2009

Optimized landscape plans for bio-oil production

David Hc Correll
Iowa State University

Optimized landscape plans for bio-oil production

by

David Correll

A thesis submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Co-Majors: Sustainable Agriculture; Biorenewable Resources and Technology

Program of Study Committee:

Michael Duffy, Major Professor
Robert Brown
Steven Fales
Robert Ruben
Lisa Schulte Moore

Iowa State University

Ames, Iowa

2009

Table of Contents

Chapter 1 Introduction and Motivations

Introduction

This thesis project considers: (1) the range of feedstock crops possible for production of bio-oil in Iowa in the near-term, and (2) what a multi-farm landscape servicing one centralized processor might look like if each acre were planted with the crop that minimizes total production and transportation costs. Can a diversity of crops make for more cost-effective farming than monocultures? How might environmental protection measures affect crop selection? Ultimately, which crops should be planted to which acres? These are the questions addressed in this thesis project.

Work proceeded in three phases: (1) compiling a database of relevant biochemical information about candidate crops for bio-oil production in the state of Iowa, (2) designing a mathematical model capable of assigning these crops to different acres, and (3) analyzing the output of the model for insights into least cost crop rotation planning.

The remainder of this chapter gives general background and motivations for this study and introduces the model's basic concepts. Chapter two introduces the crops and landscapes included in the database and the model. Chapter three introduces both fast pyrolysis, the process for which landscapes will be optimized, and network flow linear programming, which is the modeling approach used to do the optimization. Chapter four presents the model both graphically and mathematically. Chapter five discusses the results of different model runs and analyzes the model output. Chapter six presents general conclusions for optimized landscape plans drawn from this effort and suggests avenues for further research.

Global Energy Supply and Demand

The first law of thermodynamics states that energy can be neither created nor destroyed – it can only change forms. All energy on earth comes to us from our closest star, the Sun. We can neither substitute, nor exhaust this resource. Instead, we endeavor to unlock it. Throughout history, humans have unlocked the solar energy stored in plant life, animal life, running water, blowing wind, chemical reactions and fossilized remains – just to name a few. Overall, of the estimated 3,850 zettajoules (or, 10^{21} joules) of energy that pass annually through the earth's atmosphere and into land and water, today's global civilization utilizes only about 451 exajoules (10^{18} joules) annually, or less than one-one thousandth of one percent [1,2]. At first glance, future energy consumption seems governed only by our own ability to unlock this abundance.

Nevertheless, today's world faces the potential for serious energy shortages in the near-term, owing in part to: (1) our own profligate consumption of available energy sources over the last 200 years, and (2) the mounting environmental costs associated with unlocking energy with different technologies. During the advent of coal and steam power in the 19th century, energy use by humans increased 10-fold. The development of oil and natural gas resources in the 20th century improved upon this figure 16-fold. According to environmental historian J.R. McNeil, humans have likely expended more energy since 1900 than in all of preceding human history combined [3]. Our future consumption is projected by many to grow even faster. United Nations population researchers expect the number of people on earth to grow by roughly 37% from 6.7 billion people in 2007, to 9.2 billion in 2050 [4]. The U.S. Department of Energy predicts an even quicker increase in worldwide demand for energy: a 50% rise over today's levels by as soon as 2030 [5].

The costs associated with unlocking more energy for a growing market present our future's real limiting factors. Documented affects of growth in population and energy use over the last 200 years include: depletion of fossil fuels resources, changing atmospheric chemistry and climate, degradation of ecosystem services, contamination of freshwater, despoilment of soils, and diminishment of global plant and animal biodiversity [6,7]. Meeting tomorrow's energy demand with technologies that further deplete our terrestrial resource base then seems ill-conceived given the costs that are already accruing. Ultimately, it seems, future energy consumption on earth will not likely be governed by how much solar energy we find available to unlock, but rather, how much terrestrial capital we can afford to exhaust in the process.

Agriculture and Energy

The suitability of agricultural biomass to the energy challenges ahead will largely depend on our ability to overcome agriculture's known shortcomings. Growing crops demands abundant and healthy farmland, the world's supply of which has been receding since the 1980's [8]. Partly, this is because the small portion of earth that is tillable had by then already been farmed. Also, this is partly because agricultural intensification in the 20th century by means of irrigation and "chemicalization" had already degraded, eroded or desertified a portion of that limited stock [9, 10]. If we accept that it is not the quantity of energy on earth that is limiting, but rather the quantity of earth itself, then agricultural biomass systems that further exhaust this already shrinking resource base seem incapable of contributing a meaningful long-term energy solution.

One important criterion then for designing sustainable biomass farming systems is conservation of the land and soil resource base.

Moreover, biomass systems that are not dependable year after year are unlikely fit for the challenge of fueling global industry. While risks associated with pest attack, weather anomalies and price fluctuations can be mitigated with crop diversity, modern agriculture has instead moved in opposite directions, opting to plant only a few species across broad landscapes. (For history and causation of this trend see Rasumussen [11].) In Iowa, for example, for the last 20 years roughly 90% of cropland has been devoted to corn and soybeans. Biomass farming for energy applications need not necessarily rely on so few plant species. Many biorenewable processing technologies are "omnivorous", meaning that any crop species can serve as feedstock. These omnivorous end-users open the door for new cropping systems to emerge that are capable of capitalizing on the resiliency and sustainability conferred by plant diversity. Another criteria then for designing sustainable biomass farming systems is species diversity.

Optimized Landscapes for Bio-Oil Production

This thesis effort will consider cropping systems for the state of Iowa that meet both of the above sustainability criteria, resource conservation and diversity. The model designed for this project endeavors to meet those criteria while minimizing the cost of producing and delivering the biomass to a processor of bio-oil. Can we farm energy in a way that preserves our natural capital while also economizing? Can we seed a variety of plants onto the landscape that confer the benefits of species diversity while also improving feedstock quality?

To address these questions, first the agricultural and engineering literature was reviewed in order to catalogue the biochemical profiles of a variety of different candidate crops. This biochemical data was surveyed in order to enable an assessment of each crop's potential contribution to feedstock quality. In total, sixty six different crops were catalogued. For a subset of these crops, local agronomic practices were then assigned, prices were input, representative yields were assumed and soil erosion potentials were estimated.

In addition to these costs, a way of evaluating each crop's unique transportation cost was devised. The hypothetical landscape is divided into concentric circles surrounding a central collection point. This enables acres to be classified according to their distance from the processor. Thus, a particular crop grown on any given acre carries with it its cost of transporting it from that acre to the processor. Each crop's cost of transportation is then unique, and varies owing to its individual yield, bulk density, assumptions about the logistics of moving it, and the acre to which it was planted.

These production and transportation costs are then weighed against each crop's contribution to feedstock quality, as it applies to bio-oil production by means of Waterloo Process Fast Pyrolysis. (However, the model was built such that it could be easily re-calibrated for a wide variety of feed and fuel applications). Bio-oil is one of the many potential products that result when biomass is heated in the absence of oxygen. It is a liquid product and one that can be processed into a substitute for crude oil derived from fossil fuels.

The "Waterloo Process" is a special type of fast pyrolysis designed specifically for making bio-oil from biomass.

Finally, in an effort to see how least cost crop mixes might change for different parts of Iowa, three slightly different versions of this model were built. Versions of this model were constructed for the Northeastern, Central and Southern parts of the state. Iowa was divided laterally to capture the state's varying climates, soil types and topography from north to south.

Chapter 2 Crops and the Landscape

The model built for this project seeks to find optimal mixes of crops given processor needs and environmental constraints for three different parts of Iowa. This chapter begins by discussing the database of sixty six candidate crops that was prepared as a preliminary part of this work. Next, a discussion of the sub-set of crops that were included in the model is presented. Those crops and their assumptions are described in full, followed by an introduction to the three Iowa regions for which they are modeled. Discussion of the three regions includes both yield and cost of production assumptions for each crop in each region. The last section of this chapter outlines how transportation costs were calculated.

The Database of Candidate Crops

To understand any crop's suitability for processing into biorenewable fuels, it was first necessary to learn what the crop is made of. Particularly, it was important to learn the: cellulose, hemicellulose, lignin, arabinan, xylan, mannan, galactan, and glucan contents. The database also includes each crop's ultimate analysis (carbon, hydrogen, oxygen, nitrogen and sulfur content) and proximate analysis (fixed carbon, ash, and volatile matter content), as well as its higher heating value and the variety of minerals present in its ash. The resulting database includes 29 potential data points for 66 different candidate crops. (However, it was not possible to find all of the information for every crop.) Although not all of this information has been found to impact directly on bio-oil production, research into feedstock biochemical components' influence of on bio-oil production is still being done. Moreover, different biorenewable products are influenced differently by biochemical features of the feedstock. Thus, this complete cataloguing approach will enable this project's database and model to gain relevance as more research is done and different technologies are applied.

At the time of this writing, no existing resource offered a variety of crops or depth of data sufficient to the goals of this project. Compiling the database entailed reviewing journals and publications from all over the world released over the last 50 years. When multiple sources were discovered for a particular crop, the one with experimental conditions most similar to Iowan conditions was input. The database was programmed in Microsoft Access and is available upon request of the author. Sample output is given in appendix one.

Crops Included in the Model

From this database, a sub-set of five crops were selected for inclusion in the model. These five crops include: corn stover, barley straw, sweet sorghum, alfalfa and switchgrass. Inclusion of these five crops was based on: (1) suitability to Iowa landscapes; (2) compatibility with typical farm implements; (3) available biochemical information; (4) available cost of production information; and (5) functional group representation. It was important to include crops capable of contributing different functions to the overall cropping system. This meant including a mix of both annuals and perennial species, leguminous and non-leguminous crops and dual use crops (like corn) alongside dedicated energy crops (like sweet sorghum). Including these different groups was important for both testing the robustness of the modeling approach, and also for capturing a variety of strengths and weaknesses different enough that optimized cropping plans might actually capitalize on diversity.

However, choosing these five crops for modeling necessitated assumptions about how each one affects the others. For example, how might corn grown after corn yield differently than corn grown after alfalfa, barley or sorghum? How should fertilization change when one of these crops follows another? Because no studies were available looking at these effects in rotations with these particular crops, assumptions were made that erred on the side of functional diversity for the reasons mentioned above. This entailed assigning a yield penalty any time an annual crop follows another annual crop, and a yield boost for any an annual crop that follows alfalfa. Those assumptions are more fully discussed below for each crop.

Corn Stover

Corn stover consists of the leaves and stalks that are left behind after the corn grain harvest. Corn stover can be left on the field to preserve nutrients and protect against soil erosion. Or, it can be grazed by livestock, or harvested for other commercial uses.

Corn stover is harvested after a combine collects the corn grain. The stover is chopped and then raked into rows. Stover is typically allowed to field dry in open air because compacted storage of moist biomass can result in spontaneous combustion. In this model, it is assumed that: the farmer will wait until the stover can be safely compacted and stored, which happens at 10-15% moisture content; 50% of the stover will be harvested and 50% left will be left on the field for environmental protection; and the dry stover will be compacted into 4x4x8 large square bales. A bulk density of eight pounds per cubic foot was assigned to dry corn stover.

Growing corn stover impacts the model in two unique ways. First, the value of corn grain is counted as an offset against the overall cost of production. To relate corn grain and stover yields, a factor of 1:1 (by mass) was used [12]. Second, the model assigns a yield penalty to any annual crop grown immediately after corn on the same acre of land. In this model, the yield penalty applies to corn after corn, barley after corn, and sweet sorghum after corn. The yield penalty for corn stover follows ISU Extension's 2008 Estimated Cost of Crop Production [13].

Barley Straw

Barley is an annual small grain crop. Both Spring and Winter varieties are available, but Winter barely is not adapted to Iowa [14]. The model considers only Spring-planted barley, the grain of which is typically harvested for use as livestock feed. Barley straw consists of the plant stalks left behind after the grain harvest.

The costs of growing barley in Iowa were based on the work of Hansen [14] and Johnson and Janzen [15]. In the model, barley straw is collected in the same way as corn stover, and the same assumptions about harvesting operations, moisture content and residue left on the field (50%) were applied. However, a bulk density of 11 pounds per square foot was assigned to barley straw, based on consultation with an ISU agricultural engineer.

Growing barley straw affects the model in the same way that growing corn does. If barley is grown, then revenue from selling the barley grain is counted as an offset against the overall cost of production. Based on the work of Papastylianou, a residue factor of 1:0.73 (by mass) was used to relate barley grain yields to barley straw yields [16]. Also, a yield penalty is assigned to any annual crop that immediately follows barley on the same acre of land. The yield penalty for barley was also based on observation by Papastylianou.

Sweet Sorghum

Sweet sorghum is a high-yielding, annual grass and a relative of forage sorghum. Unlike forage sorghum, sweet sorghum is usually cultivated for the sugars that grow in its stalks. In recent years, sweet sorghum has attracted attention as a potentially high-yielding bio-energy crop.

The costs associated with growing sweet sorghum in this model are based on Hallam et al [17]. It is assumed that mature sweet sorghum will be harvested as a fresh hay. This entails chopping the crop while still green, similar to the harvesting of hay for bioethanol production outlined in Chen [18]. Consultation with agricultural engineers suggested that such hay is unlikely to be baled. Therefore, it is assumed that sweet sorghum will be chopped and blown with a forage blower directly into on-farm trucks, as outlined in Bennett and Anex [19]. Because freshly harvested sweet sorghum hay can have a moisture content of up to 80%, a $50 per ton drying charge was attached to sweet sorghum. $50 was chosen as an approximation based on historical drying estimates for other hays and other uses. The model showed little sensitivity to sweet sorghum drying prices that ranged between $40 to $60.

Unlike barley and corn, sweet sorghum offers no potential for cost of production off-sets owing to grain sales. Because it is an annual crop, growing sweet sorghum continuously or after corn or barley is also assumed to incur a yield penalty. The yield penalty for sweet sorghum was based on the yield penalty reported for corn in [13].

Alfalfa

Alfalfa is a perennial legume crop. It grows in herbaceous, flowering bunches. It is most commonly used as feed for livestock.

The cost of growing alfalfa in Iowa is based Hallam et all [17]. In this model, a stand of alfalfa is assumed to last for three years. In the first year, two cuttings are assumed. In the second and third year, three cuttings are assumed. Harvesting alfalfa includes mowing the plant, conditioning it, raking it into windrows and compaction with a large square baler. It is assumed that the farmer will field dry the alfalfa to 10% to 15% moisture content. For alfalfa, a bulk density of 12 pounds per square foot was assigned based on consultation with agricultural engineers.

Growing alfalfa impacts the model in two unique ways. Alfalfa's nitrogen-fixing ability gives yield boosts to any crop that immediately follows it on the same acre. It is also assumed that crops that immediately follow alfalfa on the same acre of land will require less nitrogen fertilizer. Yield increases and fertilizer reductions are based on those reported for corn following soybeans in [13]. These benefits are not applied to continuous stands of alfalfa.

Switchgrass

Switchgrass is a perennial warm-season and deep-rooted grass that is native to Iowa. It grows in dense bunches that can be harvested with conventional hay equipment, similarly to alfalfa.

Field operations and agronomic practices for growing switchgrass in Iowa are based on Hallam et al [17]. For this model, it was assumed that one stand of switchgrass lasts 10 years. Unlike alfalfa, switchgrass is harvested only once per year. Two distinct yields were assumed, one for the establishment year and another for years two through ten. Annual harvesting practices and assumptions for switchgrass are similar to those for alfalfa. A bulk density of 12 pounds per square foot was assigned to switchgrass based on consultation with agricultural engineers.

Switchgrass's long stand-life directly influenced both design of the model and its results. Because one stand is assumed to last 10 years, this model considers 10 consecutive years of cropping. Also, the model is structured such that acres may be assigned to switchgrass only in year one and must remain in switchgrass for the entire life of the stand and the model.

Regions

The model contains assumptions tailored to three regions in Iowa in order to see how location influences optimal crop mixes. Iowa was divided laterally to capture the variability of growing conditions from north to south across the state. Regions were also selected based on the Iowa landform to which they belong in an effort to capture differences in Iowa soil types and topography. In the analysis chapter, optimal crop mixes for each region are compared and differences are considered.

Counties within each region were specified for this model in order to draw upon three resources: (1) historical corn yield data by county, published by ISU extension; (2) Hallam et al's study of alfalfa, switchgrass and sweet sorghum in Story County and Lucas County [17]; and (3) the U.S. Department of Agriculture's Revised Universal Soil Loss Equation 2 (RUSLE 2) program, which considers soil type and county level climatic data to predict the soil erosion resulting from different cropping systems. Using these resources and those discussed in the crop introductions, assumptions about each crop in each region were made. The assumptions are described below.

Figure 2-1 Regions of Iowa

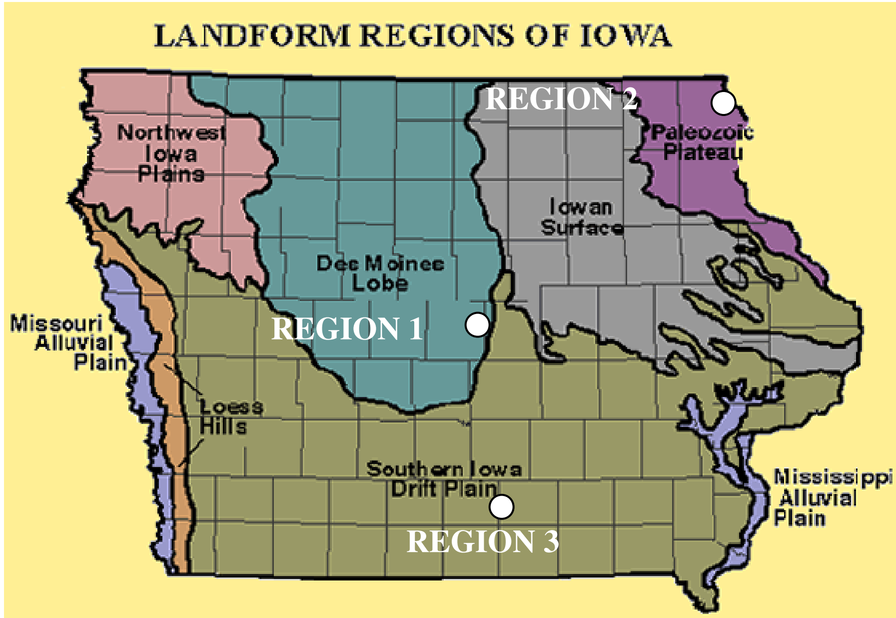


Image adapted from Iowa Department of Natural Resources (Public Domain)

Region 1: Central Iowa

In Central Iowa, assumptions were tailored to Story County. Story County is on the Des Moines Lobe, a highly fertile and flat geological region that covers most of north-central Iowa. Glaciers retreated across the Des Moines Lobe relatively recently (12,000 to 14,000 years ago), carving out a mostly even topography with deep glacial drift soils [20]. To calculate erosion, the RUSLE 2 program was calibrated for Webster clay loam soils, with 0% to 2% slopes, which are the most common characteristics for this region's soils. Below are two tables, one containing yield assumptions for region one and another detailing the costs of production for each crop.

