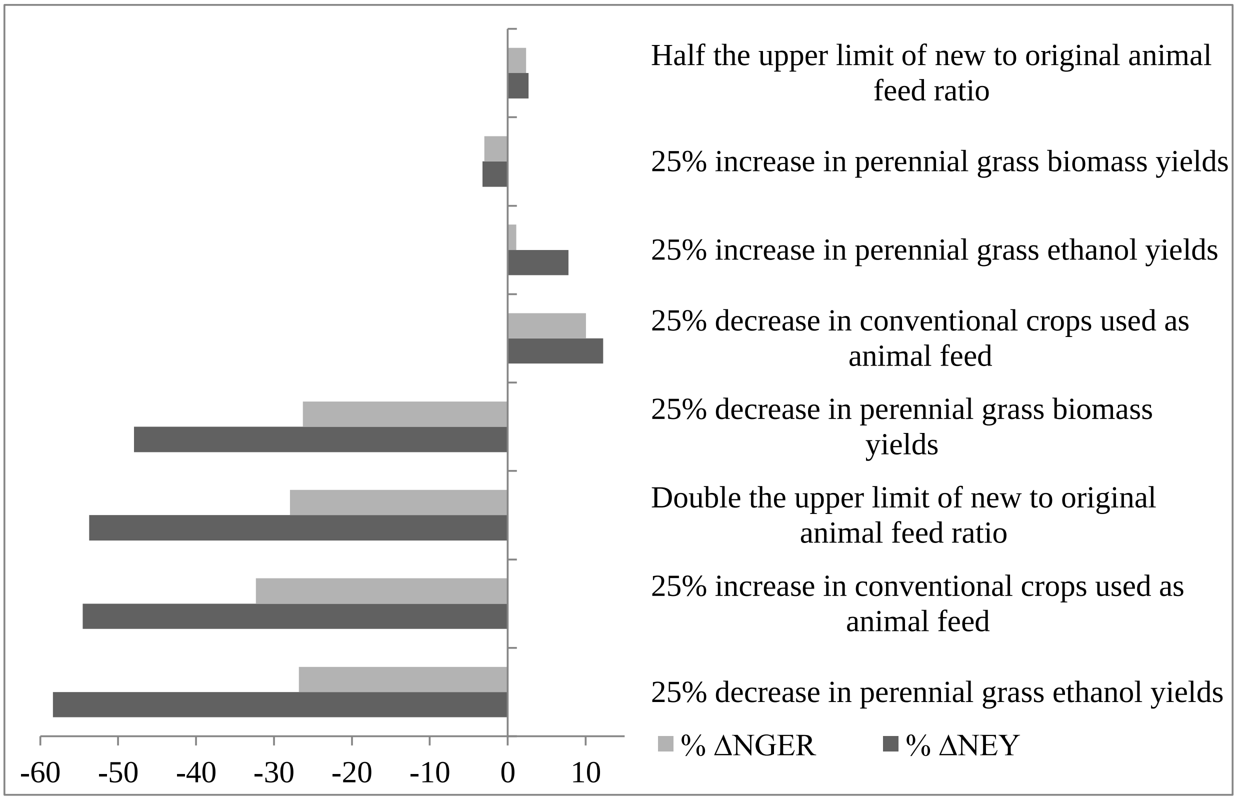


Figure 5.8: Results of sensitivity analyses performed in the WORLD model on Test 2b (maximizing ΔSOC) in Scenario 1(technical potential of landscape). This test, scenario combination was chosen to perform sensitivity analyses since this is the case where the greatest NEY and NGER are obtained.

5.4. Conclusion

Depending on the cellulosic biomass production in different scenarios, either 970 million liters of ethanol in the technical potential scenario or just 82 million liters of ethanol in the opposition to conversion scenario can be generated from the same area of interest (RIMA). NEY values in the range of 20-57 MJ/L of ethanol and NGER values in the range of 9-37 kg CO_2 e. /L of ethanol are obtained in new reconfigured landscapes within this RIMA area. Moreover, maximizing cellulosic ethanol production leads to significant improvements in positive environmental impact categories and substantial decreases in detrimental environmental impacts.

Simulations of realistic landscapes are needed to determine the potential of any region to produce biofuels without displacing food/feed provisioning services or creating negative environmental impacts. If the crops planted in a landscape are altered (in S1 where there is 60-77% change in the land cover from conventional to new feedstocks) and sustainable management practices (such as the use of marginal lands, reduced fertilizer use and no-till farming) implemented, significant net energy yields may be obtained and GHG emissions may be reduced while maintaining or potentially increasing animal feed production. Moreover, introducing perennial grasses in the landscape will increase soil organic carbon by 120% (compared to baseline) and also improve (by 20 -100%) other impact categories such as minimizing erosion, improving crop water use efficiency, and reducing N and P losses and farm GHG emissions. However, neither substantial net energy yields nor emission reductions and decreases in other negative environmental impacts are obtained when the landscape is not changed (e.g. in scenario S2 in which the landscape changes between 7- 14% from conventional to new feedstocks). Additionally, minimizing environmental impacts (such as increasing ΔSOC and minimizing N losses) leads directly to greater net energy yields and greater GHG emission reductions. The opposite also holds true, where maximizing cellulosic ethanol production leads to lower detrimental environmental impacts. Similarly, environmental impacts seem to be strongly linked. Aiming to minimize one adverse impact also helps minimize others. These improvements in environmental impacts are in turn linked to greater perennial grass production in the landscapes.

Commercial cellulosic biofuel refineries are currently being built and many more are expected in the future as crop production and processing technologies improve. This study provides a foundation for a novel approach to cellulosic biomass production that may help resolve biomass supply and supply chain constraints as biofuel demand increases. Using this comprehensive modeling approach, the most promising scenarios for cellulosic biofuel supply chains can be identified. The depot network helps bridge the gap to cellulosic biofuel commercialization by providing valuable co-products for biofuels and thereby creates more market demand in order to establish such biofuel systems. Greater energy and environmental benefits accrue to the overall system beyond simply improved logistics when the challenges associated with biomass supply and processing are minimized. By implementing land efficient techniques and by producing valuable co-products close to the feedstock operations, depot networks can respond to local and global sustainability concerns while simultaneously increasing feedstock value.

In summary, the scenarios presented here were chosen mainly to illustrate model capabilities. In reality, the landscape may be somewhere between the various extremes shown here. The WORLD model may be included in a larger-scale multi-optimization model to determine the combined effects of energy yields and environmental impacts. Improvements can also be made in the model with regard to calculating detailed water-quality impacts after planting perennial grass buffer strips and simulating a true double crop (such as winter rye) in place of an assumed double crop (winter wheat) used in the analysis. The model may also be expanded to include economic aspects of the various modules in the overall system. Alternatively, the model may be linked to agricultural economic models to assess profits earned by farmers under various landscape configurations. The methodology adopted in this analysis can be applied to a wide range of landscapes, feedstocks and flexible depots to evaluate the net energy returns and the environmental benefits of this new approach to developing supply chains for cellulosic biofuels.

The WORLD model and its inputs in an integrated LCA can be applied to many regions of interests and many different scenarios and might be further developed to serve as a decision making tool for growers, industries or policy-makers.

APPENDIX C

5.5. Appendix C

C.1. A summary of technologies in the local biomass processing depots [LBPD]

The “base-technologies” included in all depots are pretreatment and densification, including all pre-processing steps such as biomass handling, size-reduction, etc. The use of other technologies in the depots is dictated by the characteristics of the landscape generating the biomass.

The Ammonia Fiber Expansion (AFEX$^{\mathbf{TM}}$) process is a pretreatment method where hot concentrated ammonia is mixed with moistened herbaceous biomass under pressure. After the desired treatment time is complete, the pressure is then rapidly released causing the system to cool and the ammonia is recovered[31]. AFEX$^{\mathbf{TM}}$ is used as the pretreatment method in all processing facilities because of its apparently unique suitability within the depot arrangement. AFEX$^{\mathbf{TM}}$ adds value to biomass as a highly-digestible fiber-based animal feed, which is economically the most important co-product from the depots [32, 33].

Mechanical compaction or densification of biomass into pellets or briquettes post-pretreatment can increase the bulk density of cellulosic feedstocks from as low as 60 kg/m^3 to as high as 800 kg/m^3, significantly reducing transport, handling and storage burdens associated with the depots [23, 34]. Coupling densification with AFEX$^{\mathbf{TM}}$ pretreatment may also reduce the cost of densification because lignin brought to the surface during AFEX$^{\mathbf{TM}}$ eliminates the need for added binders (e.g., starch or protein) or curing agents (e.g., steam) to promote binding [32, 34, 35].

The leaf protein concentrate (LPC) extraction process involves pulping and pressing wet biomass to squeeze out a protein rich juice which is subsequently coagulated and dried to obtain a high protein powder [36, 37]. LPC can be applied to any high protein cellulosic biomass such as double crops and forage [33] to obtain a high protein animal feed supplement.

Pyrolysis is the thermochemical conversion of woody residues into biochar, producer gas and bio-oil. Producer gas can be combusted for process heat in the LBPD and bio-char is an important co-product that aids in soil amendment in the landscape[38]. Alternately, biochar can be used as a boiler fuel to substitute for coal[39]. Bio-oil however is an unstable compound that must be further processed for use as transport fuel [40].

In anaerobic digestion (AD) biogas is produced from manure and aqueous waste streams resulting from LPC production. The remaining solid residues after AD are sent back to farms to use as animal bedding or as a soil amendment [41].

Table C1: Acreages of different land categories in the current RIMA landscape

Watershed	**Corn**	**Forage[a]**	**Soy**	**Marginal**	**Buffer strips[b]**
St. Joseph	194506	42420	228603	2504	10152
Upper Grand	22701	12715	23967	115	781
Kalamazoo	153701	50344	125729	1087	7847
Black-Macatawa	31707	11183	19011	231	2295
Thornapple	54782	31998	52274	0	2990

All acreages are shown in acres.

a. Forage includes grass hay and alfalfa. Based on Michigan agricultural statistical data, alfalfa forms close to 75% of total forage land. Therefore, the remaining percentage of total forage land is assumed to be grass hay.

Table C1 (Cont'd)

b. Potentially available acreages of buffer strip are determined based on river bank lengths of major rivers present in the RIMA calculated using the BASINS model and ArcGIS and the assumed width of buffer strips (0.015 mi). However, depending on the scenario, conservative values of 30% (in S1: the technical potential scenario) or 10% (in S2: the opposition to conversion of conventional landscapes scenario) are assumed to be used for growing buffer strips.