The first table (Table 2-1) shows the yield assumptions for each of the five crops in region one. Each annual crop (corn, barley and sorghum) shows values for “after alfalfa” and “after annual.” The “after annual” values reflect the yield penalty attached when annual crops follow one another on the same acre, as discussed in the crop introductions section. “After alfalfa” reflects the yield boost and decreased nitrogen fertilizer following alfalfa that was also discussed above. Because switchgrass stands are assumed to last ten years, it is impossible in this model for any crop to follow it.

The perennial crops (alfalfa and switchgrass) also show two sets of yield assumptions. One set of values is for the establishment year, which represents the first harvest after planting. Another set of values represents annual yields for all following years. For alfalfa, “annual” refers to its second and third year. For switchgrass, “annual” refers to years two through ten. Table 2-1 can be found below.

Table 2-1: Yield assumptions for region 1

		After alfalfa	After annual
Corn	Grain (bu)	180	165
	Stover (t)	5	4.6
	Harvested Stover (t)	2.5	2.3
Barley	Grain (t)	70	57
	Straw (t)	2.6	2.2
	Harvested straw (t)	1.3	1.1
Sorghum		7	6.4
		Est.	Annual
Alfalfa (t)		2.6	4
Switchgrass (t)		3	5

The second table (Table 2-2) shows the costs of production for each of these crops in region one. Because the agronomic practices, yields and potential soil erosion resulting from a crop in any given year are directly influenced the crop that preceded it, costs are arranged as "last year – current year," or "preceding year's crop – this year's crop." The values shown in table 2-2 are estimates for only the current year's crop. All costs are given in dollars per acre, except soil erosion, which is given in tons of soil loss per acre. 'Machinery' refers to the total fixed and variable costs of field work associated with growing the crop and are based on ISU Extension's 2008 Estimated Cost of Crop Production [13]. 'N', 'P', and 'K' refer to the per acre cost of nitrogen, phosphorous and potash fertilizer, respectively. 'Chem' refers to the combined per acre cost of herbicides and insecticides. 'Seed' refers to the per acre seed cost. 'Credit' refers to the gross revenue from corn and barley grain sales and is included as a negative number because that revenue is subtracted from the overall cost of production. Erosion is an estimate of soil loss per acre based on RUSLE 2 and is given in tons.

Table 2-2: Cost matrix for region 1

(N = \$0.81/lb, P = \$0.90/lb, K = \$0.69/lb)

	Machinery	N	P	K	Chem	Seed	Credit	Erosion
Prior – Current Year	---------------------------------------			$/ acre in current year		-----------------		tons/acre
Corn-Corn	103.39	141.75	54.00	34.50	25.20	73.50	-742.50	1.30
Corn-Barley	100.63	150.19	35.45	67.06	13.85	8.64	-256.00	1.10
Corn-Sorghum	62.62	147.94	44.81	35.34	15.40	3.47	0.00	1.30
Corn-Alfalfa	82.08	0.00	142.20	430.56	8.32	28.65	0.00	0.88
Barley-Corn	103.39	141.75	54.00	34.50	25.20	73.50	-742.50	0.70
Barley-Barley	100.63	150.19	35.45	67.06	13.85	8.64	-256.00	0.59
Barley-Sorghum	62.62	147.94	44.81	35.34	15.40	3.47	0.00	1.00
Barley-Alfalfa	82.08	0.00	142.20	430.56	8.32	28.65	0.00	0.74
Sorghum-Corn	103.39	141.75	54.00	34.50	25.20	73.50	-742.50	1.20

Table 2-2 Continued

Prior – Current Year	Machinery	N	P	K	Chem	Seed	Credit	Erosion
	------------------------------------	$/ acre in current year	----------------					tons/acre
Sorghum-Barley	100.63	150.19	35.45	67.06	13.85	8.64	-256.00	1.00
Sorghum-Sorghum	62.62	147.94	44.81	35.34	15.40	3.47	0.00	1.60
Sorghum-Alfalfa	82.08	0.00	142.20	430.56	8.32	28.65	0.00	1.10
Alfalfa1 - Alfalfa2	76.97	0.00	0.00	0.00	3.52	0.00	0.00	0.61
Alfalfa2 - Alfalfa 3	76.97	0.00	0.00	0.00	3.52	0.00	0.00	0.18
Alfalfa 3 - Corn	103.85	97.20	63.00	37.95	25.20	73.50	-810.00	0.77
Alfalfa 3 - Barley	101.09	102.87	41.22	73.69	13.85	8.64	-320.00	0.61
Alfalfa 3 - Sorghum	63.52	101.33	52.11	38.83	15.40	3.47	0.00	0.88
Alfalfa 3 - Alfalfa 1	82.08	0.00	142.20	430.56	8.32	28.65	0.00	0.60
Switchgrass	15.60	99.79	28.44	64.03	0.00	0.00	0.00	0.00
Switchgrass 1	60.90	0.00	28.44	64.03	4.01	24.70	0.00	0.02

It is important to note here that the costs included in table 2-2 and the model in general are only those costs expected to vary from crop to crop. Among other things, this neglects land charges, interest rates on loans, and field liming. As such, this type of cost accounting gives a sense of the relative expense of different cropping options, but does not enable an estimate of any cropping plan’s actual cost of production and delivery per ton. This approach was chosen because this project seeks to compare the economics of different cropping mixes, not to estimate a price for a ton of biomass.

Region 2: Northeastern Iowa

Region 2 considers Allamakee County, which is located in Northeastern Iowa on the state’s Paleozoic Plateau. The Paleozoic Plateau is characterized by a rugged and deeply carved landscape due to erosion through Paleozoic-age rock strata. The terrain is dominated by sedimentary bedrock deposited 300 to 550 million years ago that has since been deformed, eroded and fractured, giving the region its distinct topography. Nineteenth century Iowa geologist Samuel Calvin once called the Paleozoic Plateau, the “Switzerland of

Iowa" [20]. To calculate erosion, Fayette silt loam soils with 9% to 14% slopes were assumed, which are the most common characteristics for this region's tillable soil. Below are yield assumptions and the model's cost matrix for region two, presented in the same fashion as region one.

Table 2-3: Yield assumptions for region 2

		After alfalfa	After annual
Corn	Grain (bu)	160	145
	Stover (t)	4.5	4
	Harvested Stover (t)	2.3	2
Barley	Grain (t)	63	50
	Straw (t)	2.4	1.8
	Harvested straw (t)	1.2	0.9
Sorghum		7.1	6.5
		Est.	Annual
Alfalfa (t)		2.6	4
Switchgrass (t)		3	5

Table 2-4: Cost matrix for region 2

(N = $0.81/lb, P = $0.90/lb, K = $0.69/lb)

	Machinery	N	P	K	Chem	Seed	Credit	Erosion
Prior – Current Year	--		$/ acre in current year				--------------------	tons/acre
Corn-Corn	102.70	141.75	49.50	31.05	25.20	63.00	-652.50	2.00
Corn-Barley	100.17	112.35	26.86	36.85	13.85	8.64	-224.00	1.60
Corn-Sorghum	62.62	152.00	44.81	35.34	15.40	3.47	0.00	1.60
Corn-Alfalfa	82.08	0.00	142.20	430.56	8.32	28.65	0.00	1.20
Barley-Corn	102.70	141.75	49.50	31.05	25.20	63.00	-652.50	1.60
Barley-Barley	100.17	112.35	26.86	36.85	13.85	8.64	-224.00	0.85
Barley-Sorghum	62.62	152.00	44.81	35.34	15.40	3.47	0.00	1.40
Barley-Alfalfa	82.08	0.00	142.20	430.56	8.32	28.65	0.00	1.00
Sorghum-Corn	102.70	141.75	49.50	31.05	25.20	63.00	-652.50	1.60

Table 2-4 Continued

Prior – Current Year	Machinery	N	P	K	Chem	Seed	Credit	Erosion
	--------------------------------------	$/ acre in current year					--------------------	tons/acre
Sorghum-Barley	100.17	112.35	26.86	36.85	13.85	8.64	-224.00	1.40
Sorghum-Sorghum	62.62	152.00	44.81	35.34	15.40	3.47	0.00	2.10
Sorghum-Alfalfa	82.08	0.00	142.20	430.56	8.32	28.65	0.00	1.40
Alfalfa1 - Alfalfa2	76.97	0.00	0.00	0.00	3.52	0.00	0.00	0.80
Alfalfa2 - Alfalfa 3	76.97	0.00	0.00	0.00	3.52	0.00	0.00	0.22
Alfalfa 3 - Corn	103.28	97.20	54.00	34.50	25.20	63.00	-720.00	1.00
Alfalfa 3 - Barley	100.86	76.95	31.23	40.49	13.85	8.64	-280.00	0.81
Alfalfa 3 - Sorghum	63.68	101.33	52.11	38.83	15.40	3.47	0.00	1.10
Alfalfa 3 - Alfalfa 1	82.08	0.00	142.20	430.56	8.32	28.65	0.00	0.78
Switchgrass	15.60	99.79	28.44	64.03	0.00	0.00	0.00	0.00
Switchgrass 1	60.90	0.00	28.44	64.03	4.01	24.70	0.00	0.02

Region 3: Southern Iowa

Roughly half of Iowa is located in what is called the Southern Iowa Drift Plain. Assumptions about crop production and erosion in Region 3 were tailored to Lucas County, Iowa. The Southern Iowa Drift Plain is similar in geologic history to the Des Moines Lobe, with retreating glaciers leaving deep sediments of glacial drift and a flat landscape. However, glacial activity here came much earlier than on the Des Moines Lobe. As a result, the landscape has undergone significantly more erosion and weathering over time than the Des Moines Lobe, creating a gently rolling landscape [20]. To calculate erosion, Zook-Olmitz-Vesser complex soils, with 0% to 5% slopes were assumed, which are the most common charachteristics of this region's soils. Below are yield assumptions and the model's cost matrix for region 3, presented in the same fashion as before.

Table 2-5: Yield assumptions for region 3

		After alfalfa	After annual
Corn	Grain (bu)	140	125
	Stover (t)	3.9	3.5
	Harvested Stover (t)	2	1.5
Barley	Grain (t)	55	44
	Straw (t)	2	1.6
	Harvested straw (t)	1	0.8
Sorghum		7.2	6.6
		Est.	Annual
Alfalfa (t)		2.6	4
Switchgrass (t)		3	5

Table 2-6: Cost matrix for region 3

(N = \$0.81/lb, P = \$0.90/lb, K = \$0.69/lb)

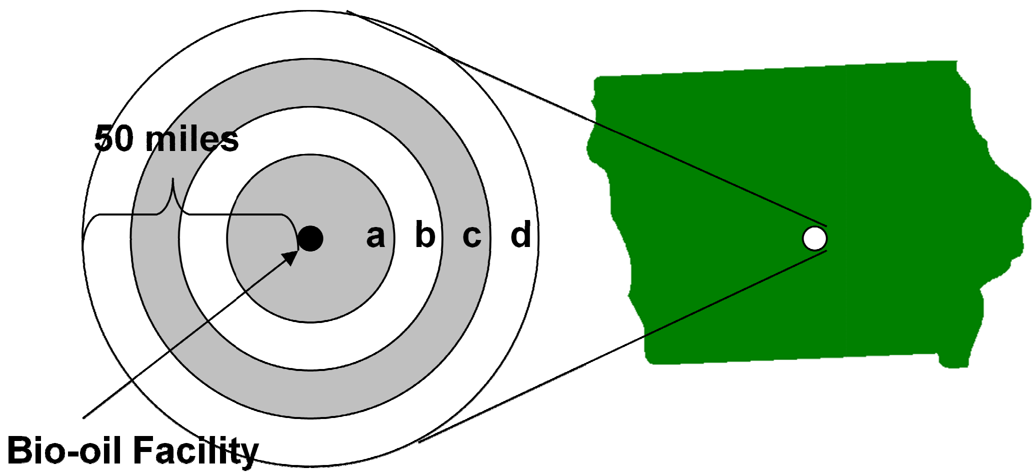
	Machinery	N	P	K	Chem	Seed	Credit	Erosion
Prior – Current Year	--- \$/ acre in current year -----------------------							tons/acre
Corn-Corn	101.60	141.75	40.50	27.60	25.20	52.50	-562.50	1.90
Corn-Barley	99.94	98.39	23.55	32.85	13.85	8.64	-196.00	1.70
Corn-Sorghum	62.88	147.94	44.81	35.34	15.40	3.47	0.00	2.20
Corn-Alfalfa	82.08	0.00	142.20	430.56	8.32	28.65	0.00	1.30
Barley-Corn	101.60	141.75	40.50	27.60	25.20	52.50	-562.50	1.20
Barley-Barley	99.94	98.39	23.55	32.85	13.85	8.64	-196.00	1.00
Barley-Sorghum	62.88	147.94	44.81	35.34	15.40	3.47	0.00	1.50
Barley-Alfalfa	82.08	0.00	142.20	430.56	8.32	28.65	0.00	1.10
Sorghum-Corn	101.60	141.75	40.50	27.60	25.20	52.50	-562.50	1.80
Sorghum-Barley	99.94	98.39	23.55	32.85	13.85	8.64	-196.00	1.50
Sorghum-Sorghum	62.88	147.94	44.81	35.34	15.40	3.47	0.00	2.00
Sorghum-Alfalfa	82.08	0.00	142.20	430.56	8.32	28.65	0.00	1.40
Alfalfa1 - Alfalfa2	76.97	0.00	0.00	0.00	3.52	0.00	0.00	0.81
Alfalfa2 - Alfalfa 3	76.97	0.00	0.00	0.00	3.52	0.00	0.00	0.24
Alfalfa 3 - Corn	101.64	97.20	49.50	27.60	25.20	52.50	-630.00	1.10
Alfalfa 3 - Barley	100.40	67.39	27.38	36.10	13.85	8.64	-220.00	0.92
Alfalfa 3 - Sorghum	63.68	101.33	52.11	38.83	15.40	3.47	0.00	1.20
Alfalfa 3 - Alfalfa 1	82.08	0.00	142.20	430.56	8.32	28.65	0.00	0.81
Switchgrass	15.60	99.79	28.44	64.03	0.00	0.00	0.00	0.00
Switchgrass 1	60.90	0.00	28.44	64.03	4.01	24.70	0.00	0.02

Transportation and Drying Costs

To be processed into fuels, crops need to be transported from the field and to a processing facility. Also, freshly harvested sweet sorghum needs to be dried. The cost of transportation is dependent on both the distance traveled and the number of trucks required. This model addresses these factors by: (1) grouping each region's acres into concentric rings around the processor, and (2) using the crop's bulk densities and yields to determine how many trucks are needed to convey one acre's yield of each crop from the field and to the processor. Including these factors in the cost of production allows the model to weigh transportation costs when selecting the optimal crop mix.

In each of the three regions, the model built for this project considers five different doughnut-shaped areas located within 10, 20, 30, 40 and 50 mile radii of the collection point (see figure 2-2). It is assumed that 76% percent of the land within each area is available cropland.

Figure 2-2: Crop areas



All crops except sweet sorghum are assumed to be compacted into large square bales. The number of bales yielded per acre is a function of the crop yields and bulk densities given in this chapter's discussion of the individual crops. For calculating transportation costs, these bale numbers were all rounded up to the nearest whole bale. Semi-trucks are assumed to hold at most 42 square bales and cost 70$/hr to operate, travelling at 45 miles per hour, based on Duffy [21]. Trucks carrying sweet sorghum are limited to 36 tons per load, based on Bennet and Anex [19]. Also, because sweet sorghum is harvested fresh, an additional $50 per ton for drying is charged. That fee is attached here to reflect the wet-weight cost of travel and the drying that will be required upon delivery.

All trucks were assigned the same hourly cost and speed of travel. Accordingly, each acre planted with a given crop results in a yield of biomass that demands a certain number of truck trips from the field and to the processor. For this model, it is assumed that each trip is two-way and that each leg of the trip incurs the same costs. Transportation costs based on assumed yields in each of the three regions, and their bulk densities, are given in the table 2-8.