Table C2: Feedstocks, management practices and yields simulated in the EPIC model

Feedstock	**Cropping system**	**Number of years simulated**	**Fertilizer application [N,P,K(kg/ha)]**	**Tillage**	**Avg. yields(ton[a]/ac)**
Switchgrass	Switchgrass	24	Medium (60,0,0)	No-till	4.7 - ML 5.4 - AL
Miscanthus	Miscanthus	24	Medium (60,0,0)	No-till	7.3 - ML 8.8 - AL
Native Prairie	Cool season native prairie	24	Medium (60,0,0)	No-till	4.25
Corn[b]	Continuous corn	24	High (175,24,34)	Chisel	2.5
Stover	Corn-soybean rotation with stover removal	12	Medium (110,24,34)	No-till	1.6
Soy[b]	Corn (c)-soybean(s) rotation	12	High (c-135,24,34; s-0,10,0)	Chisel	0.95

Table C2 (Cont'd)

Double crop	Corn(c)-soybean(s)-winter wheat(ww)	8	Medium (c-150,24,34; s-0,10,0; ww-70,24,34)	No-till	1.03
Alfalfa/grass-hay[b]	Alfalfa(A)-corn(c) rotation	15	Medium (A-120,55,0; c-49,21,30)	No-till	3.4
Canola	Corn(c)-soybean(s)-winter canola(wc)	8	High (c-175,24,34; s-0,10,0; wc-95,24,34)	Chisel	1.05
Riparian buffer strips[c]	Avg. of switchgrass and miscanthus	24	Medium (60,0,0)	No-till	6.0

ML = marginal land, AL= arable land.

a. Tons indicate short tons
b. Indicates all feedstocks present in original landscape (baseline).
c. The width of buffer strips was assumed to be about 25 m, as determined by values in literature [42, 43].

Table C3: Nutritional values of feedstocks assumed in the model to fulfill animal feed requirements

Nutritional values (g/g)	TNPDN[a]	Protein	Fiber	Oil
Perennial grasses	0.616	0.014	0.819	-
Stover	0.689	0.067	-	-
Double crop, Alfalfa (LPC)[b]	0.314	0.5	-	-
Canola	0.19	0.202	-	0.42
Corn	0.793	0.094	-	-
Soy	0.268	0.4801	-	0.196
Grass hay	0.464	0.133	0.577	
Alfalfa forage	0.387	0.202	0.396	

[a]TNPDN = Total non-protein digestible nutrients

[b]LPC indicates the protein powder extracted from alfalfa

Table C4: Environmental impacts of feedstocks from the EPIC model

Feedstocks	ΔSOC[a] (Kg CO_2/ac)	P loss (Kg P/ac)	N loss(Kg N/ac)	Erosion (Mg soil/ac)	CEF[b](Kg CO_2/ac)	N_2O emissions(kg/ac)	GHG[c](N_2O and CO_2)	Water use efficiency[d] (ton/ac/ML)
Switch grass	79	1.01	11	1.63	129	2.02	79	1.01
Miscanthus	929	0.77	10	1.18	128	2.25	929	0.77
Native prairie (cool season)	-152	0.92	20	0.65	126	2.03	-152	0.92
Continuous Corn	-663	2.01	55	4.09	379	2.85	-663	2.01
Continuous corn with stover removal	-465	1.37	14	0.73	168	1.48	-465	1.37
Corn-Soy	-476	1.60	19	2.74	236	1.45	-476	1.60
Corn-soy-DC	-504	1.47	19	0.70	193	1.40	-504	1.47
Alfalfa-corn	-499	1.76	29	2.26	156	2.14	-499	1.76
Grass hay	-169	1.63	25	1.77	140	2.27	-169	1.63
Buffer strips	504	0.89	10	1.40	129	2.14	504	0.89
Canola	-190	1.60	26	1.97	271	1.48	-190	1.60

Table C4 (Cont'd)

a. ΔSOC = change in soil carbon (final-initial). Negative values indicate loss of carbon which is detrimental to the soil. Perennial grasses are the only feedstocks that have a positive ΔSOC. The native prairie in this case does not have a positive ΔSOC since it is not an unmanaged prairie but a fertilized one. Therefore grass hay and the native prairie have comparable ΔSOC values.
b. CEF =farm CO_2 e. carbon emissions.
c. GHG emissions are calculated as: CEF+310*N_2O emissions; Where 310 is the global warming potential factor for nitrous oxide.
d. Water use efficiency is defined in this study as yield of plant product per unit of crop water use (megalitres of water lost due to evapotranspiration)

Table C5: Energy inputs of different feedstocks from literature and agricultural budgets

Feedstock	MJ/kg dry feedstock
Corn	1.776114
Stover	1.316816
Alfalfa/grass hay	0.772898
Switchgrass	0.311055
Miscanthus	0.145963
Native prairie	0.211205
Double crop	3.784182
Soy	2.57445
Canola	2.467036
Buffer strips	0.228509

Table C6: Cellulosic ethanol and electricity yields of different feedstocks assumed in the model

Cellulosic feedstock	Ethanol yield (gal/ ton)	Electricity yield (KWH/ton)
Stover	66	335
Switchgrass	66	334
Miscanthus	64	413
Native prairie	50	389
Grass hay/alfalfa(mixes)	66	294
Winter rye (double crop)	50	327

C.2. Transport calculations

LBPD to biorefinery distances were determined by combining the road network map in the BASINS model with the Arc GIS software to calculate the shortest routes from each LBPD to the central biorefinery. Using this method the processing depots and central refinery were located within the RIMA. Transport distances (collection areas and radii) of raw materials (herbaceous feedstocks, animal manure and forest slash where applicable) to LBPDs and co-products (pretreated animal feed, LPC solids, AD sludge and biochar where applicable) from LBPDs back to farms were determined using formulae from literature[44]. Transport distances for finished products (pretreated biomass to biorefinery and bio-oil where applicable) were determined using the US EPA BASINS and Arc GIS softwares. A 20% road winding factor was applied to these calculated values to account for non-linear road networks. Densified and non densified transport were differentiated by modifying the cargo payload (or truck capacity) suitably (higher payload for densified material vs. lower for non-densified) in GREET 1.8b[30]. Formula for collection distances from farms [44]:

$$\text{Collection area (mi}^2\text{)} = ß / [\delta * \rho * (1 - I) * \lambda * 640]$$

Where ß= biomass collected (dry tons/ yr), δ= density of feedstock acreage, ρ= % of farmers selling feedstock, I = % of fields inaccessible, λ= biomass yield. δ is calculated for each watershed based on acreages generating biomass (ratio of all the land area used to generate biomass in each watershed to the total land area of the watershed) . 'ß' varies in all cases based on land areas allocated to different feedstocks. 'λ' varies among feedstocks. In Scenario 1 (technical potential), 'ρ' is assumed to be 90% whereas in Scenario 2 (opposition to conversion of conventional landscapes) 'ρ' is assumed to decrease significantly to 30%. 'I' is assumed to remain constant in both scenarios at 10%.

Table C7: Transportation distances for all raw-materials and co-products

Watershed number	Distance from feedstock and animal farms to LBPD and vice-versa (mi)							Distance from LBPD to biorefinery (mi)
	Scenario 1							
	T1	T2a	T2b	T3a	T3b	T3c	T4	All cases
1	10.75	10.99	11.60	10.79	10.89	10.87	9.65	50
2	2.34	3.40	3.53	3.77	3.30	3.52	2.64	20
3	8.65	9.08	9.79	10.21	8.97	8.94	7.49	50
4	3.13	3.87	4.57	4.45	4.06	4.03	3.34	20
5	5.34	5.84	6.47	6.29	5.58	5.80	5.30	40
	Scenario 2							
	T1	T2a	T2b	T3a	T3b	T3c	T4	All cases
1	15.67	15.59	15.70	15.76	15.52	15.60	15.68	50
2	4.87	4.94	4.80	5.07	4.80	4.83	4.66	20
3	12.99	13.19	13.14	13.41	13.14	13.20	13.34	50
4	6.31	5.87	6.43	6.51	6.00	6.00	6.07	20
5	8.13	8.19	8.16	8.49	8.47	8.17	8.35	40

Table C8: Transportation energy requirements and emissions

Material transported	Units (energy-emissions)	Transport energy	Transport emissions
Non-densified biomass	(MJ/ton/mi - Kg CO_2 e/ton/mi)	2302	0.204
All other densified herbaceous material and co-products	(MJ/ton/mi - Kg CO_2 e/ton/mi)	734	0.003608
Forest slash	(MJ/ton/mi - Kg CO_2 e/ton/mi)	1511	0.03277
Bio-oil	(MJ/m^3/km - Kg CO_2 e/m^3/km)	2.59	0.143317

C.3. Co-product credit calculations

Co-product credit calculations are performed based on the amount of animal feed generated from each feedstock in the WORLD model. Similarly, co-product credit calculations are performed for emissions displaced due to growing a less emission-intensive feedstock (such as perennial grasses) and using this new feedstock as animal feed instead of a conventional animal feed. Co-product credits are calculated as follows:

$$Energy\ CPC = \alpha * \tau * (ENx * \delta - \mathrm{ENy})$$

$$Emission\ CPC = \alpha * (\tau/\gamma) * (EMx * \delta - \mathrm{EMy})$$

Where CPC = co-product credit for Y displacing X in MJ or kg CO_2 e for energy and emissions respectively, α = animal feed production (kg feed/kg Y), δ = displacement ratio based on nutritional value of feedstock, τ = tonnage of animal feed (tons), ENx and ENy = Feedstock production energy of X and Y (MJ/ton) respectively, EMx and EMy= Farming and sequestration emission of X and Y (kg CO_2 e. / ha) respectively, γ = yield of feedstock (tons/ha)

Here Y is the new animal feed product n and X is the original animal feed product being displaced. The animal feed production value is set at 1. Displacement ratio is defined as kg X displaced/kg Y animal feed produced based on nutritional values of X and Y.

For biochar, emission displacement credits for avoided emissions due to reduced fertilizer use as well as due to avoided soil nitrous oxide emissions are assigned on a per acre basis [38, 45].

C.4. Results of the WORLD model consistency checks (performing multiple runs in each scenario)

The standard error is calculated in each case as standard deviation/ [sq. root of sample size]. Although in this case all calculations were performed on the value of ethanol, these error calculations can be performed with other desired parameters as well.