Table 2-8: Transportation cost per acre

Region 1: Central	10 miles	20 miles	30 miles	40 miles	50 miles
Prior – Current Year	*------$/acre in current year----------*				
Corn-Corn	3.70	7.41	11.11	14.81	18.52
Corn-Barley	1.48	2.96	4.44	5.93	7.41
Corn-Sorghum	327.57	333.13	338.70	344.26	349.83
Corn-Alfalfa	2.96	5.93	8.89	11.85	14.81
Barley-Corn	3.70	7.41	11.11	14.81	18.52
Barley-Barley	1.48	2.96	4.44	5.93	7.41
Barley-Sorghum	327.57	333.13	338.70	344.26	349.83
Barley-Alfalfa	2.96	5.93	8.89	11.85	14.81
Sorghum-Corn	3.70	7.41	11.11	14.81	18.52
Sorghum-Barley	1.48	2.96	4.44	5.93	7.41
Sorghum-Sorghum	327.57	333.13	338.70	344.26	349.83
Sorghum-Alfalfa	2.96	5.93	8.89	11.85	14.81
Alfalfa1 - Alfalfa2	4.44	8.89	13.33	17.78	22.22
Alfalfa2 - Alfalfa 3	4.44	8.89	13.33	17.78	22.22
Alfalfa 3 - Corn	4.44	8.89	13.33	17.78	22.22
Alfalfa 3 - Barley	2.22	4.44	6.67	8.89	11.11
Alfalfa 3 - Sorghum	356.05	362.10	368.15	374.20	380.25
Alfalfa 3 - Alfalfa 1	2.96	5.93	8.89	11.85	14.81
Switchgrass	5.93	11.85	17.78	23.70	29.63
Switchgrass 1	3.70	7.41	11.11	14.81	18.52
Region 2: Northeast	10 miles	20 miles	30 miles	40 miles	50 miles
Prior – Current Year	*------$/acre in current year----------*				
Corn-Corn	3.70	7.41	11.11	14.81	18.52
Corn-Barley	1.48	2.96	4.44	5.93	7.41
Corn-Sorghum	330.62	336.23	341.85	347.47	353.09
Corn-Alfalfa	2.96	5.93	8.89	11.85	14.81
Barley-Corn	3.70	7.41	11.11	14.81	18.52
Barley-Barley	1.48	2.96	4.44	5.93	7.41
Barley-Sorghum	330.62	336.23	341.85	347.47	353.09
Barley-Alfalfa	2.96	5.93	8.89	11.85	14.81
Sorghum-Corn	3.70	7.41	11.11	14.81	18.52
Sorghum-Barley	1.48	2.96	4.44	5.93	7.41
Sorghum-Sorghum	330.62	336.23	341.85	347.47	353.09
Sorghum-Alfalfa	2.96	5.93	8.89	11.85	14.81
Alfalfa1 - Alfalfa2	4.44	8.89	13.33	17.78	22.22
Alfalfa2 - Alfalfa 3	4.44	8.89	13.33	17.78	22.22
Alfalfa 3 - Corn	3.70	7.41	11.11	14.81	18.52
Alfalfa 3 - Barley	1.48	2.96	4.44	5.93	7.41

Table 2-8 Continued

Region 2 continued	10 miles	20 miles	30 miles	40 miles	50 miles
			------$/acre in current year----------		
Alfalfa 3 - Sorghum	361.14	367.27	373.41	379.54	385.68
Alfalfa 3 - Alfalfa 1	2.96	5.93	8.89	11.85	14.81
Switchgrass	5.93	11.85	17.78	23.70	29.63
Switchgrass 1	3.70	7.41	11.11	14.81	18.52

Region 3: Southern	10 miles	20 miles	30 miles	40 miles	50 miles
Prior – Current Year			*------$/acre in current year----------*		
Corn-Corn	2.96	5.93	8.89	11.85	14.81
Corn-Barley	1.48	2.96	4.44	5.93	7.41
Corn-Sorghum	335.70	341.41	347.11	352.81	358.52
Corn-Alfalfa	2.96	5.93	8.89	11.85	14.81
Barley-Corn	2.96	5.93	8.89	11.85	14.81
Barley-Barley	1.48	2.96	4.44	5.93	7.41
Barley-Sorghum	335.70	341.41	347.11	352.81	358.52
Barley-Alfalfa	2.96	5.93	8.89	11.85	14.81
Sorghum-Corn	2.96	5.93	8.89	11.85	14.81
Sorghum-Barley	1.48	2.96	4.44	5.93	7.41
Sorghum-Sorghum	335.70	341.41	347.11	352.81	358.52
Sorghum-Alfalfa	2.96	5.93	8.89	11.85	14.81
Alfalfa1 - Alfalfa2	4.44	8.89	13.33	17.78	22.22
Alfalfa2 - Alfalfa 3	4.44	8.89	13.33	17.78	22.22
Alfalfa 3 - Corn	3.70	7.41	11.11	14.81	18.52
Alfalfa 3 - Barley	1.48	2.96	4.44	5.93	7.41
Alfalfa 3 - Sorghum	366.22	372.44	378.67	384.89	391.11
Alfalfa 3 - Alfalfa 1	2.96	5.93	8.89	11.85	14.81
Switchgrass	5.93	11.85	17.78	23.70	29.63
Switchgrass 1	3.70	7.41	11.11	14.81	18.52

Chapter 3 Technologies: Waterloo Process Fast Pyrolysis and Linear Programming

Waterloo Process Fast Pyrolysis

The model built for this project seeks to optimize feedstock landscapes for bio-oil processed by Waterloo Process Fast Pyrolysis. Pyrolysis of biomass means "the degradation of biomass by heat in the absence of oxygen" [22]. It is not a new process. The first patent for pyrolysis was granted in England in 1620 to Sir William St. John for the production of charcoal [23]. His patent covered the charcoaling of a variety of biomass forms, including "seacole, stonecole, pitcole, earthcole, turf peate, brush flagg, cannel and all other fewell" [24].

Modern biomass pyrolysis proceeds in three phases. The first phase is moisture evaporation, which begins when temperature inside the reactor reaches 130 degrees C. Next comes main devolatilization, which occurs between 130 and 450 degrees C. This is followed by continuous slight devolatilization, which occurs at temperatures above 450 degrees C. Depending on the pyrolysis technology being employed, the temperature inside the reactor will reach to between 400 and 1200 degrees C [25].

This process results in three pyrolysis products: (1) a solid char (like charcoal); (2) a volatile liquid called "pyrolitic oil", or "bio-oil"'; and (3) various gases [26]. Researchers have varied maximum heating temperature, heating rates, residence time and atmospheric qualities to investigate how these conditions affect the yield of these three products. It has been shown that longer residence time in the reactor begets higher charcoal yields and shorter residence times beget higher liquid yields. Similarly, higher temperatures in the reactor favor gaseous over liquid products [27, 28]. From the time of St. John until the First World War, coal was the energy product of choice in the Western world. During this time, pyrolitic oils were considered a byproduct of charcoaling, and occasionally found use as a condiment for meats due to their smoky smell and flavor.

Technological advancements in the latter part of the 19^{th} century, however, aroused new interest in the logistical and energetic advantages conferred by liquid fuels. In 1912, for example, then First Lord of the British Admiralty, Winston Churchill, ordered that the Royal Navy transition entirely from coal-fired, to oil-fueled ships, the first of many such transitions around the world. (Yergin reviews the history of world energy policy and oil in [29]). By 1970, roughly 5 gallons of oil were in transit around the world for every one human living on earth [30]. This new prominence, coupled with major oil supply disruptions in 1973 and 1979, prompted renewed interest in the liquid product from pyrolysis. Two new biomass pyrolysis processes were developed in the late 1970s and early 1980's that employed quick residence times and relatively low temperatures in order to maximize the yield of pyrolytic oils. This oil was called "bio-oil" and presented the world with a new substitute for crude oil.

Both processes employ "flash pyrolysis," which entails residence times that typically range from only 0.4 to 0.5 seconds and reach 500 degrees C. At that temperature, vapor is released from the biomass, which can then be cooled and condensed to make the liquid bio-oil product [31, 32]. Of the two better known biomass flash pyrolysis processes, first came the "Garret Process," which was developed from 1970 to 1974 by the Garrett Research and Development Company – a research subsidiary of the Occidental Petroleum Corporation.

The Garrett team experimented mostly with different types of waste, including animal feedlot waste, sewage sludge and solid municipal refuse in an effort to address both America's energy and garbage problems simultaneously.

Shortly thereafter, from 1979 to 1985, another team of researchers at the University of Waterloo, (Ontario, Canada) developed the "Waterloo Fast Pyrolysis Process." The Waterloo group tailored their work to agricultural biomass. Their early work experimented with several different crops, including aspen trees, poplar trees, maple trees, wheat, sweet sorghum and sweet sorghum bagasse, among others. Because the Waterloo Process has proven over time to be cost effective, and because it was designed for agricultural crops, it is the processing technology for which crop mixes are optimized in this model.

Figure 3-1: The Waterloo Fast Pyrolysis Process

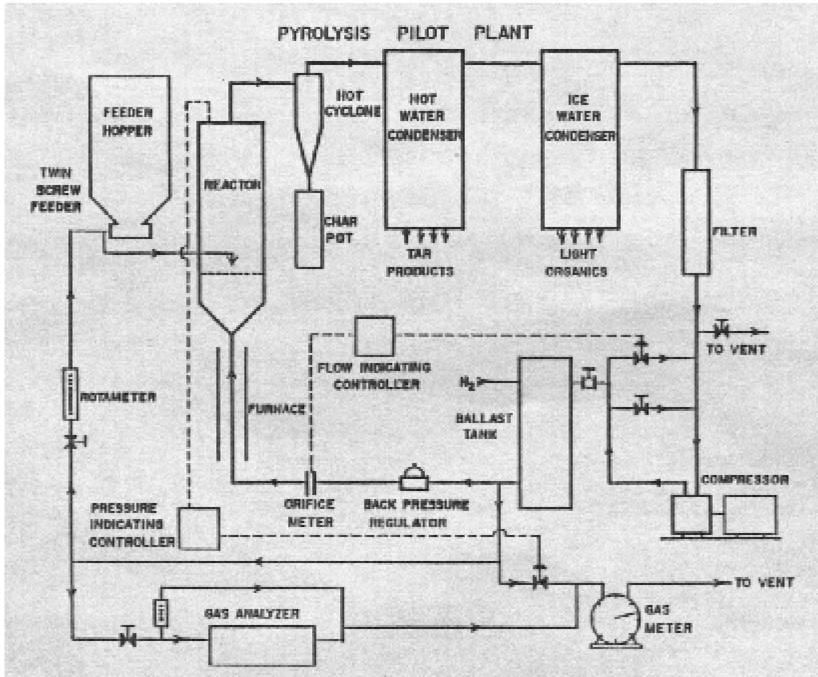


Figure 1. Flow Diagram of a Fluidized Bed Fast Pyrolysis Process [the Waterloo Fast Pyrolysis Process (WFPP)].

Image from: Rowell, R., Shultz, P., Narayan, R. eds. Emerging Technologies for Materials Chemicals From Biomass. Washington.: American Chemical Society 1992

A schematic of the Waterloo Fast Pyrolysis process is shown in figure 3-1. At the bench scale, the Waterloo process proceeds as follows: Biomass feedstock is air dried and then hammer milled and screened to a particle size of -595µm (-30 mesh). The ground biomass is then conveyed by a twin-screw feeder from the grinder to the reactor gate. A flow of recycled product gas blows the biomass off the screws and into the reactor. The reactor itself employs a fluidized bed. Fluidized beds need fluidizing material and fluidizing gas. The Waterloo process employs sand as the fluidizing material and heated and recycled product gas the fluidizing gas. Pyrolysis takes place inside the fluidized bed, where the biomass is typically held for only between 200 to 700 milliseconds at temperatures between

400 and 560 degrees C, depending on the feedstock and the goals of the operator. Pyrolysis products are swept into a cyclone, which separates the solid char from the gas and the volatiles. The solid product stream (char) is used to re-heat the fluidizing material (sand) in what is known as the “blow through” system. “Blow through” contributes significantly to the Waterloo Process’s cost effectiveness by lowering both the capital cost of the fluidized bed, and by recycling heat, which reduces expenditures on external energy. Gas and volatiles proceed to two condensers arranged in series. Both condensers use water as a cooling medium and the second condenser operates at colder temperatures than the first. Condensates from this cooling are collected in pots on top of the condensers. These condensates are bio-oil. Gas not condensated is filtered and recycled back through the system for “blow through” and for conveying new biomass from the twin screw feeder into the reactor [33].

Pyrolysis Feedstock

In addition to experimentation with process conditions during pyrolysis, researchers have explored how different biomass feedstock can impact yield of the three pyrolysis products. This research is on-going, but discoveries so far yield important results for this project. First, it has been shown that almost any form of biomass can feed a fast pyrolysis unit. Second, certain qualities of the biomass feedstock have been correlated with product yield and quality. Because the model developed for this project seeks to mix a variety of plants on the landscape that confer natural resiliency, conserve natural resources, and optimize feedstock quality for the bio-oil processor, these results are critical. A summary of feedstock experimentation results is shown in table 3-1.

Table 3-1 Summary of Pyrolysis Feedstock Experimentation

Authors	Year	Feedstock analyzed	Relevant Observations	REF
Finney & Garrett	1974	Douglas Fir Rice hulls Grass straw Manure	Douglas fir tree bark behaves differently than the other feedstock.	[34]
Scott & Piskorz	1984	Maple wood, Hybrid poplar Wheat straw	Wheat straw gives significantly lower liquid yield than hard wood and has a higher optimal temperature.	[35]
Maschio	1992	Wood Hazelnut shells Olive husks Corn cobs Wheat straw Lucerne cake	Yields depend mainly on the chemical composition of the feedstock and the operating temperature. In lignin-rich biomass, charcoal production is favored, but higher pyrolysis time is needed. Wood represents biomass rich in cellulosic compounds, while olive husks are rich in lignin.	[36]
Raveend-ran	1995	Bagasse Coconut coir Coconut shell Coir pith Corn cob Corn stalks Cotton gin waste Groundnut shell Millet husk Rice husk Rice straw Subabul wood Wheat Straw	Lignin gives higher char yield than cellulose and hemicelluloses. Small amounts of inorganic material can significantly alter pyrolysis. When volatiles go up, char yields go down. Char yield increases on demineralization. Liquid yield goes up with demineralization. $ZnCl_2$ in high concentrations increase gas yield by 170% and reduce liquid by 59%. More volatiles released reduces residence time, reducing condensation. HHV of liquid products increases with demineralization For liquefaction, corn cob, groundnut shell and rice husk could be better feedstock. Wood is better for gasifciation. The composition of liquid products is similar to composition of biomass.	[37]

Table 3-1 Continued

Authors	Year	Feedstock analyzed	Relevant Observations	REF
Ghetti	1996	Wheat Sorghum Kenaf Maidengrass Artichoke thistle Giant Reed Black poplar Umbrella pine	Perennial species have higher calorific value and higher carbon value. Higher volatile matter begets more pyrolysis products. Lower lignin in the biomass begets higher reactivity. Lower lignin gives "lighter" pyrolysis products (wheat gave lighter than woods). Lighter product is usually better for combustion.	[38]
Piskorz & Majerski	1998	Sweet Sorghum Sweet Sorghum Bagasse	Sorghum bagasse is an intermediate quality feedstock Sorghum bagasse is better than raw sweet sorghum because it has less sugars. High sugar content begets more C02 in the product and lower liquid yields. Deionized bagasse can reduce the low molecular weight of the liquid product.	[39]
Sensoz	2002	Pine chips	Pine chips had lower ash and fixed carbon, but higher volatile matter than pine bark. Higher volatile matter indicates the wood is more reactive than the bark.	[40]
Yorgun & Simsek	2003	Miscanthus X giganteus	Particle size influences yield. Bigger particles get more char, less liquid.	[41]

Table 3-1 shows the wide variety of plants that can serve as fast pyrolysis feedstock, and that these plants behave differently when pyrolyzed under similar conditions. In the model developed for this project, those characteristics that improve the yield and quality of liquid pyrolysis products, particularly bio-oil derived from pyrolytic lignin, were selected to reflect the bio-oil processor's needs. The model is designed to find crop mixes that maximize these characteristics and minimize the characteristics that inhibit product yield, while also minimizing cost and conserving soil. Crop component characteristics included in this model are:

Lignin

Pyrolytic lignin is the product of pyrolyzing the natural lignin found in plants. Researchers are currently developing ways of upgrading pyrolytic lignin into stable hydrocarbons that are similar in form and function to those found in conventional crude oil [42]. More natural lignin in the biomass feedstock results in more pyrolytic lignin after pyrolysis, and ultimately, the potential for more liquid fuel production per acre of land.

Higher Heating Value

Higher Heating Value (HHV) is "the net enthalpy released upon reacting a particular fuel with oxygen under isothermal conditions" [43]. It is a measure of energy stored in the feedstock, and thus represents an upper bound of the energy we can unlock from it. Biomass with a greater HHV has a greater potential for yielding high energy products.

Ash

Ash in the feedstock can reduce conversion efficiency of biomass into pyrolysis products [44]. Ash is known to interfere with all types of combustion.

Table 3-2 shows the lignin, HHV and ash content of each of the five crops that were selected for inclusion in the model. For this project, these values are assumed to be the same for each crop, regardless of the region or year it is grown.

Table 3-2: Crop components

Crop	Ash (%Mass)	Lignin (%Mass)	HHV (BTUs/Lb.)
Corn Stover	10.24%[45]	17.69%[45]	7894[45]
Barley Straw	4.30%[46]	16.40%[46]	7929[46]
Sweet Sorghum	8.45%[47]	22.04%[47]	7876[48]
Alfalfa	10.30%[49]	7.00%[50]	7820[49]
Switchgrass	5.76%[45]	17.56%[45]	7998[45]

Numbered citations refer to sources listed in the Literature Cited section.

Linear Programming

Linear Programming (LP) is a mathematical technique for finding the optimal allocation of resources. It is especially applicable to agriculture and biorenewable resources because it allows for the development of models that simultaneously weigh a variety of costs and benefits. For this reason, it is the approach used in this study.

LP models are made up of linear inequalities that describe the resources available, the boundaries of feasible solutions and the goals of the decision maker. When the system of linear inequalities is solved, an allotment of resources that best meets the decision maker's goal is determined. Mathematical modeling using systems of inequalities has no precise origin. However, algorithms for solving large sets of inequalities can be traced back at least to the work of Fourier in 1826. During the early 20^{th} century, researchers working in both Russia and America recognized the importance of solving linear programming-type problems. In 1939, Russian mathematician L.V. Kantorovitch proposed an algorithm for solving sets of linear inequalities that went mostly unnoticed until 1975, when Kantorovitch and his colleague T.C. Koopman were awarded a Nobel Prize in economics for contributions "to the theory of optimum allocation of resources" [51]. Perhaps more significantly for industry though, in 1947 George B. Dantzig published the "Simplex Method" for solving large linear programs, which unlocked LP's potential for Western governments, and later industry.

A basic linear programming model has 4 fundamental features: (1) decision variables (also known as "activities" and "activity levels"); (2) coefficients; (3) constraints; and (4) an objective function. Decision variables are the allocation quantities for which the model is designed to solve. These quantities represent participation in an activity and are typically bound to a lower limit of 0, which represents inactivity or non-use. Negative resource use or negative participation is generally not realistic. For example, in the model designed for this project, decision variables represent the acres assigned to the crops.

Coefficients relate participation in an activity to a cost or benefit in a fixed proportion. In this project's model, coefficients have been estimated for all of the crops' biochemical components, agronomic practices, cost of production and potential to erode soils. Constraints use these coefficients to restrict the model such that a program of activities does not exceed a user-determined cost, or, conversely, ensure that a minimum benefit is accrued. Depending on the nature of the problem, a wider variety of constraints are possible.

The model built for this project employs three basic types of constraints: "greater-than-or-equal-to," "less-than-or-equal-to," and "equal-to-zero." "Greater-than-or-equal-to constraints" are related to total biomass yield from the landscape (measured in tons); total lignin yield from the landscape (measured in tons); and total Higher Heating Value yielded from the landscape (measured in million British Thermal Units (MMBTU's). In essence, the model allocates acres to crops in a mix that ensures that minimum levels of biomass, lignin and HHV are satisfied at minimum cost.

The next type of restriction is "less-than-or-equal-to." "Less-than-or-equal-to" constraints are related to: ash content (measured in tons) and soil erosion (measured in tons of soil loss from the landscape). The model's solution set is restricted to those values that do not exceed maximum user-determined quantities for these values, while also minimizing cost.

"Equal-to-zero" constraints ensure that all of the acres and costs are accounted for every year. Because these constraints relate specifically to one unique component of this model, they are discussed more fully in the next section.

Objective functions represent the decision maker's goal. The objective function relates the LP's solution to a quantity that the decision maker seeks to minimize (such as cost), or maximize (such as profit). In this model, the objective is to minimize the cost of producing and delivering biomass to a centralized collection point, subject to the constraints imposed.

Bazaraa, Jarvis and Sherali suggest four major assumptions of linear programming [52]:

(1) Proportionality. Each additional unit of a particular activity contributes equally to the cost and benefit of the overall program. The relationship is always linear. There are no economies of scale.

(2) Additivity. The total cost and benefit of the program of all activities is equal to the sum of each activity's contribution. There can be no substitution or interaction effects between activities.

(3) Divisibility. Participation levels in an activity are not restricted to integers. Decision variables can be allocated at fractional levels.

(4) Deterministic. Coefficients and restrictions are determined by the modeler *a priori* and cannot change as the model is run. Any variation in demand, costs, prices or the like is assumed to be approximated by the fixed coefficients assigned by the modeler.

A Mathematical Statement of Generalized Linear Programming

Linear programming uses algebraic inequalities to describe the constraints and objectives that govern the decision being modeled. A generalized algebraic presentation is given below.

Essentially, the model is built to find a solution set (x_1, $x_{2,}$ $x_{3,}$ …x_n) that maximizes or minimizes an objective function of the form:

$$MIN = \sum C_J X_J \quad (E1)$$

Where, equation E1 is subject to linear constraints:

$$X_j >= 0 \quad (E2)$$

$$\sum a_{ij} x_j <= b_i \quad (E3)$$

Where:

a_{ij} represents a coefficient for the units of resource i associated with one of unit of activity j. For example, acres planted to corn (j), associated with erosion per acre (i)

b_i is the limit on resource i. For example, allowable soil erosion.

C_J represents the cost of one unit of activity j. For example, the cost of producing one acre of corn.

n is the number of possible activities. For example, all of the possible crops.

X_J is the level of activity j. Or, the number of acres planted to crop j.

In this simplified example, equation E2 restricts the solution set to positive values and equation E3 restricts the solution set to one that results in less than or equal to “b” tons of soil loss.

Linear Programming and Crop Rotations

Shortly after Dantzig published the Simplex method for solving linear programs, Hidreth and Reiter published the first application of LP to crop rotations [54]. They defined each activity (X) as a pre-determined sequence of crops over time. This approach dominated the agricultural literature for decades. Numerous contributions were also made by Earl Heady [55] and Raymond Beneke [56] using this approach. This approach came to be known as the “explicit sequential method.”

In the 1980s, agricultural economists began reconsidering the explicit sequential method. In their article “The Choice of Crop Rotation: A Modeling Approach and Case Study”, Talaat El-Nazer and Bruce McCarl point out that the explicit sequential method imposes serious limitations on the possible combinations of crops that could make up an optimized rotation. They write: “This explicit sequential method of rotation modeling limits the choice of rotation to the combinations that the modeler develops. There are model size and data availability reasons for such a limitation. Nevertheless, the modeling method limits the options” [57, pp. 128]. El-Nazer and McCarl suggest using an incidence matrix, wherein every possible combination of crops over the life of the model is defined, and acres are assigned to one of the choices. In El-Nazer and McCarl’s approach, incidence matrix columns correspond to all possible combinations over the time span of the model (in their case $t = 4$ years), while all possible combinations over 3 years (t-1) are arranged in rows.

While El-Nazer and McCarl's approach to crop rotation modeling overcomes some of the limitations of the explicit sequential method, it has its own drawbacks. This approach requires that the modeler define every possible combination of crops. The number of possible combinations of crops grows exponentially with every year of the model. In the above example, two crops modeled over four years results in 16 (2^4) different activities. The model developed for this project considers five crops over 10 years, which would require an incidence matrix with 9,675,625 (5^{10}) columns. Such a matrix would be time-intensive and wrought with the potential for confusion.

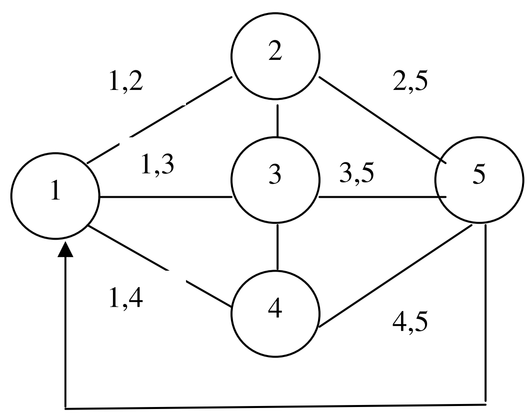
Network Flow Linear Programming

More recently, crop rotation modelers have used an operations research application of linear programming for a solution to larger problems. In their article, "Modeling Optimal Crop Sequences Using Network Flows," Nina Detlefsen and Allan Jensen suggest using "network flow" linear programming models, noting that "[T]he network formulation of the crop rotation problem can be generalized to include any number of pre-crop years and any number of future production years" [58 pp. 571]. In building a network formulation, the number of activities does not increase exponentially with each year under consideration. Moreover, "[S]olution procedures for network models are taught in many LP-courses…Writing algorithms to solve network problems is straightforward because it does not involve inverting matrices as in simplex-based algorithms" [ibid].

Network Models Explained

A network flow model is a special type of linear programming model. As before, the model is built with algebraic inequalities and the four assumptions (proportionality, additivity, divisibility and deterministic) still apply. In network flow models, decision variables represent paths from one point to another. The network flow problem often seeks to assign units to a sequence of paths from beginning to end that minimize the cost of transportation. An example diagram and objective function are shown in figure 3-1.

Figure 3-1: A generalized network flow model



Between the starting and ending points on the above diagram are nodes and arcs. Nodes are represented by circles numbered one through five. Nodes are connected by arcs, which are represented by lines with the designation "from node i, to node j (i,j)." Sending a unit across an arc represents a decision by which costs and benefit coefficients can be multiplied, just as in the generalized linear programming model described above. This is called decision modeling "on the arcs." Essentially, such a model seeks to move all units from beginning to end along the pathway of arcs that ensures minimal transportation cost.

This can be shown algebraically as:

Objective:

$$\text{MIN } \sum\sum C_{ij} X_{ij} \qquad \text{(E4)}$$

Where

C_{ij} represents the cost of 1 unit following an arc going from node i to node j.

X_{ij} represents the number of units following an arc going from node i to node j.

Network flow models demand a particular type of restriction, known as "flow conservation," "mass conservation," "nodal balance," and/or "Kirchoff" restrictions [52]. These restrictions impose the logical condition that all units must pass through contiguous arcs in sequence on their way to the end point. Essentially, flow conservation restrictions ensure that what flows into a node equals what flows out and it accounts for every step of the path. This is where this project's model employs its "must-equal-zero" constraints. Generalized flow conservation restrictions for the preceding network flow problem are shown below.

$$\sum_{j=1}^{m} x_{ij} - \sum_{k=1}^{m} x_{ki} = 0 \qquad \text{(E5)}$$

Where:

$\sum_{j=1}^{m} x_{ij}$ = total flow out of node i

And

$\sum_{k=1}^{m} x_{ki}$ = total flow into node i

In crop rotation network flow modeling, decisions are made "on the arcs", and the nodes represent crops in a given year, which means the model is built to solve for the number of acres transitioning from one crop to another every year. This is particularly advantageous because it allows the modeler to account for the effect of a preceding year's crop on the fertilization and tillage regimes in the current year. This is especially important when the model includes perennial crops and the yield penalty effects discussed in chapter two.

Chapter 4 Network Flow Linear Programming Model for Optimized Feedstock Landscapes for Bio-Oil Production

Program design

Chapter three outlined the four fundamental features of a linear programming model: (1) decision variables; (2) coefficients; (3) constraints; and (4) an objective function. Chapter three also introduced the concept of network flow linear programming in which decisions are made "on the arcs." This chapter presents the design for this project's network flow linear programming model graphically, then algebraically.

Decisions in this model are made "on the arcs" in order to capture the effects of the prior year's crop. Each arc represents an acre transitioning from one crop to another between years. Thus, both perennial crops and the yield penalty effects associated with annual crops can be handled by properly designating arcs in the model. For example, because alfalfa stands are assumed to last three years, only one arc follows first-year alfalfa – the arc connecting it to second year alfalfa. Similarly, only one arc follows second-year alfalfa – the arc connecting it to third-year alfalfa. After three years, five arcs follow out of third-year alfalfa, as after three years an acre previously assigned to it can again be re-assigned to any of the five crops. As is shown in the diagrams below, switchgrass is handled similarly. Only one arc follows out of any switchgrass node because one switchgrass stand is assumed to last for the 10-year life of the model.

It is important to note that this design only accommodates the influence of the prior year's crop. Longer-term yield effects cannot be modeled with this approach. The five figures below visually represent this model's network flow design.

Figure 4-1: Node and arc map for years 0 and 1

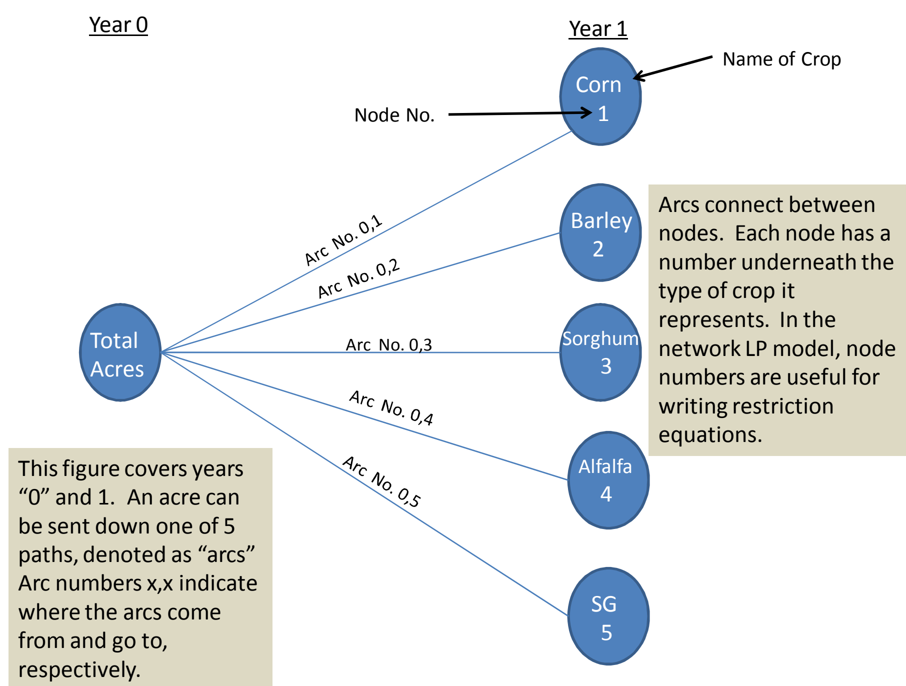


Figure 4-2: Node and arc map for years 1 and 2

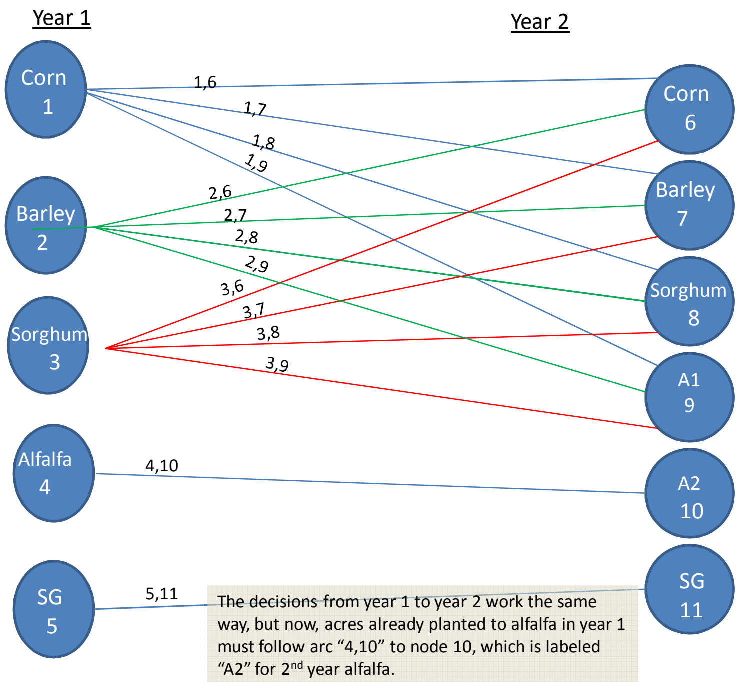


Figure 4-3: Node and arc map for years 2 and 3

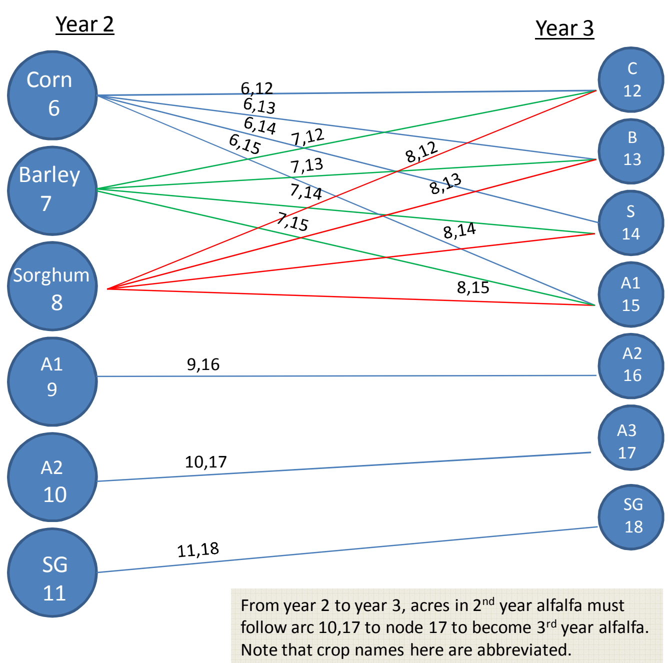
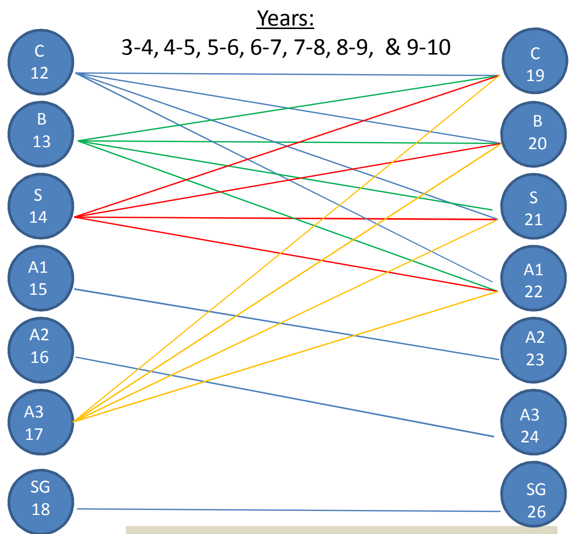


Figure 4-4: Node and arc map for years 3 through 10



By year 3, all the possibilities open for year 4. After 3 years of alfalfa, a new set of nodes open up (shown in orange). 3rd year alfalfa can go into any of the annual crops, or be re-planted into a new stand of alfalfa.

This figure shows the potential paths from year to year that are relevant for the years shown in the title. The node numbers apply to years 3 and 4. In later years, node numbers go up sequentially. Arc numbers are not shown because they too change from year to year.

Figure 4-5: Node and arc map for years 10 to End

The nodes after 10 do not represent decisions, but are necessary to ensure continuity. The sum of these nodes is restricted to the total number of acres to make sure all acres are accounted for throughout the system.

The design depicted above covers one of the five cropping areas, or concentric circles surrounding the processor that were discussed in chapter two. The entire model consists of five replications of this design, with different transportation costs for each one to reflect the distance of each cropping area from the processing facility. To capture variability between soil types and climactic conditions across the three regions of Iowa, this five-piece model was run three different times with the different yield, cost of production, and soil erosion assumptions unique to each region that were outlined in chapter two. An algebraic representation of the model is given below.

Program Functions and Restrictions

The model's objective function, which is to minimize the cost of production and transportation to a centralized location, is given by:

$$MIN \sum_{T=1}^{10} \sum_{A=1}^{5} \sum_{a,b}^{n} X_{a,b}^{TA} \, [Mach_{a,b} + N_{a,b} + P_{a,b} + K_{a,b} + Chem_{a,b} + Seed_{a,b} + Credit_{a,b} + Trans\&Drying_{a,b}^{A}]$$

Subject to:

$X_{a,b}^{TA} \geq 0 \; \forall \, T, A, a, b$ (R1)

$X_{b,c}^{TA} - X_{a,b}^{(T-1)A} = 0 \; \forall T, A, a, b$ (R2)

$\sum_{a,b}^{n} X_{a,b}^{TA} \leq L^{A} \; \forall \, T$ (R3)

$\sum_{T=1}^{10} \sum_{A=1}^{5} \sum_{a,b}^{n} X_{a,b}^{TA} \times Biomass_{a,b} \geq BR$ (R4)

$\sum_{T=1}^{10} \sum_{A=1}^{5} \sum_{a,b}^{n} X_{a,b}^{TA} \times Biomass_{a,b} \times Lignin_{a,b} \geq LR$ (R5)

$\sum_{T=1}^{10} \sum_{A=1}^{5} \sum_{a,b}^{n} X_{a,b}^{TA} \times Biomass_{a,b} \times HHV_{a,b} \geq HR$ (R6)

$\sum_{T=1}^{10} \sum_{A=1}^{5} \sum_{a,b}^{n} X_{a,b}^{TA} \times Biomass_{a,b} \times Ash_{a,b} \leq AR$ (R7)

$$\sum_{T=1}^{10} \sum_{A=1}^{5} \sum_{a,b}^{n} X_{a,b}^{TA} \times Eros_{a,b} \geq ER \qquad \text{(R8)}$$

Where:

X = the number of assigned to arc a,b

a,b = an index of arcs travelling from node a to node b for all nodes over 10 years

A = an index of cropping areas one through five

T = an index of years one through ten

Mach = the machinery cost associated with one acre assigned to arc a,b

N = the nitrogen cost associated with one acre assigned to arc a,b

P = the phosphorous cost associated with one acre assigned to arc a,b

K = the potash cost associated with one acre assigned to arc a,b

Seed = the seed cost associated with one acre assigned to arc a,b

Credit = the credit from grain sales attached to one acre assigned arc a,b (expressed as a negative number)

Trans&Drying = the transportation and drying cost attached to one acre assigned to arc a,b in area A

Biomass = the tons of biomass attached to one acre assigned to arc a,b

Lignin = the percentage of mass that is lignin attached to one acre assigned to arc a,b

HHV = the BTU content per ton attached to one acre assigned to arc a,b

Ash = the percentage of mass that is ash attached to one acre assigned to arc a,b

Eros = the soil loss per acre attached to one acre assigned to arc a,b

L^A = the total number of acres available in the landscape in area A

BR = a user-defined minimum value for total biomass yield from the landscape

LR = a user-defined minimum value for total lignin yield from the landscape

HR = a user-defined minimum value for total HHV yield from the landscape

AR = a user-defined maximum value for total ash yield from the landscape

ER = a user-defined maximum vale for total soil erosion from the landscape

Restriction R1 is a non-negativity constraint. Arcs cannot be assigned with negative acres.