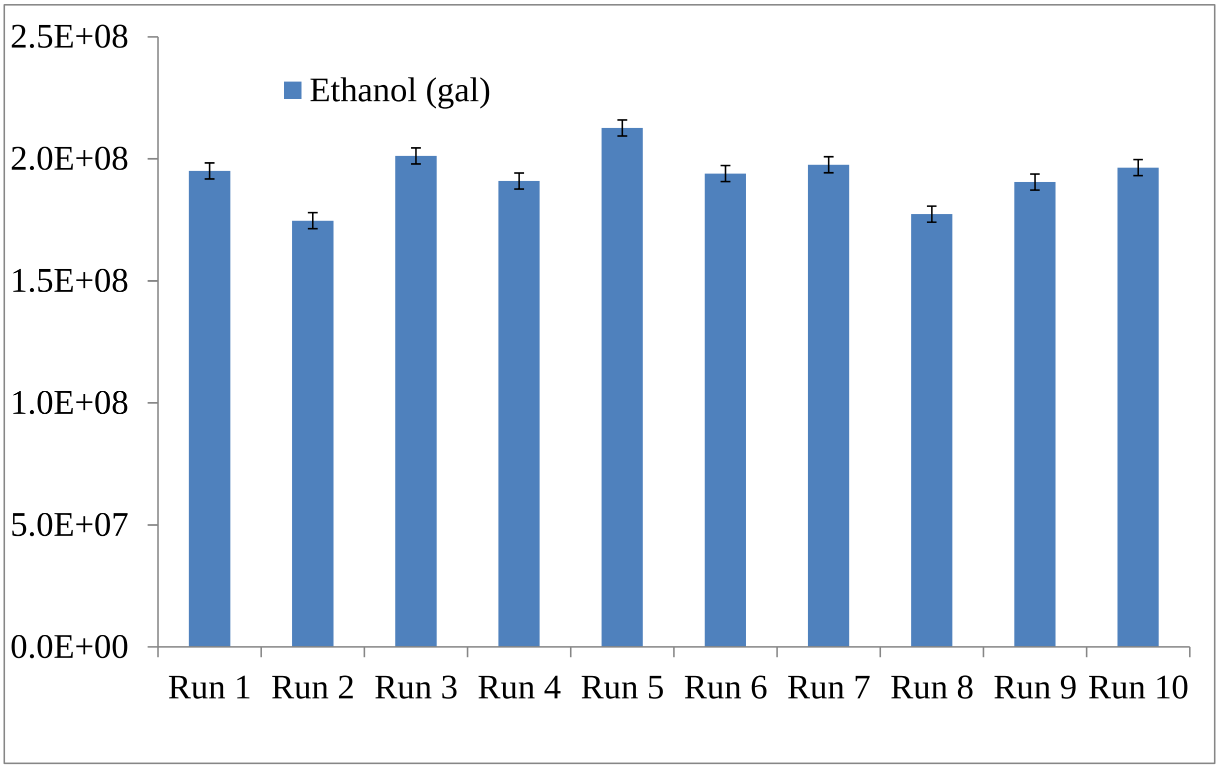


Figure C.1: Consistency check for T1S1

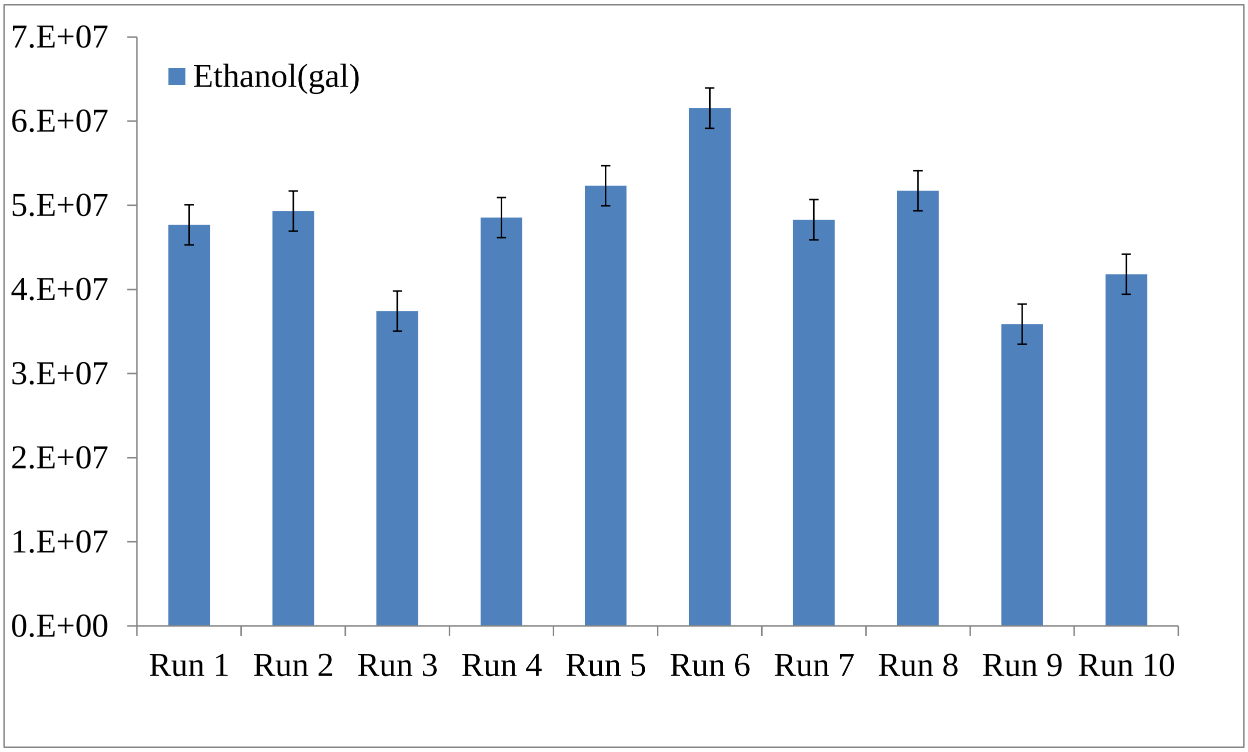


Figure C.2: Consistency check for T1S2

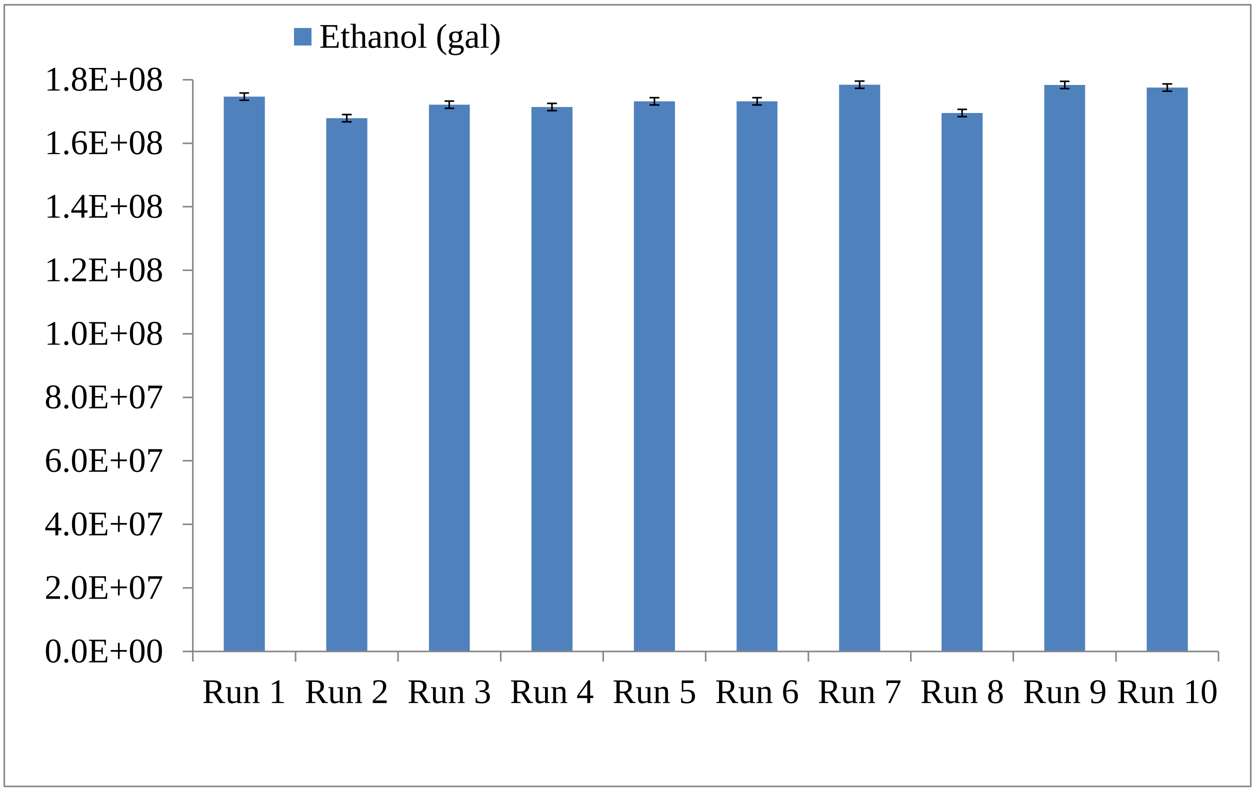


Figure C.3: Consistency check for T2aS1

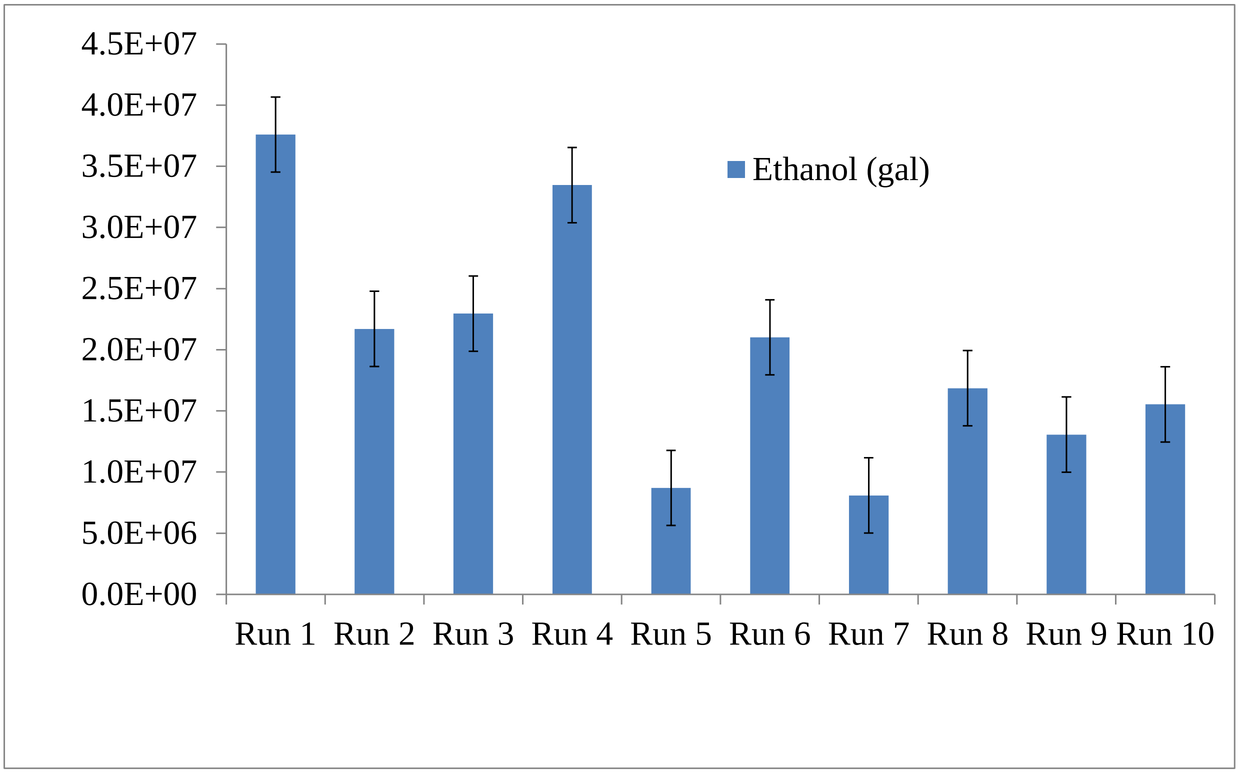


Figure C.4: Consistency check for T2aS2