Restriction R2 is this model's flow conservation restriction. The number of acres that follow any arcs out of a particular node in year T (for example barley straw in year 4) must equal the number of acres following all paths into that same node in the previous year.

Restriction R3 is a land area restriction. The model cannot assign more acres than are available in the landscape. This project assumed that 76% of the acres within a 50-mile radius could serve as available cropland. A circle with a radius of 50 miles was then divided into five concentric rings surrounding a centralized collection point, as explained in chapter 2. Values for L^1 through L^5 are given below.

L^1	L^2	L^3	L^4	L^5
152,730 acres	458,189 acres	763,648 acres	1,069,107 acres	1,374,566 acres

Restriction R4 through R8 are the restrictions used in the analysis. R4 ensures that a user-determined minimum of biomass is yielded by the cropping plan. Restrictions R5 through R8 perform the same function for lignin, higher heating value (HHV), ash content, and soil erosion, respectively. Biomass, lignin and HHV represent maximizing goals for the cropping plan, therefore restrictions R4, R5, and R6 are "greater-than-or-equal-to" restrictions. Ash content and soil erosion are minimizing goals for the cropping plan; therefore, restrictions R7 and R8 are "less-than-or-equal-to" restrictions. Lignin, HHV, and ash coefficients for each crop are entered as a fraction of total mass; therefore, each of these coefficients is multiplied by the biomass yield assigned to each acre.

The next chapter analyzes this model using different values for restrictions R4 through R8, as well as the different agronomic and soil erosion assumptions that were prepared for three regions of Iowa that were considered.

Chapter 5 Scenarios and Analysis

The previous chapter presented the design and mathematics of the model, which seeks to find crop mixes that meet user-defined goals for a feedstock landscape at minimum cost. This chapter presents the model output. Analysis proceeds in two stages: (1) comparing how goals are achieved in each of the three regions and (2) looking at interactions and trade-offs between goals in this model.

Regional Outcomes

Region 1: Central Iowa

Region one considers Story County with input and output prices roughly representative of today's environment. To run the model, the five user-determined restrictions needed to be input. These restrictions include: biomass yield (≥ BR), lignin yield (≥ LR), higher heating value yield (≥ HR), ash content yield (≤ AR), and soil erosion (≤ ER). To come up with these restrictions, ten alternative models were built. Each alternative model has one objective function: to maximize or minimize one of these five user-determined restrictions. These alternative models face only non-user determined restrictions, which include non-negativity (the model cannot assign negative acres), land use (the model cannot assign more acres than exist on the landscape), and network flow restrictions. The alternative models do not seek to minimize cost. They simply employ the network flow design described in chapter four to find the minimum and maximum quantities of biomass, lignin, higher heating value, ash, and soil erosion that are possible for the landscape with this set of crops. Once minimum and maximum quantities for each of the user-determined restrictions were found, their range was divided into three evenly-spaced increments, resulting in five selectable restrictions (minimum, 2, 3, 4 and maximum), where “3” represents the mid-point between minimum and maximum.

For model runs in each of the regions, the user-determined restrictions were then all calibrated moderately, meaning at level “3”, the middle between the minimum and maximum possible for the region as determined above. Prices and restrictions employed for region one’s run are shown below, followed by the lowest cost rotation plan.

Table 5-1 Prices in region 1

N ($/lb)	0.81
P ($/lb)	0.90
K ($/lb)	0.69
Corn ($/bushel)	4.50
Barley ($/bushel)	4.00
Trucking ($/hour)	70
Sweet sorghum drying ($/ton)	50

Table 5-2: Restrictions in region 1

Biomass (million tons) >=	144
Lignin (million tons) >=	31
HHV (MMBtus) >=	2.3×10^9
Ash (million tons) <=	11
Soil erosion (million tons) <=	29

Figure 5-1: Results for region 1

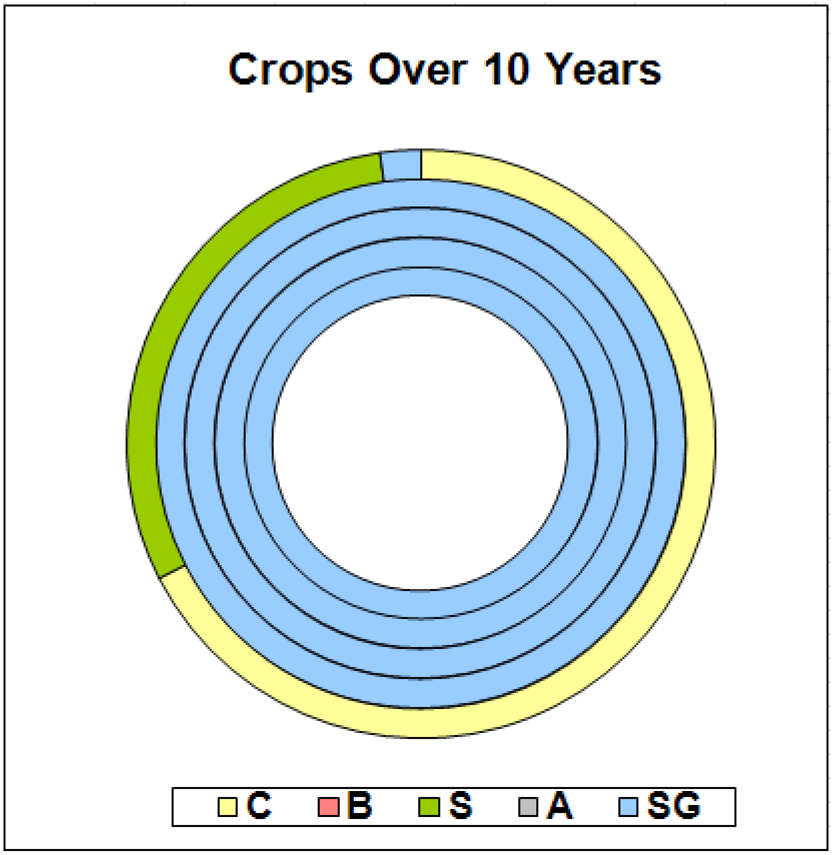


Figure 5-1 shows model output for region one (Story County). All of the user-determined restrictions in table 5-2 are achieved with minimal production and transportation cost. Rings on the "doughnut" chart in figure 5-1 correspond to each of the five crop areas, or concentric circles of acres surrounding the collection point. The rings closer to the center in figure 5-1 represent the crop areas located closest to the collection point. The rings on the outer edge of the doughnut in figure 5-1 represent those farthest away. Colors in the rings show the distribution of each crop in each ring over the entire life of the model.

The results for region one suggest that a mix of crops can satisfy all of the restrictions presented in table 5-2 at the lowest possible cost. In this scenario, switchgrass, a low-cost, minimally erosive and high-yielding perennial is planted in the acres closest to the collection point. Corn, a lower yielding crop with higher potential for erosion, is planted in the outer ring in order to capitalize on the credits from corn grain, which significantly offset total production cost. Planting lower yielding crops along the outer-ring minimizes the number of delivery trucks needed to travel to the outer rings and back.

Although sweet sorghum yields more per acre than switchgrass, an acre's worth costs less to transport per mile due to this model's assumptions about sweet sorghum yield and transportation (outlined in chapter 2). Sweet sorghum is not baled like the other crops. It is transported in-bulk by truck. Moreover, in region one, sweet sorghum yields the lowest of all three regions. With the yield and transportation cost assumptions for region one, switchgrass costs more per acre to haul and is therefore planted closer to the collection point.

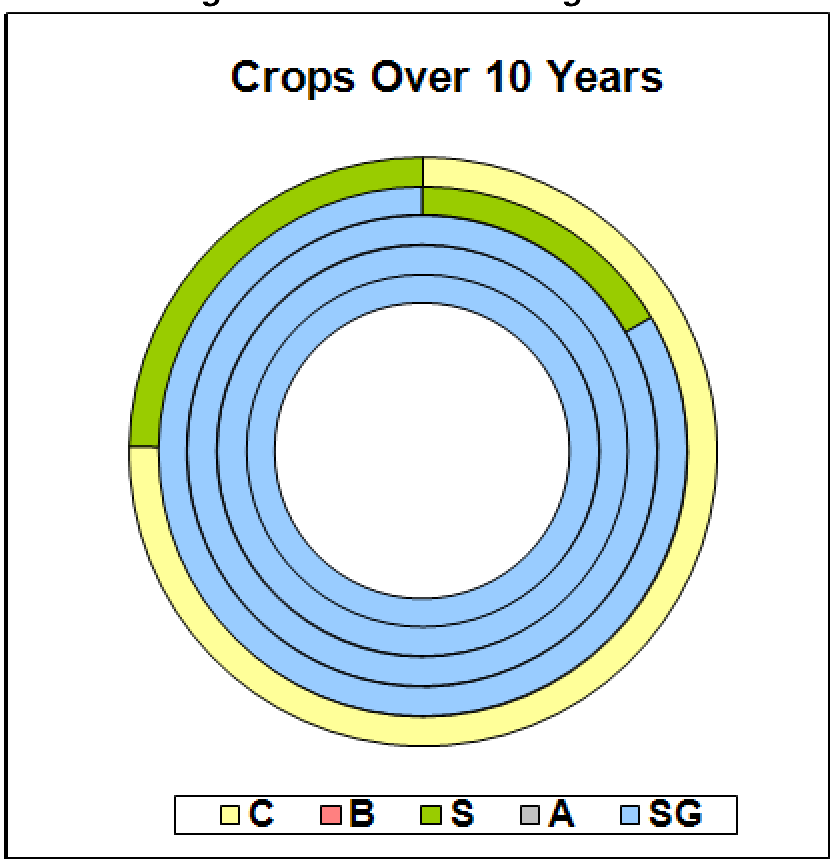
Region 2: Northeastern Iowa

Region two considers Allamakee County, which has yield potentials slightly lower than Central Iowa for all crops except sweet sorghum and higher potential for soil erosion from all crops. Input and output prices are the same as were used in region one. User-determined restrictions were calculated in the same way as they were for region one, but with assumptions about crop yields, agronomic practices and soil erosion tailored to Northeastern Iowa. These restrictions, calibrated moderately in the same way as before, are shown in table 5-3. Model output is shown below in figure 5-2.

Table 5-3: Restrictions in region 2

Biomass (million tons) >=	141
Lignin (million tons) >=	30
HHV (MMBtus) >=	2.3×10^9
Ash (million tons) <=	11
Soil erosion (million tons) <=	39

Figure 5-2: Results for Region 2



Region two shows the same mix of crops (corn stover, switchgrass and sweet sorghum) but in different proportions. Compared to region one, more sweet sorghum and less switchgrass is planted. This is primarily driven by the yield differences assumed for this region.

In region two, a lower corn stover yield is assumed. Therefore, corn stover contributes less biomass, lignin and higher heating value. To satisfy the restrictions for these parameters, more high-yielding sweet sorghum must be planted. However, because the revenue from corn grain sales offers a significant cost off-set, corn stover stays on the fields. The rest of the landscape is planted to switchgrass to lower the overall cropping plan's erosion profile to below the restriction and provide relatively low-cost biomass.

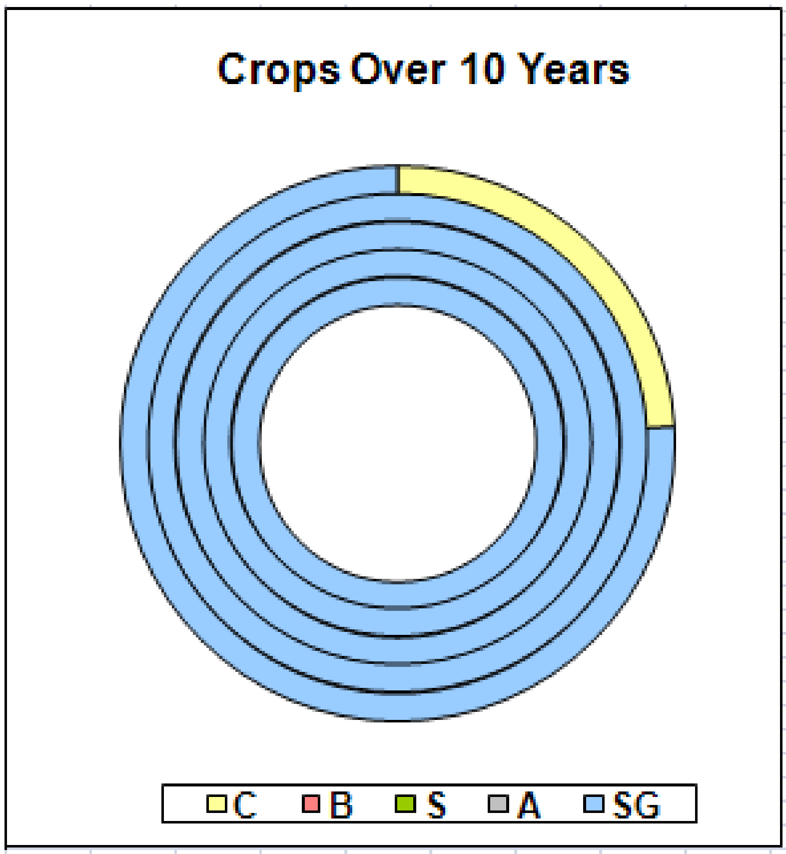
Region 3: Southern Iowa

Region three considers Lucas County, in Southern Iowa. Prices are set at the same level as the previous scenarios, but restrictions were re-calibrated to reflect what is possible in this region using the same minimum and maximum approach that was applied before. Again, these user-determined restrictions on biomass, lignin, HHV, ash, and soil erosion represent the mid-point between minimum and maximum quantities for Southern Iowa given the five crops modeled and the assumptions employed. These restrictions are shown in table 5-4. Model output is shown in figure 5-3.

Table 5-4: Restrictions in region 3

Biomass (million tons)	141
Lignin (million tons)	30
HHV (MMBtus)	2.23 X 10^9
Ash (million tons)	11
Erosion (million tons)	37

Figure 5-3: Results for region 3



Region three's cropping plan is markedly different than region one and region two's. Here, the landscape is planted almost entirely with switchgrass. Only a small part of the outermost ring is planted with corn. Because switchgrass stands are assumed to last for the life of the model, these corn acres in the outer ring must be assumed to be grown as continuous corn on the same acres. The reason for this reveals the model's sensitivity to yield and transportation costs.

Transportation costs per hour of operation in this model are assumed to be the same ($70), regardless of truck type. Sweet sorghum is assumed to be transported in a weight-limited bulk container truck, while switchgrass is carried in a bale-limited flatbed truck. In region three, sweet sorghum following an annual crop yields 6.6 tons per acre. A sweet sorghum truck can carry 36 tons, so the yield from one acre planted with sweet sorghum in region three requires 0.183 truck beds. For comparison, one acre planted with sweet sorghum after an annual in region one yields 6.44 tons, and thusly requires 0.179 truck beds; in region two it would require 0.180 truck beds. Switchgrass yields are assumed to be the same in each region, and switchgrass is assumed to be transported via flatbed truck capable of carrying 42 bales. In the establishment year, switchgrass yields 3 tons per acre. For the rest of the stand's life (9 years), switchgrass yields 5 tons per acre. An acre of switchgrass yielding 3 tons per acre at a bulk density of 12 pounds per cubic foot (192 kg/m^3) results in 5 bales yielded per acre. Similarly, 5 tons of switchgrass per acre with the same density results in 8 bales. Over the 10 year life of the model, the weighted average bale yield is thusly 7.7, which would require 0.183 flatbed trucks – precisely the same fraction of truck space required to move one acre's worth of sweet sorghum after an annual in region three.

As a result of this surprising coincidence, the cost of transporting switchgrass and sweet sorghum are equalized in region three. Switchgrass's lower cost of production and erosion profile, coupled with the added expense of drying sweet sorghum make switchgrass a preferable biomass crop in this region. Consequently, model output for region three shows the minimal amount of switchgrass necessary to meet the region's biomass goals, while the remaining acres are planted to corn stover in order to collect the corn grain off-set. Corn stover, however, is planted in the ring farthest from the center, as was the case in regions one and two, because of its per-acre transportation cost is the lowest.

Interactions and Tradeoffs

To consider how different goals for the landscape interact, each of the five user-determined restrictions (biomass yield, lignin yield, higher heating value yield, ash yield, and soil erosion) for region one were looked at more closely. Minimum, medium, and maximum levels for these restrictions were calculated using alternative models with special objective functions, as described on page 45, and employed for the three model runs described above. These values for region one are presented in table 5-5.