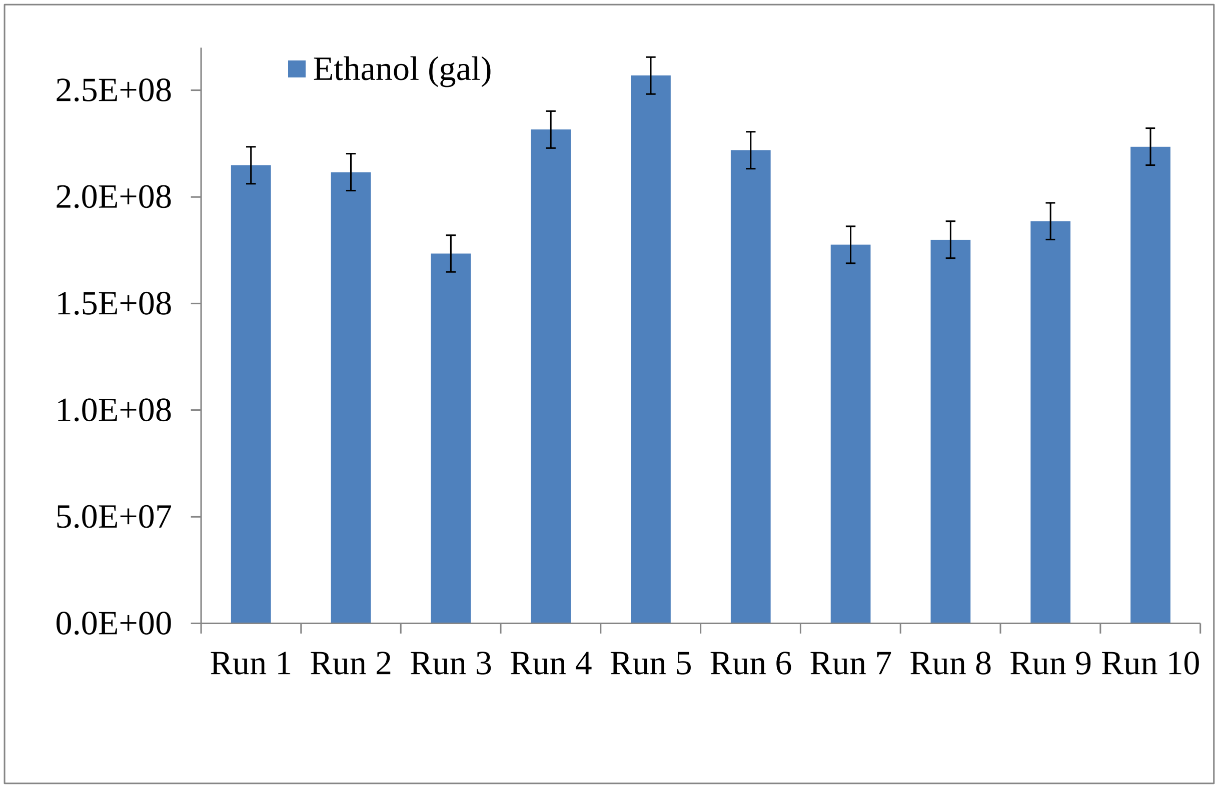


Figure C.5: Consistency check for T2bS1

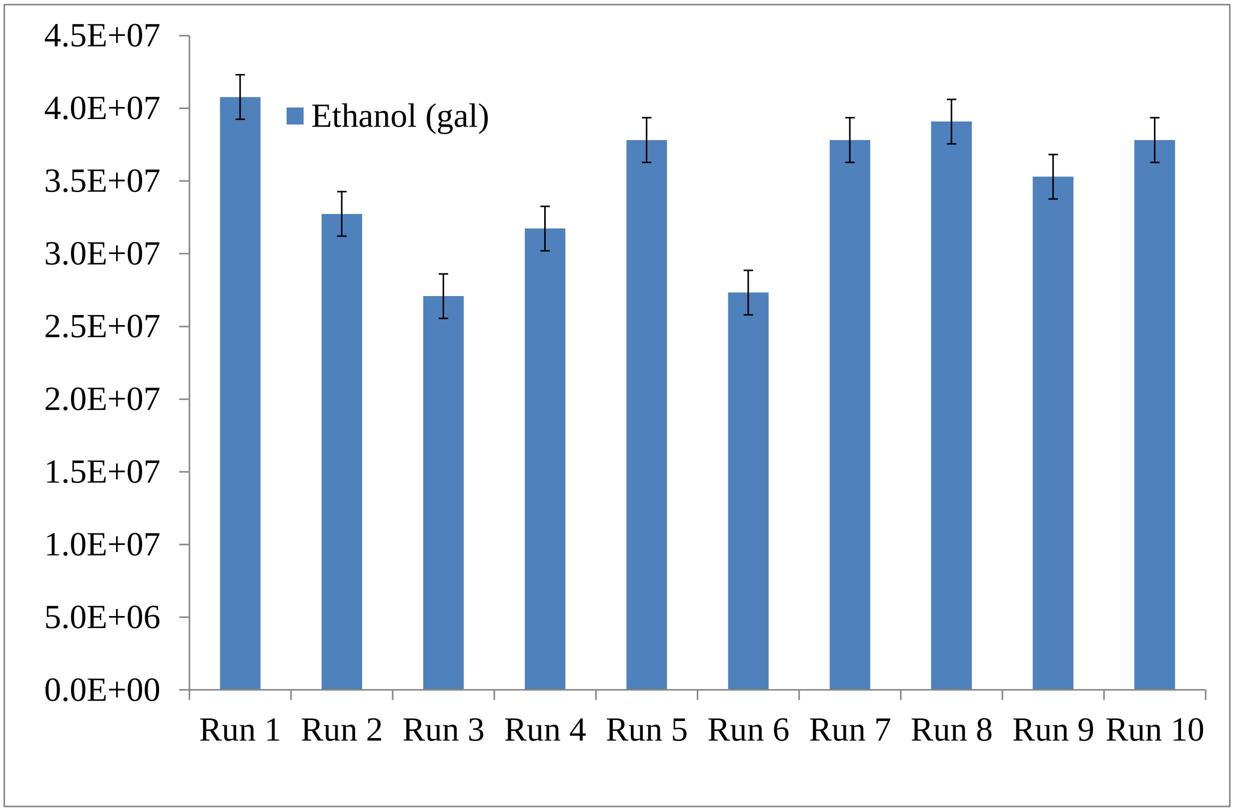


Figure C.6: Consistency check for T2bS2

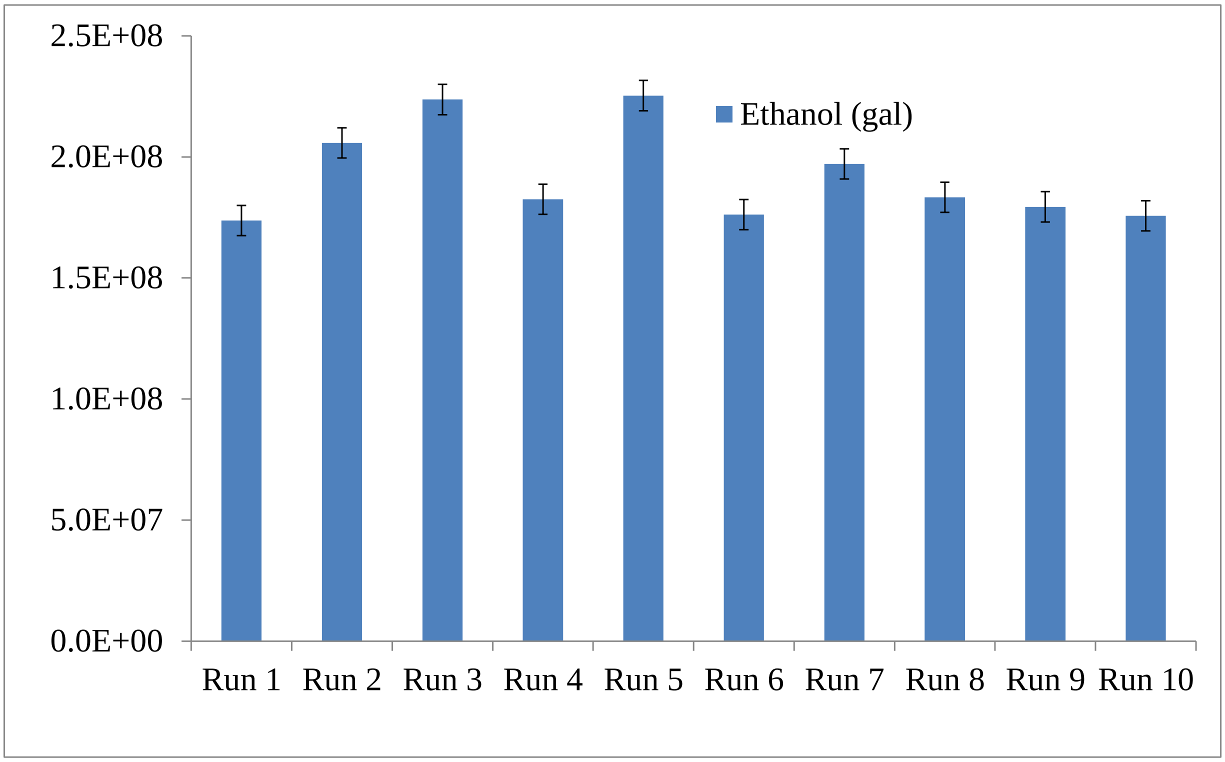


Figure C.7: Consistency check for T3aS1

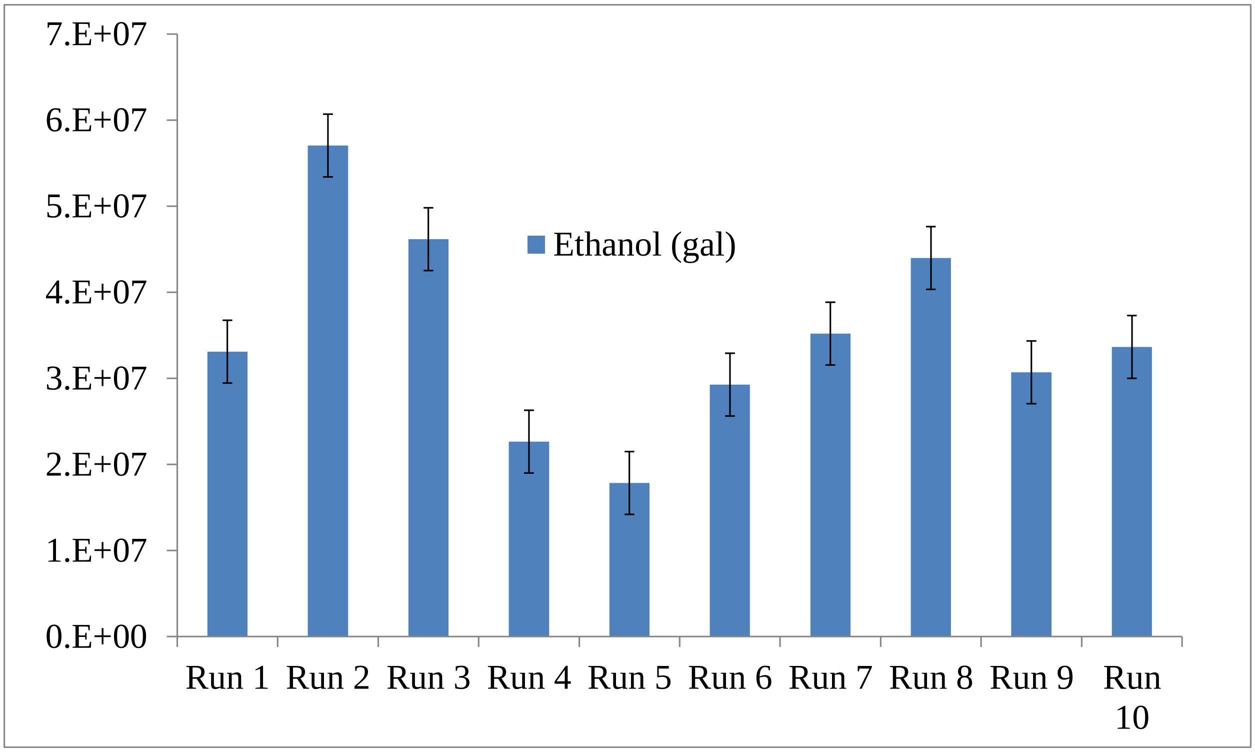


Figure C.8: Consistency check for T3aS2

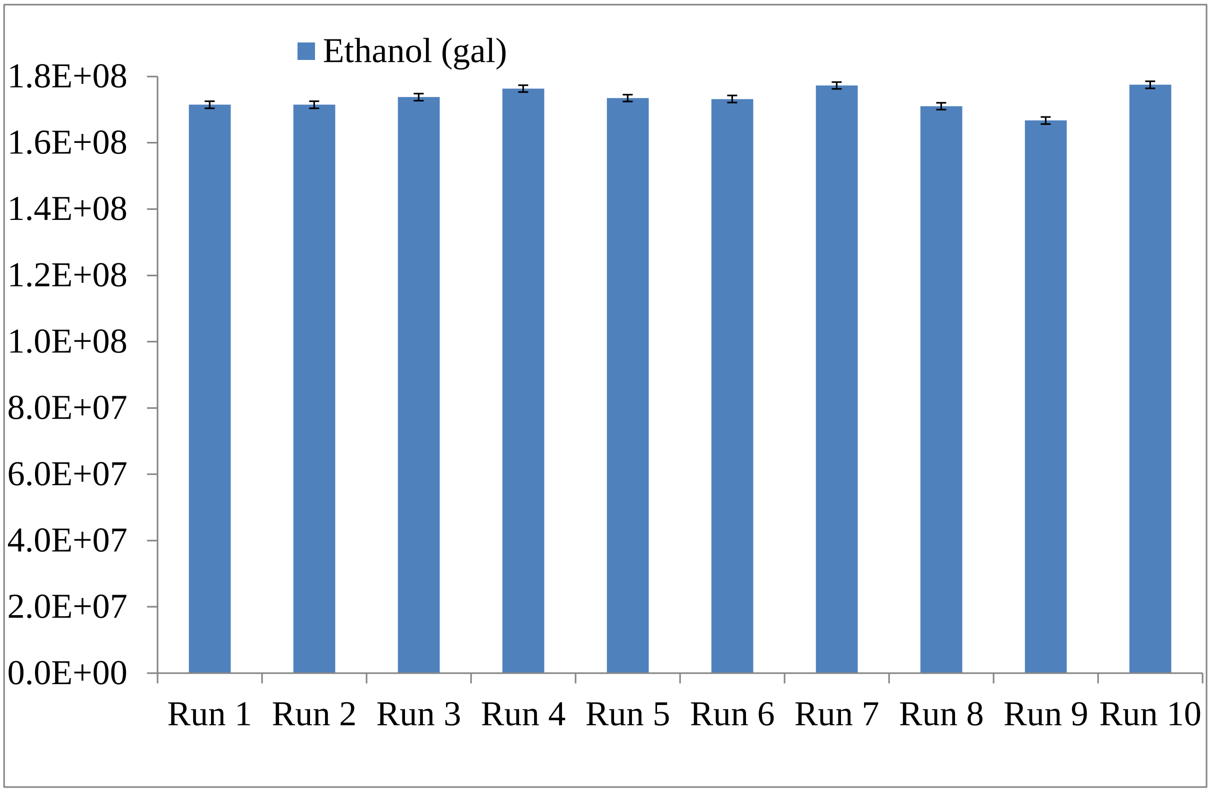


Figure C.9: Consistency check for T3bS1

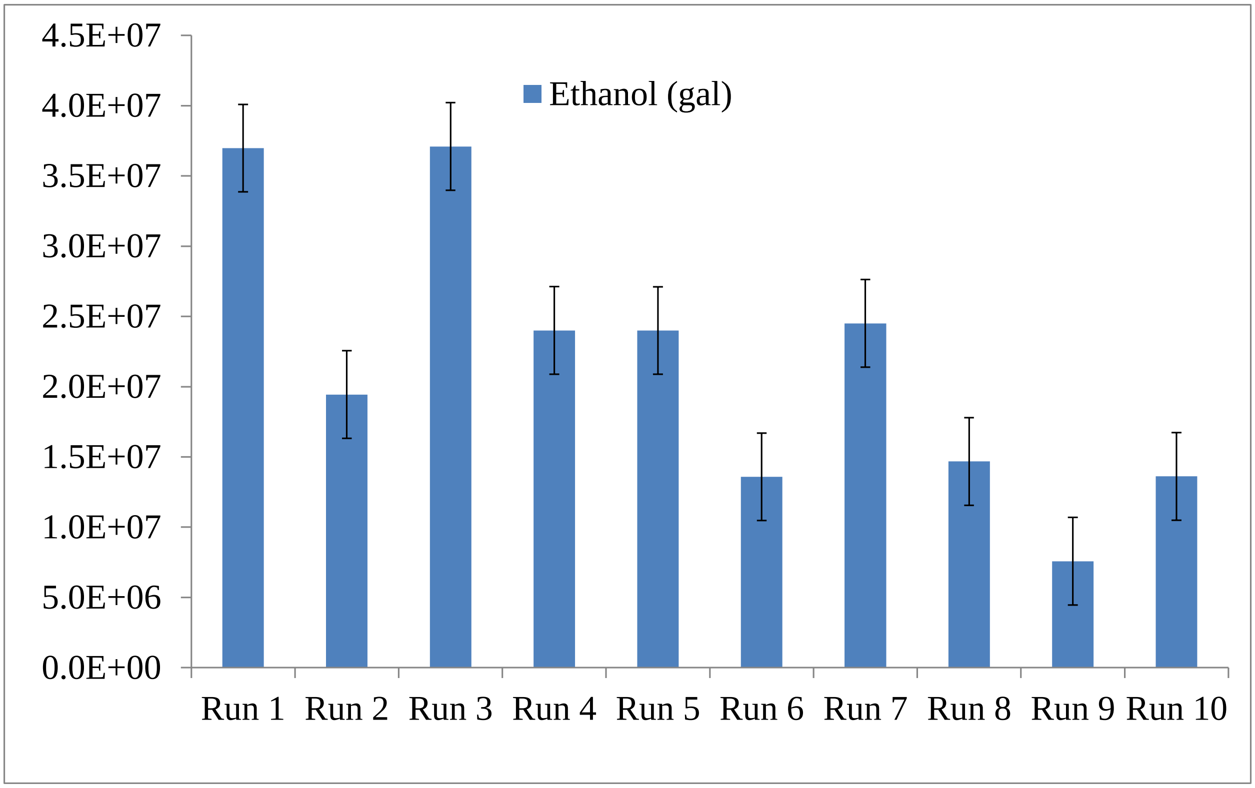


Figure C.10: Consistency check for T3bS2

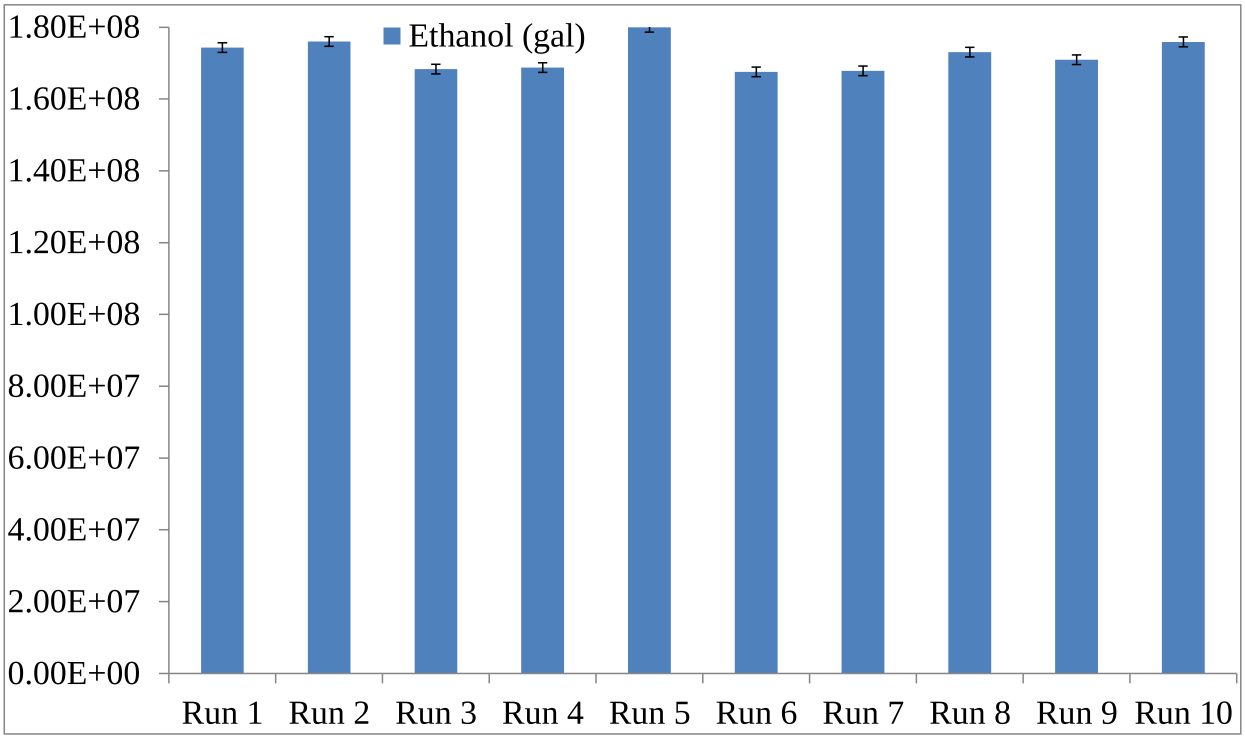


Figure C.11: Consistency check for T3cS1

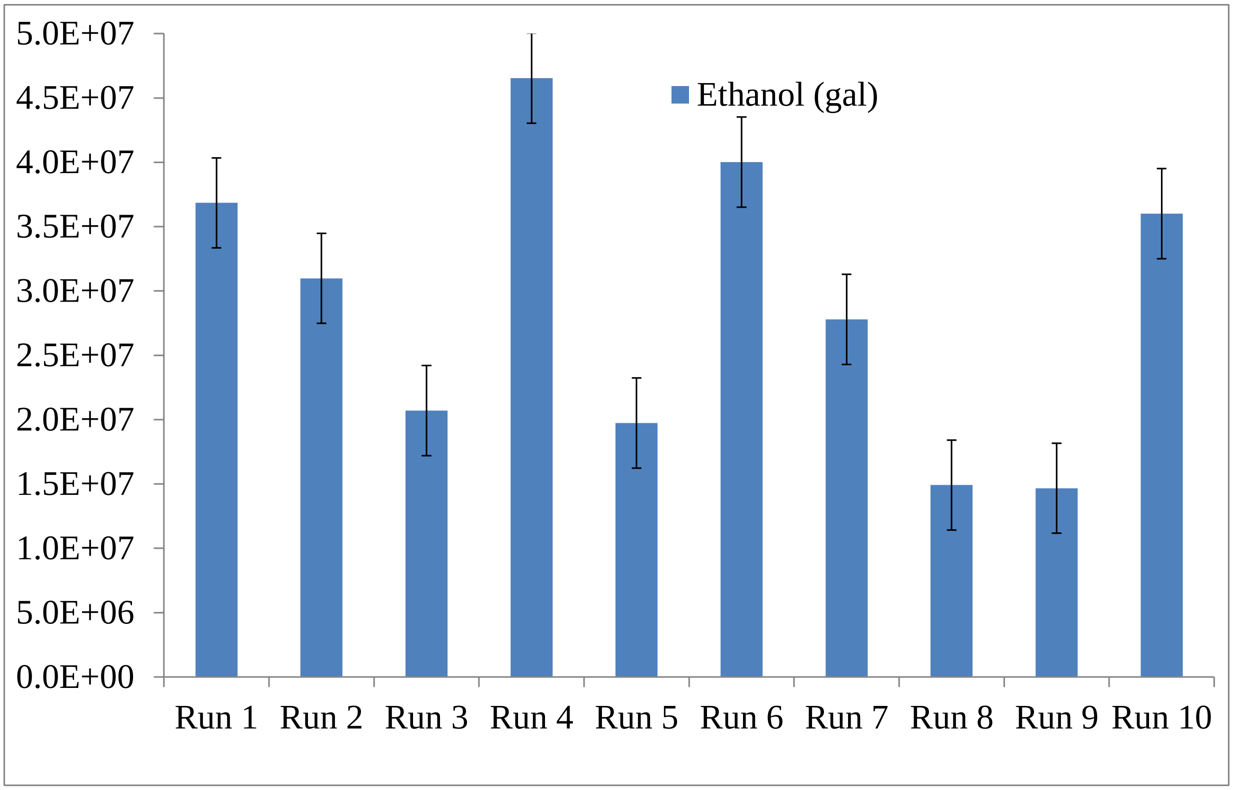


Figure C.12: Consistency check for T3cS2