Table 5-5: User determined restrictions in region one

	Minimum value	Medium value	Maximum value
Biomass yield (million tons)	42	144	246
Lignin yield (million tons)	7	31	54
Higher Heating Value yield (MMBTUS)	0.6×10^9	2.3×10^9	3.9×10^9
Ash yield (million tons)	2	11	21
Total soil erosion (million tons)	0.8	29	59

Region one's model was then run with its cost-minimizing objective function, but was restricted to meet every possible pair-wise combination of the values presented in table 5-5. That is, for example, the model calculated the cost of providing a medium level of biomass (144 million tons), while also achieving a maximum level of lignin (54 million tons), or, perhaps, a medium level of biomass with a minimal level of soil erosion (0.8

million tons). In all, 90 such pair-wise runs were made for region one in an effort to look at how these different user-determined restrictions might affect or interact with model output.

Because this model includes three parameters that one might seek to maximize (biomass, lignin, and HHV) the following analysis proceeds by considering how demanding maximum and medium levels of these parameters influences options for optimization and the resulting cropping plan. Because demanding minimum biomass, lignin, or HHV is an unlikely application of this model, minimum demands are not considered as starting points for this analysis. However, minimum values of soil erosion and ash content are considered as options when possible.

Biomass Optimized Landscapes

If one expects a maximum yield of biomass from the landscape, this type of analysis shows what potential is left to optimize for lignin content, higher heating value, soil erosion and ash content. The results of this particular run are shown in figure 5-4 and discussed below.

Figure 5-4: Options for a Maximum Biomass Landscape

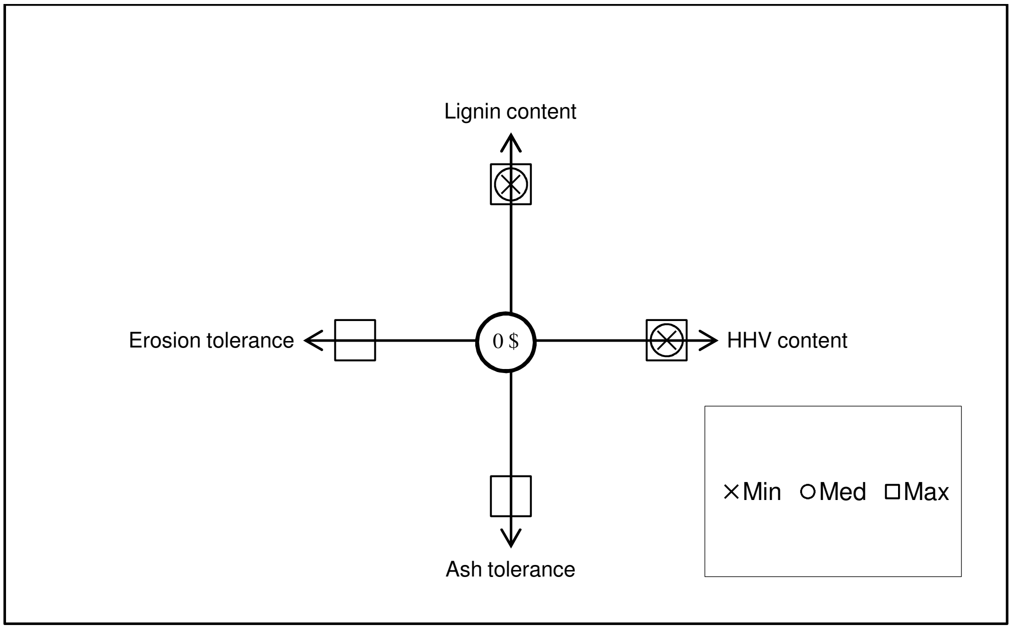
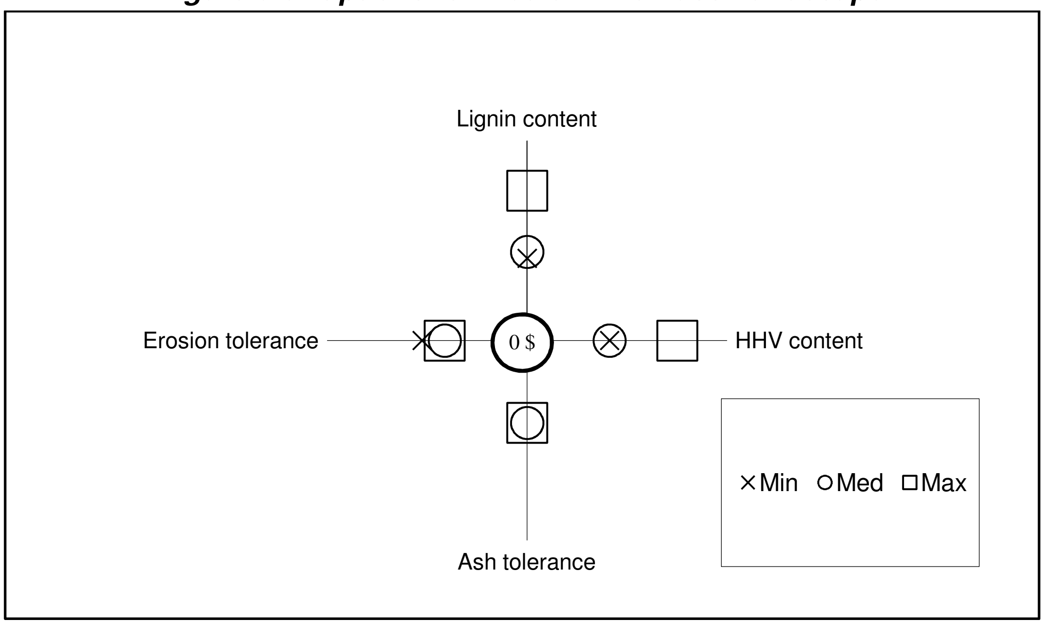


Figure 5-4 is a "radar chart." It shows that once maximum biomass is required from the landscape, only a few options are open relative to the other four parameters (lignin content, higher heating value, ash content, and soil erosion). Each of these four parameters is represented on an axis. The symbols represent the minimum, medium, and maximum levels for the parameter on their axis. On the erosion tolerance axis, only one symbol is shown, the symbol for maximum. This indicates that when maximum biomass is demanded from the landscape, maximum possible soil erosion must be accepted. Moving counter-clockwise, the same situation is true for ash tolerance: with maximum biomass necessarily comes maximum ash content.

Lignin and higher heating value show different relationships to biomass. Beginning with lignin content, all three symbols are present on this axis. This is because the model shows that with maximum possible biomass yield, minimum, medium, and maximum lignin requirements are met. Notably, minimum (denoted by an "X"), medium (denoted by a circle), and maximum (denoted by a square) in figure 5-4 are all located at the same point for both lignin content and higher heating value. This indicates that there is only one way to achieve maximum possible biomass form the landscape (in this case, to plant all the acres entirely with sweet sorghum), and in doing so, all of the possible requirements for lignin and higher heating value are also met. Figure 5-5 shows how these relationships change when expectations for biomass yield are scaled back to the middle point.

Figure 5-5: Options for Medium Biomass Landscape



Beginning with erosion tolerance, figure 5-5 shows that scaling biomass yield expectations back opens up new options for managing the landscape with respect to soil erosion. All three symbols are now shown on the erosion axis. Symbols are located at specific distances from the chart's origin, which is labeled "0 $." Distance from the origin represents the overall cost of growing the biomass and delivering it to the processor. For these radar charts, costs were normalized on a zero to one scale, meaning that the least expensive cropping system equals "0," and the most expensive equals "1." These normalized radar graphs allow for consideration of both the options available for landscape planning, and also the cost of these options relative to one another.

The radar chart in figure 5-5 then shows that a medium-level biomass yield can be achieved in two different ways with respect to soil erosion. The most expensive option comes with minimal tolerance for soil erosion, which is shown farthest away from the origin. To the right, the middle and maximum points are shown overlapping, indicating that the same cropping plan meets both criteria with minimal cost. These medium biomass cropping plans with respect to soil erosion are shown in figure 5-6.

Figure 5-6: Erosion options for a medium biomass landscape

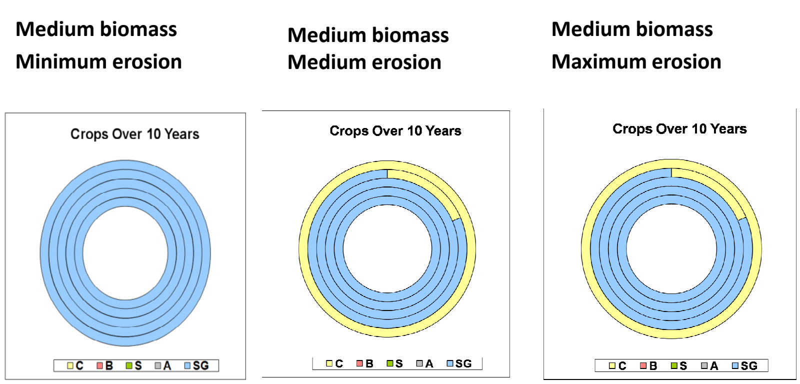
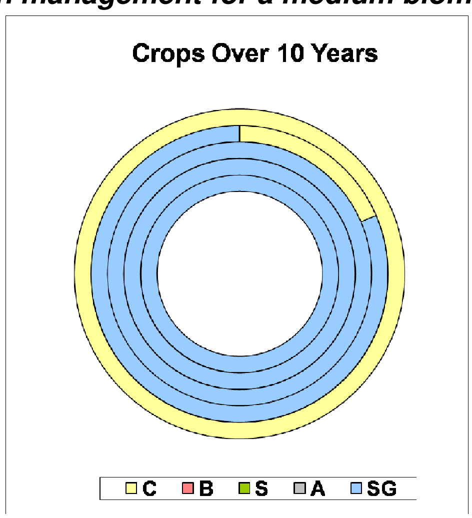


Figure 5-6 shows two different ways to achieve the same level of biomass yield at minimum cost in region one. On the left hand side, the landscape is planted entirely with switchgrass, which meets the minimum possible soil erosion tolerance. The center and right doughnuts show the same cropping plan meeting both the medium and maximum erosion requirements. In this plan, more corn is included as more erosion is tolerated across the landscape. However, in the third doughnut the amount of corn planted is limited by the biomass restriction placed on the landscape.

The ash tolerance axis in figure 5-5 shows a slightly different relationship to biomass yield. The ash tolerance axis does not show a symbol for minimal ash tolerance, and shows the symbols for both medium and maximum ash tolerance overlapping. This indicates that: (1) there is no way to achieve a medium level of biomass without exceeding the minimal ash tolerance; and (2) the same cropping plan meets both medium and maximum ash criteria at minimal cost. . This cropping systems are shown in figure 5-7.

Figure 5-7: Ash management for a medium biomass landscape

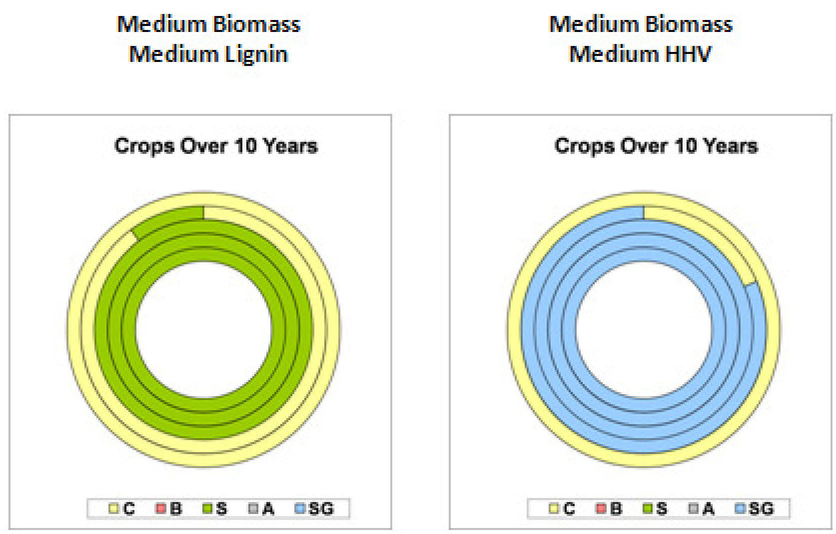


The doughnut chart above shows how a middle level of ash can be achieved along with a middle level of biomass. This cropping plan also falls under the maximum ash threshold at minimum cost. In this plan, switchgrass is planted in the center rings owing to its higher per-acre transportation cost, while corn stover is planted in the outer rings. Notably, this is the same cropping plan that met both the medium and maximum threshold criteria for soil erosion.

The radar chart in figure 5-5 also suggests something unique about biomass and its relationship to lignin and higher heating value. All three symbols (X, circle, and square) are found on both the lignin and higher heating value axes. The maximum symbols are located farthest from the origin, while the middle and minimum symbols for both lignin and HHV share the same points closer to the origin. This indicates that there are two ways to achieve – at least – a medium level of biomass from the landscape with regard to lignin and higher heating value. One way maximizes all of the parameters at a relatively high cost, and another way ensures a moderate level of biomass at lower cost but achieves lower levels of lignin and higher heating value. As more research is done into plant biochemistry and the processing of biorenewable fuels, this type of analysis could allow planners to tailor cropping plans to processors' requirements better.

For both lignin and higher heating value, maximum possible quantities can only be achieved with maximum total landscape yield, which in this region is achieved by planting only sweet sorghum. Demanding middle level biomass yield along with middle level lignin, or middle level higher heating value, results in two different cropping systems, as shown in figure 5-8.

Figure 5-8: Comparison of Lignin-based and HHV-based cropping systems



Depending on which is more important, lignin or higher heating value, the landscape plan changes significantly. The doughnut on the left shows a landscape required only to deliver middle-level biomass yields and middle level lignin yields at the lowest possible cost. On the left, the landscape is planted entirely with sweet sorghum and corn stover. Just enough high-yielding sweet sorghum is grown to meet biomass and lignin goals, while the remainder is dedicated to low-yielding corn stover for its grain off-set. On the right, sweet sorghum is replaced with switchgrass closer to the facility, with corn stover again grown in the outer rings. The reason for this difference is explored in figure 5-9.

Figure 5-9: Relative yields of lignin and HHV per acre

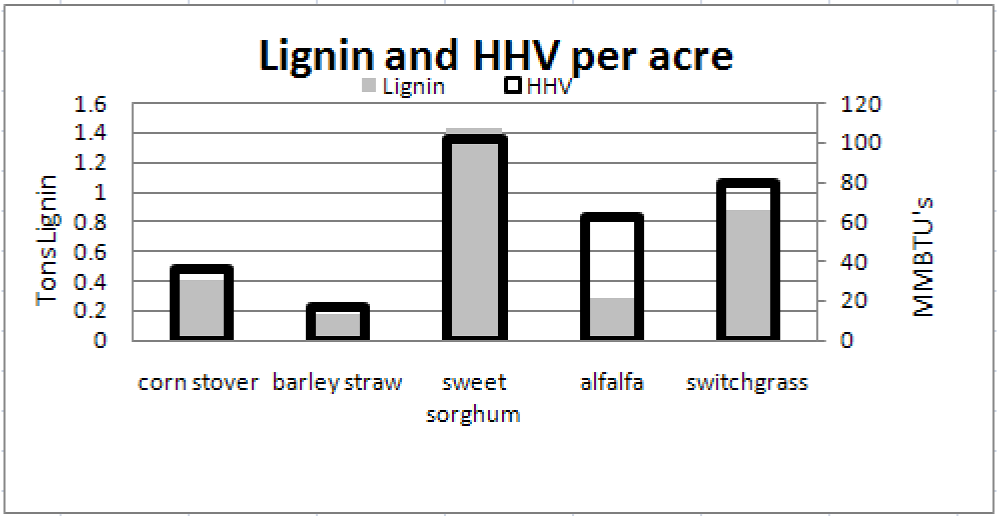
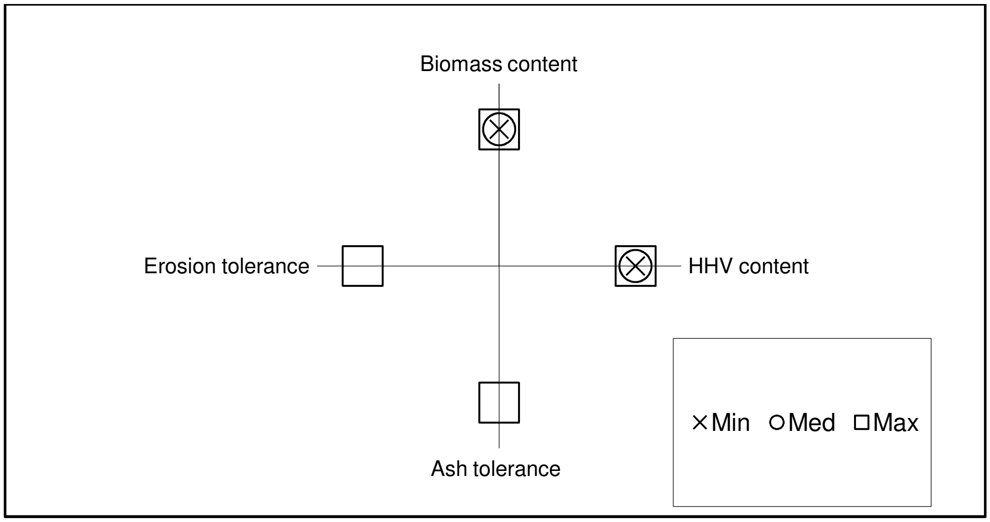


Figure 5-9 shows the yield per acre of lignin and higher heating value from each of the five crops in region one. It is worth noting that sweet sorghum, switchgrass and corn stover relate to each other differently in terms of lignin and higher heating value. Grey columns in figure 5-9 represent lignin yield per acre. Black boxes represent HHV yield per acre. Note that sweet sorghum differs from corn stover and switchgrass in the relative heights of the two data points. Sweet sorghum does not yield proportionally equal amounts of both lignin and HHV. Both corn stover and switchgrass yield proportionally more HHV than lignin. Switchgrass is the opposite. As a result, when lignin is a priority, sweet sorghum is more attractive. When HHV is a priority, switchgrass offers comparable yields to switchgrass but at a lower cost. Notably, both plans include corn grain in the outer rings as a cost off-set.