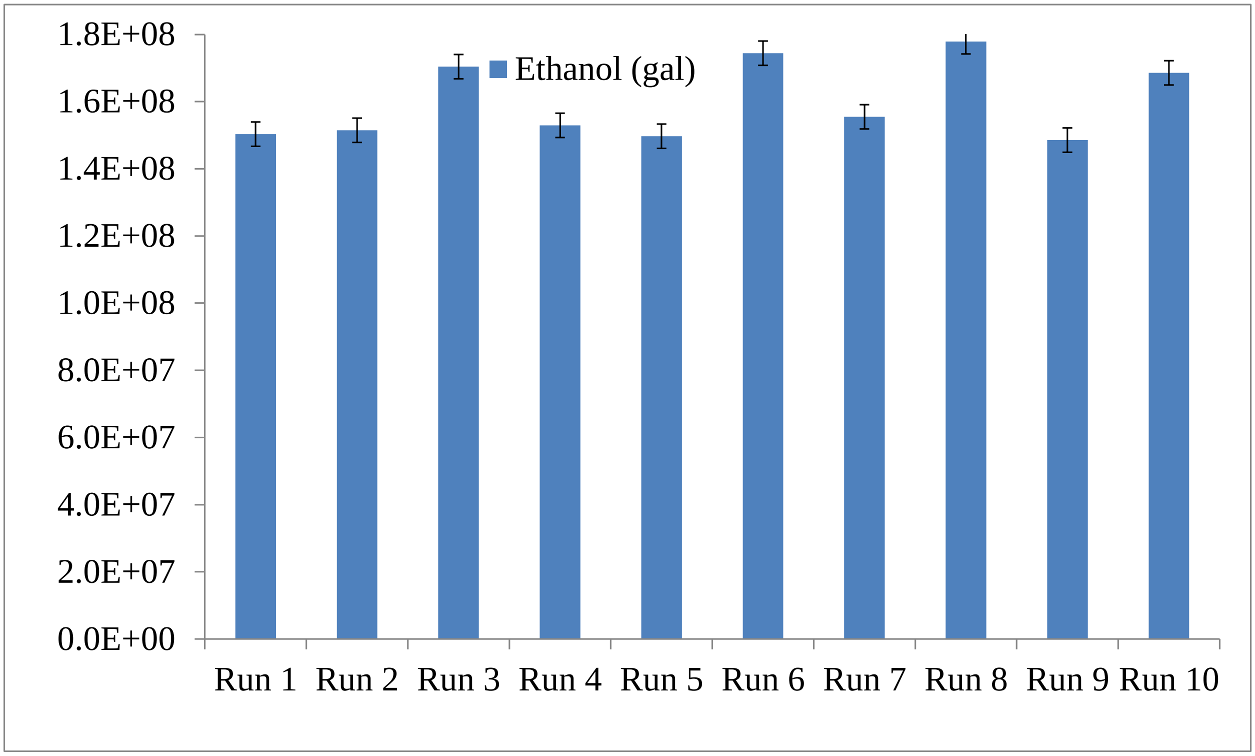


Figure C.13: Consistency check for T4S1

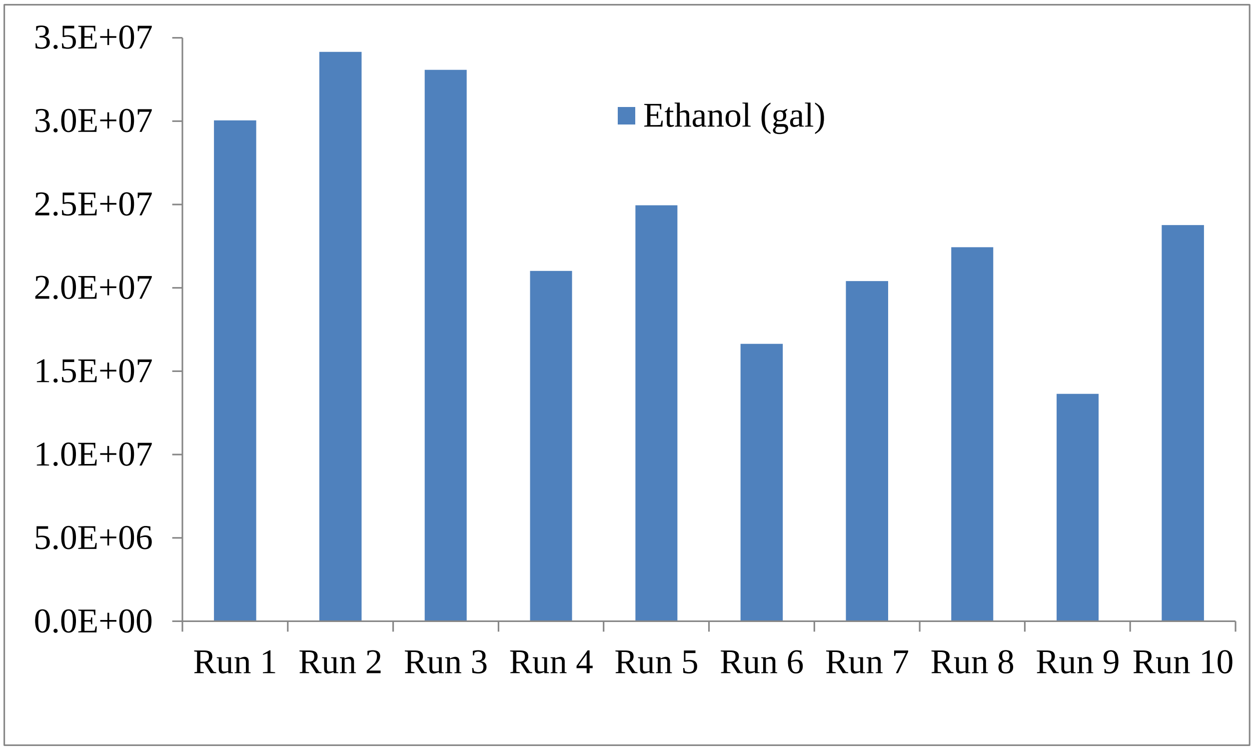


Figure C.14: Consistency check for T4S2

APPENDIX D

5.6. Appendix D

D.1. Instructions to run the WORLD model and perform the integrated LCA

D.1.1. Running the WORLD model (MS Excel):