Lignin-Optimized Landscapes

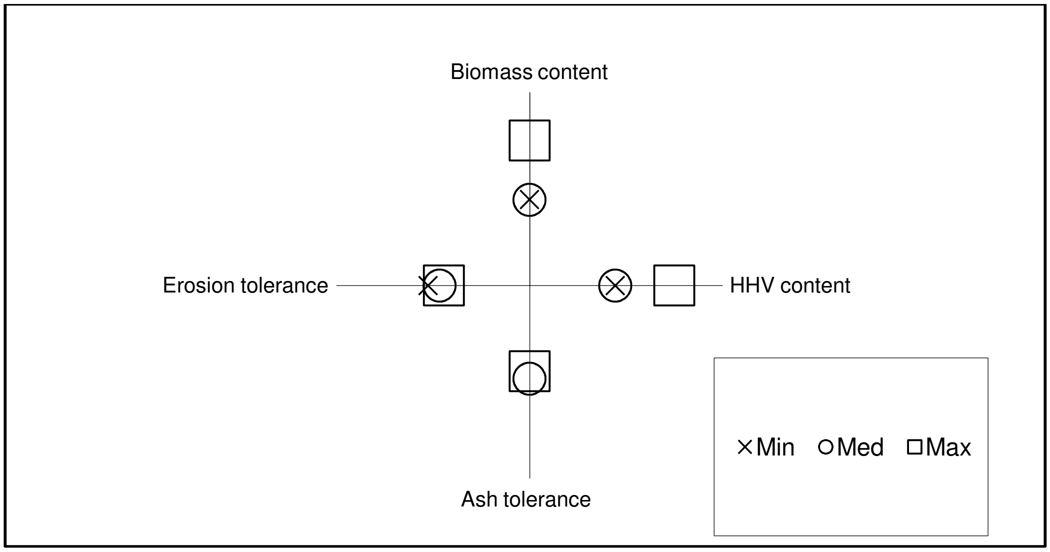
The radar chart in figure 5-10 shows the options available for maximum lignin landscapes.

Figure 5-10: Options for a Maximum Lignin Landscape



When demanding maximum lignin from the landscape, options for optimizing other parameters are limited similarly to a maximum biomass landscape. Only by planting sweet sorghum exclusively can the maximum lignin requirement be met. This cropping plan compels the highest possible erosion and ash content tolerances. It also achieves every level of lignin and higher heating value content. Figure 5-11 shows how new options become available when expectations of lignin yield from the landscape are scaled back to the middle level.

Figure 5-11: Options for a Medium Lignin Landscape



Options available for a medium lignin landscape mirror almost exactly what is available for medium-level biomass landscapes. With biomass and higher heating value, two distinct options are available: a maximum yield option that meets all of the requirements at a relatively high cost, and a lower cost option that meets the middle requirements.

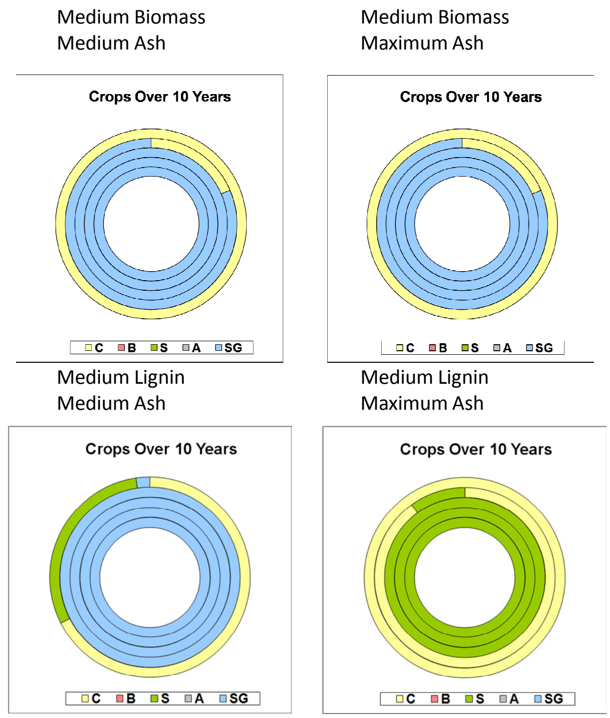
There are, however, differences in regard to erosion tolerance and ash tolerance. Starting with erosion, a middle level of lignin can again be achieved in three different ways: one way for each of the three soil erosion tolerances. As was the case with middle-level biomass landscapes, lower tolerances for soil erosion result in higher cost. It is interesting to note that the grouping of the three options shown with regard to soil erosion shown in figures 5-5 and 5-12 is similar, but not identical. A side-by-side comparison of cropping plans is shown in figure 5-12.

Figure 5-12: Soil erosion options in medium biomass and medium lignin landscapes

Comparing the top set of doughnut charts with the bottom reveals why, in this model, lignin content is an expensive biomass component to optimize. With a minimal erosion tolerance, both biomass and lignin goals can be met by a landscape planted entirely to switchgrass. With a middle-level tolerance for soil erosion, the cropping plans differ. A middle level of lignin requires more high-yielding sweet sorghum than a middle level of biomass, again due to sweet sorghum's high proportional lignin content. . As more sweet sorghum is planted in this landscape, it incurs significant production and drying costs, and comes at the expense of corn, which reduces the corn grain off-set. The same situation holds true with a maximum tolerance for soil erosion: more sweet sorghum is planted to meet the lignin requirements at the expense of switchgrass and corn stover.

Options for a middle-level lignin landscape in regards to ash management tell a different story. Figure 5-13 compares the medium and maximum ash tolerance landscapes for medium and maximum biomass and lignin goals.

Figure 5-13: Ash content options for medium biomass and lignin landscapes



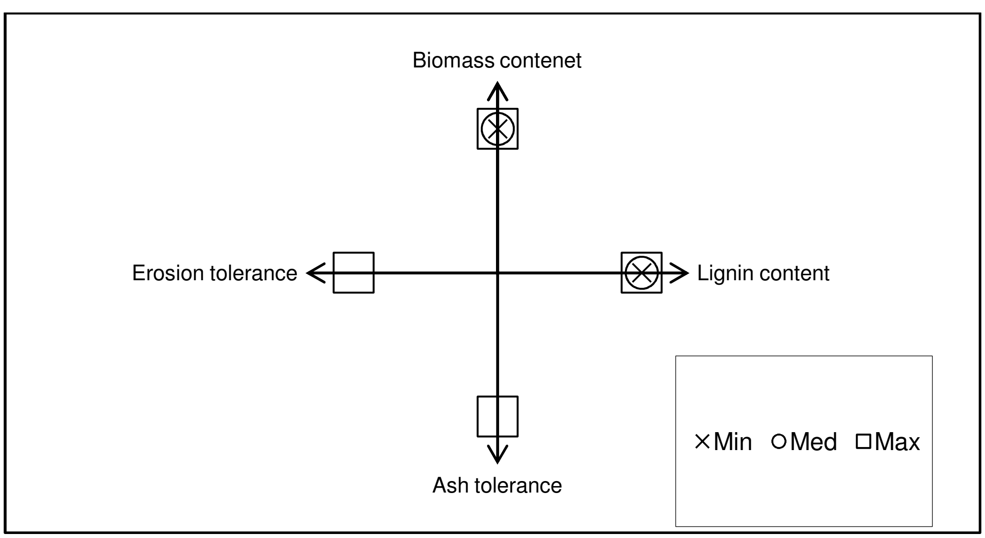
The figure above indicates that a middle-level lignin, middle-level ash content landscape is more expensive than a middle-level biomass, middle-level ash content landscape due to the inclusion of more sweet sorghum in the lignin-optimized landscape. The same is true for both landscapes with maximum ash tolerance. Again, sweet sorghum's lignin advantage pushes the model to plant more of it and less switchgrass when faced with a lignin constraint.

Figure 5-13 also suggests that switchgrass plays a more prominent role in lignin-optimized, ash-limited landscapes than in biomass-optimized, ash-limited ones. This is due to another characteristic of corn stover in this model, its relatively high ash content. Corn stover has the highest percentage of ash of any of the five crops. However, because of its low yield, it results in only about one-half the ash yield per acre of sweet sorghum. Switchgrass, on the other hand, has a much lower ash content, and higher yield of both lignin and biomass per acre. As a result, switchgrass can deliver 62% of the per-acre lignin yield sweet sorghum can with 53% of the ash. Corn stover, however, yields only 29% of the lignin sweet sorghum does, along with 44% of the ash on a per-acre basis. With middle-level lignin goals and ash tolerances, switchgrass confers significant advantages from a biochemical perspective that merit its inclusion in the cropping plan. However, corn stover still finds its way on to the landscape because of the cost reductions offered by the corn grain off-set.

High Higher Heating Value-Optimized Landscapes

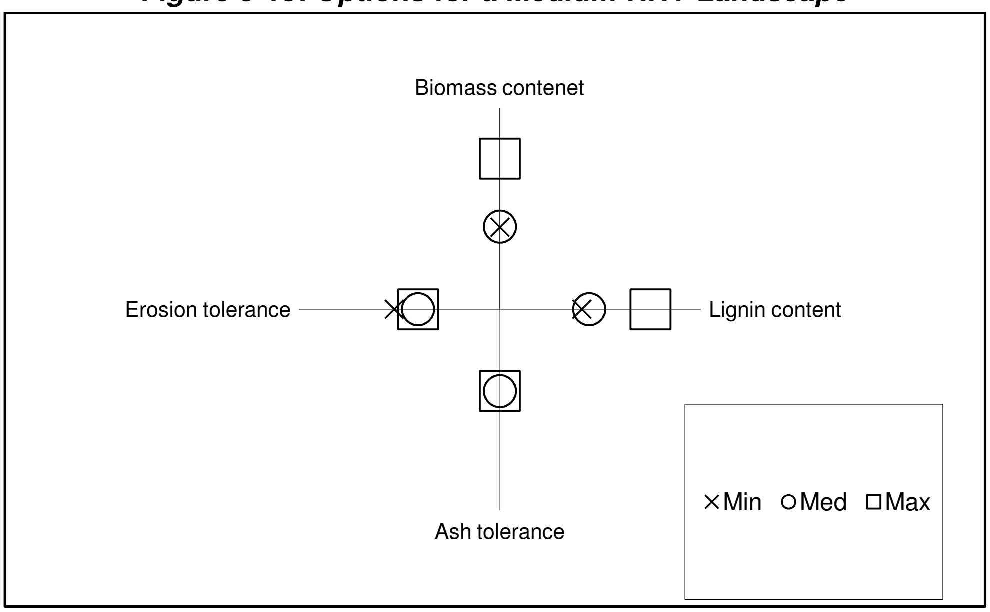
Figure 5-14 shows the options available for a maximum higher heating value landscape.

Figure 5-14: Options for a Maximum HHV Landscape



Similar to biomass and lignin, there is only one way to achieve maximum higher heating value yield from the landscape, and that is to plant only sweet sorghum. Figure 5-14 shows that when maximum higher heating value is demanded, maximum tolerances for soil erosion and ash content are compelled. Similarly, all of the possible biomass and lignin goals are met with this cropping plan. Figure 5-15 shows which options become available when expectations for higher heating value yield are scaled back to the middle level.

Figure 5-15: Options for a Medium-HHV Landscape



The radar chart in figure 5-15 very closely reflects what was seen in the medium lignin and medium biomass landscapes. Three options are available for soil erosion management, and two for ash tolerance and biomass yield. Resulting cropping plans in each of these scenarios are similar to the cropping plans shown above for the medium-level lignin landscape, except the lignin-optimized landscapes included more sweet sorghum than corn due to corn stover's relative lignin deficiency noted above. Figure 5-16 compares the soil erosion management options for biomass-optimized, lignin-optimized and HHV-optimized landscapes.

Figure 5-16: Soil erosion management options for medium biomass, lignin and HHV landscapes

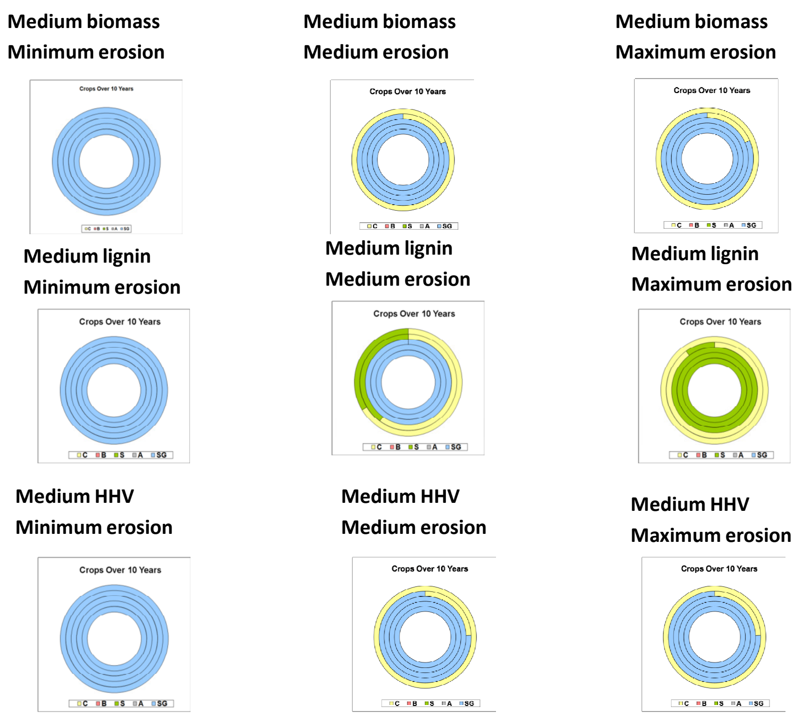


Figure 5-16 again exhibits the influence of sweet sorghum's proportional lignin yield relative to switchgrass. Middle-level biomass and HHV goals can be managed with respect to soil erosion with exactly the same cropping plans. Lignin-optimized landscapes, however, require more sweet sorghum, which results in a higher cost of production.

Figure 5-17 considers ash content management options in a similar fashion.

Figure 5-17: Ash content management options for medium biomass, lignin and HHV landscapes

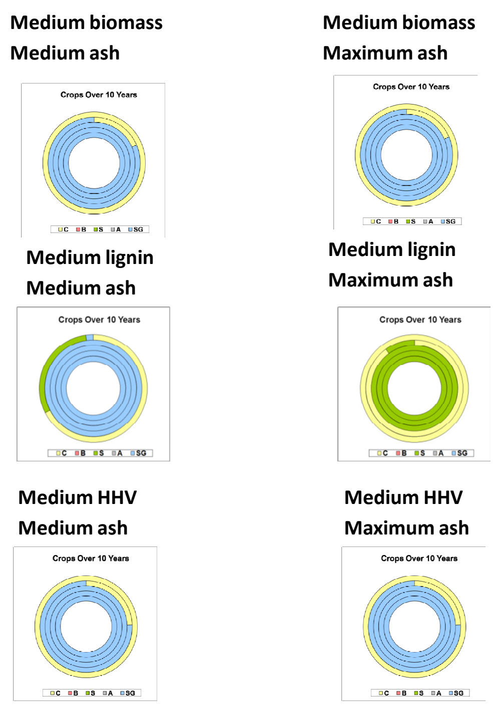


Figure 5-17 again shows that when managing for ash content, middle-level biomass and HHV demands can be met with the same cropping plans. However, when optimizing for lignin, the medium-level cropping plans include more sweet sorghum.

Because the biomass and HHV cropping plans are identical, the differences observed earlier concerning the prominence of switchgrass in lignin-optimized, ash-limited landscapes still apply: switchgrass contains more lignin than corn stover and delivers it with less ash. As a result, when ash is limiting, the model suggests planting more switchgrass to the landscape.

Chapter 6: Conclusions and suggestions for further work

This model was designed to determine if a well-selected mix of crops might be employed to preserve natural capital while also meeting a bio-oil processor's needs at minimal cost. Although five crops were input, the model consistently selected only three for optimal crop mixes. The conclusions below consider each crop in turn, looking at why or why not crops were included and what functions these crops performed. The restrictions imposed on the model are also considered for their affect on the optimal crop mix and overall cost. Finally, differences and similarities between regions are considered in an effort to glean general insights into designing optimal crop mixes for bio-oil production.

Crop Selection

Switchgrass, corn stover, and sweet sorghum appeared most commonly in the scenarios analyzed. Barley straw and alfalfa failed to appear. Switchgrass was always gorwn in the rings closests to the facility, while corn stover and sweet sorghum, when planted, were always located in the outer rings. Each of these three crops appear to bring something unique to optimized landscape planning.

Corn stover appears prominently due to the cost off-set from selling corn grain. Barley straw also had the potential for a grain sales off-set, but its low yield of both grain and straw made it an inferior option to corn. This model did not consider any scenarios where barley straw outperformed corn stover. As modeled, on a per-acre basis, corn stover does not yield quantities of biomass, lignin, or higher heating value comparable to sweet sorghum, switchgrass or alfalfa. However, when modeled with today's prices, the corn grain off-set alone merited its inclusion in most of the optimized feedstock landscapes. In many cases, model output suggested coupling corn stover with switchgrass and/or sweet sorghum in proportions that seeded only as much of the higher-yielding crop as was necessary to meet yield goals. Without other restrictions, the rest of the landscape was planted to corn, suggesting that coupling dual-use crops like corn with dedicated energy crops is one likely way to produce low-cost, high-yield feedstock landscapes.

Switchgrass proved to be preferable to alfalfa in today's price environment. Switchgrass yields more per acre and costs less to produce than alfalfa. As modeled, alfalfa gave yield boosts to any annual crop that followed it and also reduced the need for nitrogen fertilizer of crops that followed it. However, when modeled at today's prices, that benefit failed to outweigh switchgrass's yield and cost of production advantages.

Sweet sorghum offered considerable yield advantages over all the other crops, but came with considerable extra cost, owing mostly to drying operations. However, when a high priority was placed on yields (especially lignin yields) sweet sorghum make up a large part of the optimized landscape plan.

Optimal Crop Mixes and Regional Variation

In each of the three regions, the crop with the highest per-acre transportation cost was planted closest to the collection point. Notably, per-acre transportation cost was influenced most by yield, not by bulk density. As yield for the crops changed from region to region, their transportation costs relative to one another also changed. This resulted in planting switchgrass closer to the collection point than sweet sorghum in regions one and two. However, in region three, when transportation costs for sweet sorghum and switchgrass were equal, sweet sorghum offered little advantage over switchgrass and therefore was not included in the optimized landscape plan.

Of the three maximizing parameters (biomass, lignin and HHV), lignin proved to be the most expensive one to optimize. This was because sweet sorghum is relatively lignin-rich and corn stover is relatively lignin deficient. Landscapes that couple dedicated energy crops and corn stover, with only enough of the dedicated energy crop to meet lignin goals receive less lignin benefit per acre of corn stover, thusly compelling more sweet sorghum and raising costs.