1. Click on the "initialize" macro button on model sheet
2. Select "data" tab> "solver", click on the "solve" button (If constraints need to be altered this can be done in the solver window before running the model)
3. If the model does not converge and/or solution is not found go to step 1
4. If model converges and/or runs well go to step 5
5. Select "Home">"Insert">"Insert sheet" or select an empty existing sheet. Rename the sheet as **"Sheet1"** (It is very important to rename the sheet in order for macros to run)
6. Click on the "consistency runs" macros button on model sheet. (Note: consistency macros will not run if there is no sheet named "Sheet1")
7. Sheet 1 will now populate. Now rename "Sheet1" as "Run n"(where n is the number of your consistency check run e.g. Run 1 or Run 2, etc.)
8. Make sure a new sheet called “Sheet1” is inserted in the excel workbook
9. Run each scenario multiple number of times (10- 20) following the instructions sheet in the WORLD model.
10. Make sure each run within the optimization scenario is consistent (in ethanol production range, number of LBPDs etc.)
11. Once all runs are complete, choose a single run from the results of which the integrated LCA is to be performed. Then copy and paste these results into a new sheet and rename it “Run”. This sheet now contains values of land allocations in different watersheds, ethanol

and electricity yields, animal feed fractions, number and capacity of LBPDs and absolute values of environmental impacts as well as their relative percentage changes compared to the original landscape. This is helpful if modifications are to be made to the model and to summarize and compare results from various scenarios.

D.1.2. Conducting the integrated LCA:

1. All the following operations are performed in the sheet named “I-O sheet” in the WORLD model spreadsheet
2. Obtain biomass values of different types of feedstocks from the sheet named “Run” (Note: In the WORLD these numbers are in short tons. In the LBPD model they have to be entered in metric tons. Therefore a conversion is required). Enter these values as input in the input sheet of the LBPD technical model. The summary sheet in the LBPD technical model provides diesel, electricity and natural gas requirements for each LBPD in each watershed (already determined in WORLD). For the purpose of calculations, a single LBPD can be assumed as a model LBPD in a particular watershed and the energy inputs of this LBPD can be multiplied with the total number of LBPDs in that watershed for total energy requirements and emissions from distributed processing in that watershed. In this way, determine energy and environmental inputs of distributed processing in all watersheds for the scenario.
3. The amounts of different co-products produced in LBPDs are also obtained from the technical model. Copy these values into the “Transport” sheet of the WORLD model and assume 10% dry matter losses.

4. Calculate total energy and environmental inputs of transport of all raw materials and co-products using the methodology described in Appendix C and the values in Tables C7 and C8.
5. Calculate energy and environmental inputs for agriculture for all cellulosic feedstock acreages and for unchanging conventional feedstock (corn, soy, grass hay and alfalfa acreages) determined by the WORLD model for the new landscape configuration based on values in Tables C4 and C5.
6. Obtain ethanol generated and electricity values from results of the WORLD model and calculate their energy outputs (in MJ or GJ)
7. Perform co-product credit calculations as described in the methodology in Appendix C
8. Consolidate all inputs and outputs for energy and emissions to determine absolute and relative values of NEY and NGER as described in Chapter 5. Environmental impacts (absolute and percentage changes from original configuration (baseline) are already present in the sheet named “Run”)
9. Summarize all results in a separate workbook for all tests and scenarios for the purposes of comparison.

Table D.1: List of variables and their interpretation in the WORLD model

Variable name	Interpretation
SG (ML)	Switchgrass on marginal land
SG (PL)	Switchgrass on pasture land
SG (AL)	Switchgrass on arable land
M (ML)	Miscanthus on marginal land
M(PL)	Miscanthus on pasture land
M(AL)	Miscanthus on arable land
NP(M)	Native prairie on marginal land
A (PL)	Alfalfa on pasture land
Grass hay (PL)	Grass hay on pasture land
Corn (AL)	Corn on arable land
Soy (AL)	Soy on arable land
DC(AL)	Double crop on arable land
Canola(AL)	Canola on arable land
FeedFrac(SG)	Fraction of switchgrass to animal feed
FeedFrac(M)	Fraction of miscanthus to animal feed
FeedFrac(s)	Fraction of stover to animal feed
FeedFrac(dc)	Fraction of double crop to animal feed
FeedFrac(A)	Fraction of alfalfa to animal feed
FeedFrac(corn)	Fraction of corn to animal feed
FeedFrac(Soy)	Fraction of soy to animal feed
FeedFrac(grass hay)	Fraction of grass hay to animal feed

Table D.1 (Cont'd)

FeedFrac(canola)[a]	Fraction of canola to animal feed
FeedFrac(np)	Fraction of native prairie to animal feed

a. Although, in the list of variables, the variable for canola is set up as an animal feed fraction, it is only used to replace the oil that is displaced from soy

D.2. Macros

Multiple runs have to be performed on the model for each optimization test and scenario in order to check for consistency, model robustness and to ensure global maxima and minima. However, it is a laborious process to enter individual values of model variables as well as to copy and paste the results from each run every time to compare results and to select a run for the integrated LCA. Hence these macros were created to simplify the process. The following macros are examples of only a particular optimization and need to be modified or adjusted as required.

D.2.1. The "Initialize" macro

In order to ensure that the model converges from any starting point, it is necessary to initialize model variables for each single run using random numbers. Instead of entering a random number for each individual model variable, the initialize macro was created to copy random numbers [created in a separate sheet using the formula RAND()] and paste them in the cells reserved for model variables. The subroutine for this macro in Visual Basic is as follows:

```
Sub Initialize()
'
' Initialize Macro
' Initializing sequence with random numbers
```

```
'

'

    Sheets("Random numbers").Select
    ActiveWindow.SmallScroll Down:=-9
    Range("A1:A13").Select
    Application.CutCopyMode = False
    Selection.Copy
    Sheets("model_TS 1").Select
    Range("T2").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    ActiveWindow.SmallScroll Down:=6
    Range("T20").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    ActiveWindow.SmallScroll Down:=12
    Range("T38").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
        :=False, Transpose:=False
    ActiveWindow.SmallScroll Down:=30
    Range("T56").Select
    Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
```

```
    :=False, Transpose:=False
ActiveWindow.SmallScroll Down:=12
Range("T74").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
ActiveWindow.SmallScroll Down:=12
Sheets("Random numbers").Select
Range("B1:B5").Select
Application.CutCopyMode = False
Selection.Copy
Sheets("model_TS 1").Select
ActiveWindow.SmallScroll Down:=-78
Range("T15").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
Range("W15").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
ActiveWindow.SmallScroll Down:=18
Range("T33").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
Range("W33").Select
```

```
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
ActiveWindow.SmallScroll Down:=21
Range("T51").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
Range("V51").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
ActiveWindow.SmallScroll Down:=21
Range("T69").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
Range("W69").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
ActiveWindow.SmallScroll Down:=12
Range("T87").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
Range("W87").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
```

```
End Sub
```

D.2.2. The "Consistency runs" macro

After running the model (using solver), the consistency macro was created to automatically copy and paste all important values from the model sheet such as land area allocations of each watershed, the combined environmental impacts of these land areas and ethanol, electricity and animal feed yields into a separate sheet. The subroutine for this macro in Visual Basic is as follows:

```
Sub consistency()
'
' consistency Macro
'

'
    ActiveWindow.ScrollColumn = 7
    ActiveWindow.ScrollColumn = 6
    ActiveWindow.ScrollColumn = 5
    ActiveWindow.ScrollColumn = 4
    ActiveWindow.ScrollColumn = 3
    ActiveWindow.ScrollColumn = 2
    ActiveWindow.ScrollColumn = 1
    Range("A10:E22,I10:I22,Q10:Q22").Select
    Selection.Copy
```

```
Sheets("Sheet1").Select
Range("A1").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
Sheets("model_TS 1").Select
ActiveWindow.SmallScroll Down:=18
Range("A30:E42,I30:I42,Q30:Q42").Select
Application.CutCopyMode = False
Selection.Copy
Sheets("Sheet1").Select
Range("A15").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
ActiveWindow.SmallScroll Down:=12
Sheets("model_TS 1").Select
ActiveWindow.SmallScroll Down:=18
Range("A50:E62,I50:I62,Q50:Q62").Select
Application.CutCopyMode = False
Selection.Copy
Sheets("Sheet1").Select
Range("A29").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
```

```
ActiveWindow.SmallScroll Down:=15
Sheets("model_TS 1").Select
ActiveWindow.SmallScroll Down:=18
Range("A70:E82,I70:I82,Q70:Q82").Select
Application.CutCopyMode = False
Selection.Copy
Sheets("Sheet1").Select
Range("A43").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
ActiveWindow.SmallScroll Down:=18
Sheets("model_TS 1").Select
ActiveWindow.SmallScroll Down:=24
Range("A90:E102,I90:I102,Q90:Q102").Select
Application.CutCopyMode = False
Selection.Copy
Sheets("Sheet1").Select
Range("A57").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
Sheets("model_TS 1").Select
ActiveWindow.SmallScroll Down:=18
Range("A111:D116").Select
```

```
Application.CutCopyMode = False
Selection.Copy
Sheets("Sheet1").Select
Range("H22").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
Sheets("model_TS 1").Select
ActiveWindow.ScrollColumn = 2
ActiveWindow.ScrollColumn = 3
ActiveWindow.ScrollColumn = 4
ActiveWindow.ScrollColumn = 5
ActiveWindow.ScrollColumn = 6
ActiveWindow.ScrollColumn = 7
ActiveWindow.SmallScroll Down:=-87
ActiveWindow.SmallScroll ToRight:=2
  Sheets("model_TS 1").Select
ActiveWindow.SmallScroll Down:=-6
Range("L2:N3").Select
Application.CutCopyMode = False
Selection.Copy
Sheets("Sheet1").Select
Range("I1").Select
Selection.PasteSpecial Paste:=xlPasteValuesAndNumberFormats, Operation:= _
```

```
    xlNone, SkipBlanks:=False, Transpose:=False
Sheets("model_TS 1").Select
Range("O1:Q1").Select
Application.CutCopyMode = False
Selection.Copy
Sheets("Sheet1").Select
Range("I3").Select
Selection.PasteSpecial Paste:=xlPasteValuesAndNumberFormats, Operation:= _
    xlNone, SkipBlanks:=False, Transpose:=False
    ActiveWindow.ScrollWorkbookTabs Position:=xlFirst
Sheets("model_TS 1").Select
Range("Q3:Q7").Select
Application.CutCopyMode = False
Selection.Copy
ActiveWindow.ScrollWorkbookTabs Position:=xlLast
Sheets("Sheet1").Select
Range("I5").Select
Selection.PasteSpecial Paste:=xlPasteValues, Operation:=xlNone, SkipBlanks _
    :=False, Transpose:=False
    Sheets("model_TS 1").Select
ActiveWindow.ScrollColumn = 11
ActiveWindow.ScrollColumn = 12
ActiveWindow.ScrollColumn = 13
```

```
    Range("AA1:AI21").Select
    Application.CutCopyMode = False
    Selection.Copy
    ActiveWindow.ScrollWorkbookTabs Position:=xlLast
    Sheets("Sheet1").Select
    Range("N1").Select
    Selection.PasteSpecial Paste:=xlPasteValuesAndNumberFormats, Operation:= _
        xlNone, SkipBlanks:=False, Transpose:=False
End Sub
```