Suggestions for further work

This model assumed a homogeneity of soil types and yield potentials within each region, which is not likely to be the case on a real farm. Varying individual acre's or groups of acres' yield and cost assumptions within a region in the same way they were varied across regions would give a more detailed and accurate picture at the farm level.

This model included only five crops, for the reasons given in chapter two. Further work might consider more perennials or woody crops, which would bring a new set of strengths and weaknesses to the landscape model, allowing, perhaps, for even better performing landscapes with greater diversity.

Machinery use was not explicitly optimized in this model. As more exotic crops are considered, the availability of specialized machinery could be restricted, allowing a group of growers in a region, or perhaps a farm cooperative, to design a landscape that most efficiently employs scarce capital equipment like specialized harvesters.

Finally, following the proof of concept established in this project, all of the assumptions input into the model about agronomic practices, crop yields, rotation yield effects and transportation costs could be refined to elicit even more useful results for optimized landscape planning.

Literature Cited

Chapter 1: Motivations and Introductions

[1] Smil, Vaclav. General Energetics: Energy in the Biosphere and Civilization. New York: John Wiley & Sons Inc., 1991.

[2] U.S. Energy Information Administration, www.eia.doe.gov

[3] McNeill, J.R.. Something New Under the Sun: An Environmental History of the Twentieth-Century World. New York: W.W. Norton and Company Inc., 2000.

[4] "*Population Newsletter*" No. 83, June 2007. The United Nations Department of Economic and Social Affairs – Population Division (www.unpopulation.org).

[5] U.S. Energy Information Administration.

[6] Costanza, R, Graumlich, L., Steffen, W., Crumley, C., Dearing, J., Hibbard, K., Leemans, R., Redman, C. and Schimel, D.; "Sustainability or Collapse: What can We Learn from Integrating the History of Humans and the Rest of Nature". Ambio 36.7 (2007): 522-527.

[7] Hall, C. Tharakan, P., Hallock, J., Cleveland, C., and Jefferson, M. "Hydrocarbons and the evolution of human culture." Nature 426 (2003): 318-322.

[8] McNeil, pg. 215

[9] Ibid

[10] Brown L., Young J., State of the World 1990: A Worldwatch Institute Report on Progress Towards a Sustainable Society. New York: W.W. Norton, 1990.

[11] Rasumussen, W. "The Mechanization of Agriculture." Scientific American 247.3 (1982): 77-89.

Chapter 2: Crops and the Landscape

[12] Shahbazi, A. and Li, Y., "Assessment of Crop Residues for Bioethanol Production in North Carolina" Proceedings of the American Society of Agricultural Engineers Annual International Meeting, 2005 , St. Joseph, MO., *Paper No. 056044.*

[13] Duffy, M., Smith, D., "Estimated Costs of Crop Production in Iowa – 2008," Ag Decision Maker, Iowa State University Extension File A1-20

[14] Hansen, W., "Production of Small Grains in Iowa," Iowa State University Extension, File PM-1080

[15] Johson, D., Janzen, E., "Barley Production Costs: A Cross-Border Comparison", Agricultural Experiment Station, North Dakota State University. Agricultural Economics Report No. 425, 1999.

[16] Papastylianou, I., "Effect of rotation system and N fertilizer on barley and vetch grown in various crop combinations and cycle lengths," Journal of Agricultural Science 142 (2004): 42-48.

[17] Hallam, A., Anderson, I., Buxton, D., "Comparative economic analysis of perennial, annual and intercrops for biomass production," Biomass and Bioenergy 21 (2001): 407-424.

[18] Chen, Y., "Potential of Ag Residues and Hay for Bioethanol Production," Applied Biochemistry and Biotechnology 142 (2007): 276-290.

[19] Bennett, A., Anex, R., "Farm-Gate Production Costs of Sweet Sorghum as a Bioethanol Feedstock," Transactions of the ASABE 51.2 (2008): 603-613.

[20] Prior, J., Landforms of Iowa. Iowa City: University of Iowa Press. 1991.

[21] Duffy, M. "Estimated costs for production, storage and transportation of switchgrass," Iowa State University Extension File A1-22.

Chapter 3: Technologies: Waterloo Process Fast Pyrolysis and Linear Programming

[22] Brown, R. Biorenewable Resources: Engineering New Products from Agriculture. Wiley-Blackwell: Ames, Iowa. 2003.

[23] Finney, C. and Garret D., "The flash pyrolysis of solid wastes," Energy Sources 1.3 (1974) 295-314.

[24] Ibid.

[25] Rowell, R., Schultz, T. and Narayan, R. (eds.). Emerging Technology for Materials and Chemicals from Biomass, Washington, DC: American Chemical Society. 1992.

[26] Chen, G. and Leung D., "Experimental investigation of biomass waste (rice, straw, cotton stalk and pine sawdust) pyrolysis characteristics," Energy Sources 25:4 (2003): 331-337.

[27] Rowell, Schultz and Narayan, eds.

[28] Demirbas, A. "Producing bio-oil from olive cake by fast pyrolysis," Energy Sources 30.1 (2008): 38-44.

[29] Yergin, D. The Prize: The Epic Quest for Oil, Money and Power. New York: Touchstone. 1992.

[30] McNeil, p. 305

[31] Piskorz J., Majerski, P., Radlein, D., Scott, D., and Bridgewater, A., "Fast pyrolysis of sweet sorghum and sweet sorghum bagasse," Journal of Analytical and Applied. Pyrolysis 46 (1998): 15-29.

[32] Wisconsin Biorefining Development Initiative (www.wisbiorefine.org)

[33] Scott D., Piskorz J. "The continuous flash pyrolysis of biomass," Canadian Journal of Chemical Engineering 62 (1984) 404-412.

[34] Finney and Garrett

[35] Scott and Piskorz

[36] Maschio, G., "Pyrolysis, a promising route for biomass utilization," Bioresource 42 (1992): 219-231.

[37] Raveendran, K. "Influence of mineral matter on biomass pyrolysis characteristics," Fuel 74.12 (1995): 1812-1822.

[38] Ghetti, P. "Thermal analysis of biomass pyrolysis products," Fuel 75.5 (1996): 565-573.

[39] Piskorz and Majerski

[40] Sensoz, S. "Pyrolysis of pine chips: 2. Structural analysis of bio-oil," Energy Sources 24 (2002): 357-364.

[41] Yorgun, S. "Fixed-bed pyrolysis of miscanthus x giganteus: Product yields and bio-oil characterization," Energy Sources 25 (2003): 779-790.

[42] Sharma, R., and Bakshi, N. "Catalytic upgrading of pyrolysis oil," Energy & Fuels 7 (1993): 306-314.

[43] Brown

[44] Raveendran

[45] U.S. Department of Energy Biomass Feedstock Composition and Property Database (www1.eere.energy.gov/biomass/feedstock_database.html).

[46] "Biomass Resource Assessment and Utilization Options for Three Counties in Eastern Oregon," Prepared for the Oregon Department of Energy. McNeil Technologies, Inc. 2003.

[47] Chen, Y., "Potential of agricultural residues and hay for bioethanol production," Applied Biochemistry and Biotechnology 142 (2007): 142-276.

[48] "PHYLLIS: The Composition of Biomass and Waste". Energy Research Center of the Netherlands (www.ecn.nl/phyllis)

[49] Ibid.

[50] Janick, J., and Simon, J.E., eds. Advances in New Crops. Portland: Timber Press, 1990.

[51] Vanderbei, R., Linear Programming: Foundations and Extensions. Norwell, MA: Kluwer Academic Publishers, 1996.

[52] Bazaraa, M., Jarvis, J. and Sherali, H. Linear Programming and Network Flows. New York: John Wiley and Sons, Inc., 1990.

[53] Dorfman, R., Samuelson, P., Solow, R., Linear Programming and Economic Analysis. New York: McGraw-Hill, 1958.

[54] Hildreth, C., Reiter, S. "On the choice of a crop rotation plan," in Activity Analysis of Production and Allocation, New York: John Wiley and Sons, Inc., 1951.

[55] Candler, W., Heady, E., Linear Programming Methods, Ames, Iowa: Iowa State College Press., 1958.

[56] Beneke, R. and Winterboer, R., Linear Programming Applications to Agriculture, Ames, Iowa: Iowa State University Press, 1973.

[57] El-Nazer, T. and McCarl, B., "The choice of crop rotation: a modeling approach and case study," American Journal of Agricultural Economics, 68.1 (1986): 127-136.

[58] Detlefsen, N., and Jensen, A., "Modeling optimal crop sequences using network flows," Agricultural Systems, 94.2 (2007): 566-572.

Acknowledgments

The author wishes to acknowledge the guidance, supervision and review offered by Professor Michael Duffy, who served as major advisor for this thesis work. Debts of gratitude are also owed to Professor Robert Ruben for his counsel and suggestions on model building and notation, and Professor Robert Brown for thoughtful introductions to the world of biorenewable fuels.

This work was financially supported by the ConocoPhillips company, and the author wishes to thank Cyndi Tucker, Maxine Jones and Lisa Meyers at ConocoPhillips for their involvement and encouragement.

Thanks are also due to support from family and friends, including Dave and Pam Correll, and the students, faculty and the staff of ISU's graduate programs in Sustainable Agriculture and Biorenewable Resources and Technology.

Finally, collaboration over the years with Maccarone Diaber Declements on all questions, big and small, has proven invaluable, and with this work finally behind him, the author looks forward to Mr. Declements' graduation with almost as much as excitement as he does his own.

Appendix one: Samples from Candidate Crop Database

Sample 1: Switchgrass

Common Switchgrass

Scientific *Panicum virgatum*

Crop ID No. 2 **Complete** ☑

Herbaceous	☑	**Leguminous**	☐
Woody	☐	**Perennial**	☐
Oil Seed	☐	**Agricultural residue**	☐

Image

% Mass

Cellulose	30.97%	Arabinan	2.75%
Hemicellulose	24.39%	Xylan	20.42%
Lignin	17.56%	Mannan	0.29%
		Galactan	0.92%
		Glucan	30.97%

C	47.27%
H	5.31%
N	0.51%
O	41.59%
S	0.10%

Fixed Carbon	21.57%
Ash	5.76%
Volatile Matter	73.75%
BTU/lb	
HHV	7998

wt% Ash

SiO2	66.53%
Al2O3	6.98%
TiO2	0.34%
Fe2O	3.56%
CaO	7.14%
MgO	3.17%
Na2O	1.03%
K20	7.00%
P2O5	2.80%
SO3	2.00%
Cl	
Co2	

Notes

A perennial, warm-season herbaceous crop. Establishment can take 2-3 years. Switchgrass is native to the prairie and can be harvested with conventional hay equipment.

Cell Walls source DOE/EERE Database

Cell Wall sugars source DOE/EERE Database

Ultimate Analysis source DOE/EERE Database

Proximate Analysis source DOE/EERE Database

Image source WikiMedia Commons - USDA/Robert H. Mohlenbrock

HHV source: DOE/EERE Database

Bulk Density source

Moisture Content source Oregon Dept. of Energy Report, Dec 2003

Ash Analysis source:

Thursday, November 27, 2008 Page 3 of 3

Sample 2: Barley Straw

Common Barley Straw

Scientific *Hordeum spp.*

Crop ID No. 18 **Complete** ☑

Herbaceous ☑ **Leguminous** ☐

Woody ☐ **Perennial** ☐

Oil Seed ☐ **Agricultural residue** ☑

Image

% Mass

Cellulose	42.40%	Arabinan	4.00%	C	46.80%	Fixed Carbon	13.29%
Hemicellulose	22.70%	Xylan	15.00%	H	5.53%	Ash	4.30%
Lignin	16.40%	Mannan	1.30%	N	0.41%	Volatile Matter	82.41%
		Galactan	1.70%	O	41.90%	**BTU/lb**	
		Glucan	37.50%	S	0.05%	HHV	7929

wt% Ash

SiO_2	50.60%
Al_2O_3	1.90%
TiO_2	0.20%
Fe_2O	0.80%
CaO	2.40%
MgO	3.20%
Na_2O	1.60%
K_2O	14.50%
P_2O_5	0.00%
SO_3	3.00%
Cl	
Co_2	

Notes

Barley is one of the two major small grain crops grown in Iowa. The plant will typically grow to a height of 26 inches. Grain can be sold, while the remaining straw can be used as hay or biomass.

Cell Walls source Oregon Dept. of Energy Report, Dec. 2003
Cell Wall Sugars source Oregon Dept. of Energy Report, Dec. 2003
Ultimate Analysis source PHYLLIS
Proximate Analysis source Perlkh, 2007 Fuel 86/12: p.1710-1719
Image source UGA Forestry Images - USDA

HHV source: Oregon Dept. of Energy Report, Dec. 2003
Bulk Density source
Moisture Content source Oregon Dept. of Energy Report, Dec. 2003
Ash Analysis source: Alltalo (ed.), 1st World Conf. on Biomass..V.2. Pg.2061

Thursday, November 27, 2008 Page 5 of 20

Sample 3: Cotton stalks

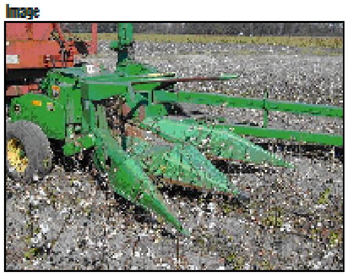
Common Cotton stalks

Scientific *Gossypium Sp.*

Crop ID No. 30 **Complete** ☑

Herbaceous	☑	**Leguminous**	☐
Woody	☐	**Perennial**	☐
Oil Seed	☐	**Agricultural residue**	☑

Image



% Mass

Cellulose	58.48%	Arabinan	1.30%	C	43.64%	Fixed Carbon	22.43%
Hemicellulose	14.38%	Xylan	8.30%	H	5.81%	Ash	6.68%
Lignin	21.45%	Mannan	0.00%	N	0.00%	Volatile Matter	70.89%
		Galactan	1.10%	O	43.87%	**BTU/lb**	
		Glucan	31.10%	S		HHV	7852.6

wt % Ash

SiO2	33.00%
Al2O3	
TiO2	
Fe2O	2.80%
CaO	3.56%
MgO	6.05%
Na2O	1.37%
K20	21.40%
P2O5	6.40%
SO3	6.50%
Cl	
Co2	

Notes

Cotton stalks are typically destroyed after the cotton has been picked from them harvested from the field. However, stalks can be harvested with a silage harvester and then balled.

Cell Walls source Jimenez, 2007, Bioresource Tech. 98/18: p.3487-3490

Cell Wall sugars source Silverstein, 2004, Ph.D Thesis, NCSU

Ultimate Analysis source Biomass Energy Foundation: www.woodgas.com

Proximate Analysis source Biomass Energy Foundation: www.woodgas.com

Image source www.cals.ncsu.edu/..../reports/cottonstalk1.jpg

HHV source: Biomass Energy Foundation: www.woodgas.com

Bulk Density source

Moisture Content source

Ash Analysis source: Jarungthammachote S. -abstract on file

Thursday, November 27, 2008 Page 8 of 20

Sample 4: Industrial Hemp

Common Hemp

Scientific *Cannabis sativa L*

Crop ID No. 8 **Complete** ☑

Herbaceous ☑ **Leguminous** ☐

Woody ☐ **Perennial** ☐

Oil Seed ☐ **Agricultural residue** ☐

Image

% Mass

Cellulose	71.41%	Arabinan	0.50%	C	44.30%	Fixed Carbon	16.72%
Hemicellulose	15.52%	Xylan	1.10%	H	5.34%	Ash	4.06%
Lignin	6.59%	Mannan	5.40%	N	0.85%	Volatile Matter	79.22%
		Galactan	1.90%	O	42.90%	**BTU/lb**	
		Glucan	70.20%	S	0.20%	HHV	8029

wt% Ash

SiO2	22.69%
Al2O3	11.80%
TiO2	1.13%
Fe2O	5.76%
CaO	11.10%
MgO	3.86%
Na2O	1.93%
K20	30.70%
P2O5	1.23%
SO3	0.76%
Cl	4.23%
Co2	5.15%

Notes

Industrial hemp is grown worldwide for fiber and food. It is a restricted crop in the United States.

Cell Walls source Gumuskaya, 2007, Bioresource Tech. 98:p.491-497

Cell Wall sugars source Kelley, 2004, Biomass & Bioenergy 27:p.77-88

Ultimate Analysis source PHYLLIS

Proximate Analysis source

Image source WikiMedia Commons

HHV source: PHYLLIS

Bulk Density source

Moisture Content source

Ash Analysis source: Analysis of Hawaii Biomass Energy Resources, Dec. 2002

Thursday, November 27, 2008 Page 9 of 20

Sample 5: Miscanthus

Common	Miscanthus	Herbaceous	☑	Leguminous	☐
Scientific	*Miscanthus*	Woody	☐	Perennial	☐
Crop ID No.	7 Complete ☑	Oil Seed	☐	Agricultural residue	☐

Image

% Mass

Cellulose	38.20%	Arabinan	1.80%	C	49.85%	Fixed Carbon	19.30%
Hemicellulose	24.30%	Xylan	19.00%	H	4.69%	Ash	1.90%
Lignin	25.00%	Mannan	0.00%	N	0.41%	Volatile Matter	78.80%
		Galactan	0.40%	O	44.95%	BTU/lb	
		Glucan	39.50%	S	0.10%	HHV	7737

wt % Ash

SiO2	61.84%
Al2O3	0.98%
TiO2	0.05%
Fe2O	1.35%
CaO	9.61%
MgO	2.46%
Na2O	0.33%
K20	11.60%
P2O5	4.20%
SO3	2.63%
Cl	
Co2	

Notes

Miscanthus is a popular candidate for biofuels because of its tall and rapid growth and low mineral content.

Cell Walls source	de Vrije, 2002, Int. J. of Hydrogen Economy 27:p.1381-1390
Cell Wall Sugars source	de Vrije, 2002, Int. J. of Hydrogen Economy 27:p.1381-1390
Ultimate Analysis source	Chen, 2004, Energy Sources, 26:p.485-498
Proximate Analysis source	Chen, 2004, Energy Sources, 26:p.485-498
Image source	WikiMedia Commons - Pat Schmitz
HHV source:	Bassam, 1998, Energy Plant Species p. 30
Bulk Density source	Skurlock, "Bioenergy Feedstock Charachteristics" ORNL Facts
Moisture Content source	Yourgun, 2003, Energy Sources 25:p.779-790
Ash Analysis source:	Bain, 2003. "Biopower Technical Assessment" NREL/TP-510-3

Thursday, November 27, 2008

Page 12 of 20