D.2.3. The "error" macro

In order to check for the consistency of the model and to ensure low error values, the error macro was created in order to obtain values of the parameter from different runs in the same test and scenario for which error is to be calculated. The subroutine for this macro in Visual Basic is as follows:

```
Sub Error()
'
' Error Macro
'

'
    Range("B13").Select
    ActiveCell.FormulaR1C1 = "='Run 1'!R[-12]C[9]"
```

```
    Range("C13").Select
    ActiveCell.FormulaR1C1 = "='Run 2'!R[-12]C[8]"
    Range("D13").Select
    ActiveCell.FormulaR1C1 = "='Run 3'!R[-12]C[7]"
    Range("E13").Select
    ActiveCell.FormulaR1C1 = "='Run 4'!R[-12]C[6]"
    Range("F13").Select
    ActiveCell.FormulaR1C1 = "='Run 5'!R[-12]C[5]"
    Range("G13").Select
    ActiveCell.FormulaR1C1 = "='Run 6'!R[-12]C[4]"
    Range("H13").Select
    ActiveCell.FormulaR1C1 = "='Run 7'!R[-12]C[3]"
    Range("I13").Select
    ActiveCell.FormulaR1C1 = "='Run 8'!R[-12]C[2]"
    Range("J13").Select
    ActiveCell.FormulaR1C1 = "='Run 9'!R[-12]C[1]"
    Range("K13").Select
    ActiveCell.FormulaR1C1 = "='Run 10'!R[-12]C"
    Range("K14").Select
End Sub
```

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5.7. REFERENCES

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CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Based on the comparative LCA study between distributed and centralized processing systems on farm-scale landscapes, combining depots with high yielding perennial grasses can achieve net energy yields comparable to those of a centralized biorefinery and with lower GHG emissions. When modeling landscape conversions from current conventional croplands containing annual crops such as corn to landscapes containing perennial grassland systems, it is important to evaluate increases in (or accumulation of) soil carbon. These increases occur due to soil carbon sequestration properties of perennial grass root masses and due to the absence of plowing and tillage of soil each year. Low yielding perennial grasses lead to lower net energy yields. In such cases, it is more beneficial to use other feedstocks such as corn stover along with perennial grasses in combination with depots. Densification following pretreatment is crucial in the successful establishment of distributed biomass processing systems since it is a major factor in shrinking the transport and storage footprints of the overall system. Moreover, pretreated and densified biomass has the potential to become a commodity that can be used as an end-product (as animal feed) as well as raw material for multiple processes and industries such as biofuel production. Products generated from biofuel landscapes such as pretreated biomass and solid protein extracted from certain feedstocks such as double crops may satisfy animal feed requirements for digestible nutrients, protein and fiber.

Implementing land-efficient techniques and producing multiple co-products can help address sustainability concerns of biofuel production systems and increase the value of feedstocks. Some of these techniques include, no-till farming, using marginal/idle lands to grow low-input perennial grasses or native prairies, double cropping on the same agricultural land areas used to generate conventional crops and to produce animal protein supplements, recycling wastes within the different modules of the system and forming positive feedback loops between different operations in the system (e.g. using animal manure in anaerobic digestion to generate energy for different processes in the depot). Without bringing more land into production and by utilizing idle land, landscapes can be modified to generate as much as ten-fold greater biomass output. Overall, perennial grasses are inextricably tied with sustainable biofuel production. In order to achieve substantial net energy yields and environmental benefits the landscape must contain perennial grasses.

Depots can act as a link between the biorefining industry and farm operations. They can standardize feedstocks with variable properties and streamline the logistics of biofuel production. Enhanced depots (depots containing technologies in addition to pretreatment) can prove to be more advantageous as they can better adapt to the characteristics of landscapes and can be customized to include technologies on an as-needed basis and also since there are mutually beneficial synergies among these technologies.

A comprehensive, integrated modeling and assessment approach is required to make realistic and thorough evaluations of the biofuel production system. A sequential procedure is necessary starting from land area availability and feedstock production to technology requirements, co-product production and transport burdens for all raw-materials and products included in the system. The WORLD model deals with the feedstock production and sustainability aspects of the feedstock system whereas the integrated LCA ties the WORLD model to the processing and transport modules. As a whole, this integrated analysis can be a useful tool to evaluate biofuel production systems in real landscape settings.

6.2. Recommendations

Based on the results of this project, suggestions for further analysis in different categories of interest are as follows:

- **Economics:** Integrated LCAs give insight into the energy yields and environmental aspects of distributed processing systems and shed light on the social aspects of the overall biofuel production system. However, it is essential to assess the third facet of sustainability in the form of economic analyses. A comprehensive economic model for the combined feedstock-transport-processing system is needed. An economic component should be built into the WORLD model based on agricultural budgets for existing crops and literature values for costs of farming operations and projected prices for new feedstocks such as perennial grasses. In the future, when carbon sequestration systems receive economic incentives or when prices are set for co-products generated in the depots, these components should be integrated into the economic model in order to determine the overall economic and environmental benefits of biofuel production systems.
- **Transport:** This analysis primarily assumes the transport of raw materials and products via trucks. However, other modes of transportation such as rail and barge should also be taken into consideration and compared. Just as dry matter losses, road winding factors and distances of transport from real road networks in GIS based systems were considered in this analysis; realistic data should be used for future analysis of other transportation systems wherever applicable. Moreover, energy and environmental burdens of transportation of densified material were obtained from the GREET model. It may be advantageous to compare these values with data from other models that are currently

being developed such as the Integrated Biomass Supply Analysis and Logistics (IBSAL) model [1].

- **Biogeochemical modeling data:** Due to a lack of comprehensive data for relatively new feedstocks such as some perennial grasses, certain assumptions were made in this analysis and literature values were used to fill these data gaps. However, as biogeochemical modeling for these new feedstocks improves, the data used in the analyses should be updated. For example, simulations of water quality improvements in water-bodies on the banks of which riparian buffer strips are grown should be performed and these results should be incorporated in environmental analyses. Similarly, data from simulations of double crops such as winter wheat, rye and hairy vetch (*Vicia villosa*) are required. Moreover, simulations of feedstocks systems other than switchgrass and miscanthus such as energy sorghum (*Sorghum bicolor*) are needed so that the data from these simulations can be used in integrated analyses. Simulation of forest systems is also needed in order to obtain data for woody residues that are used in pyrolysis. The possibility of incurring "carbon-debts" [8] must be analyzed and incorporated in calculations while converting from one land-use to another (especially if there is a conversion of marginal/abandoned/forage land to conventional crops such as corn). A statistical analysis of data generated from biogeochemical models (usually containing large data-sets) must be performed to assess errors. It may also be beneficial to compare simulation data from different biogeochemical models such as EPIC, DayCent and Biome-BGC [2] in order to standardize and validate results of these relatively new feedstocks.

- **The WORLD model and integrated life cycle assessments:** This analysis includes the only a nascent stage of the WORLD model and primarily illustrates its capabilities by simulating landscapes for a single region of interest- the Michigan RIMA. The model should be applied to different regions of interest, for example, starting with the second RIMA in central Wisconsin, under investigation in the modeling group of the GLBRC. The model should then be extended to a completely different watershed in the United States where cellulosic feedstocks are grown that are not dealt with in this analysis (such as sugarcane bagasse or poplar) and with different soil and climatic conditions; so that the model might be further tested and validated. Although the WORLD model assesses fuel, soil, water and GHG emissions, the model should also be able to assess biodiversity and ecosystem services. Using individual categories of sustainability measurement, for instance biological control of insects (such as the soybean aphid) [3] or avian populations or using an index that combines various categories of biodiversity, the overall ecosystem services provided by biofuel feedstock landscapes should be determined and incorporated in the WORLD model. For example, Meehan et al. [4] suggested that increasing the production of annual bioenergy crops on marginal lands decreases avian richness between 7% and 65% whereas substituting annual crops with varied perennial bioenergy crops may increases avian richness between 12% and 207% while also recovering species of conservational concern. Such effects should be incorporated in sustainability analyses within the WORLD model. The WORLD model should also be extended to perform multi-objective optimization. For example, trying to minimize nitrogen losses while simultaneously obtaining large energy yields. Maximizing energy gains while incurring the least amount of soil erosion and also improving soil quality by amassing large amounts of soil organic carbon.

The LCAs performed in this project are cradle-to-gate; however this may be extended to cradle-to-grave or well-to-wheel analyses by including transportation, blending and end-use of the ethanol and other co-products generated. Also, taking into account the nature of biofuels, Eco-LCAs (a framework to account for the role of ecosystem goods and services in the life cycle of economic activities) [5, 6] may also be appropriate for biofuel systems. Although comprehensive LCAs can be performed independently, it is recommended that a LCA software platform such as GaBi [7] be used for future assessments in order to standardize biofuel LCAs within different modeling groups in the GLBRC. Using GaBi will also facilitate data exchange and comparison of results using the same databases and system boundaries. All modules in the biofuel production system should be built in GaBi for thorough assessments and scenario analyses.

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