PRODUCTION ECONOMICS OF POTENTIAL

PERENNIAL AND ANNUAL BIOMASS FEEDSTOCKS

By

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PREFACE

This dissertation is composed of three papers that have been produced by research projects designed to determine economically efficient crop production systems. The first project was designed to determine if polycultures of diverse species could produce feedstock more economically than a monoculuture. The second project was designed to determine whether a winter canola - winter wheat crop rotation could compete economically with continuous winter wheat in the traditional winter wheat belt region of Oklahoma. The third project was designed to determine and compare the cost to deliver a year round flow of biomass to a biorefinery for both a system that uses forage sorghum exclusively and a system that uses switchgrass exclusively. This preface includes a summary of each of the projects.

Chapter I

The U.S. Energy Independence and Security Act of 2007 (EISA) mandates that 136 billion liters (36 billion gallons) per year of biofuels be produced in the United States by 2022, with 79 billion liters (21 billion gallons) coming from feedstocks other than corn grain. Fulfilling this aggressive goal may require the use of lignocellulosic feedstocks such as forest biomass, urban waste, and biomass from dedicated energy crops such as switchgrass. The U.S. Department of Energy envisioned the development of energy crops as a way to convert marginal land to a more productive use and at the same time reduce the cost of government commodity and conservation programs that are funded to entice land owners to set aside land from the production of traditional crops.

To produce the volume of biomass required to fulfill EISA mandates large quantities of land would be necessary. Land could either be seeded to a single perennial grass (monoculture) such as switchgrass or alternatively to a mixture of grasses and forbs. Side-by-side field trials managed to represent production on a large scale are necessary to test the economics, performance, and persistence of diverse mixtures relative to the performance of a monoculture such as switchgrass on a scale required to fulfill EISA mandates.

Scientists at Oklahoma State University with the assistance of personnel and the contribution of land and other resources provided by the U. S. Department of Agriculture Agricultural Research Service, Southern Plains Range Research Station, near Woodward, Oklahoma conducted a multiyear study at two locations. The research objective was to determine the lowest cost lignocellulosic biomass feedstock production system for marginal lands in western Oklahoma from among three monocultures and four polycultures at two locations that included diverse mixtures of grasses and forbs.

The study found that biomass yields of diverse mixtures were no different than yields of monocultures. Even though no herbicides were applied and the plots were not weeded, the proportion of weeds declined from the first year to the third year harvest in every treatment at both locations. Forbs did not persist in the study plots. A dominate grass species emerged by the third harvest for every treatment that included a mix of species. Monoculture treatments resulted in lower production costs because they produced at least as much, and in some cases more, biomass and had lower seed costs.

Samuel D. Fuhlendorf and Robert Gillen who designed and conducted the field research, expressed that disease and pest pressure may be reduced in diverse landscapes and society may value a variable landscape and other attributes resulting from polycultures more than those of monocultures. However, if the objective is to produce massive quantities of biomass for biorefinery feedstock under the constraint that land area is limited, for the conditions that prevailed at these locations during the time of the study, internal economics favored monocultures of productive species.

Chapter II

Crop rotation is rare on rain fed cropland in western Oklahoma. On average from 2000 to 2010 about 75% of the land planted to annual crops in the state was seeded to winter wheat. Difficult to control winter annual grasses that have been used to produce forage, especially Italian ryegrass and feral rye, have invaded Oklahoma fields traditionally used to produce continuous winter wheat. The value of a wheat crop is likely to decrease when winter annual weeds are present because they compete directly with winter wheat resulting in lower grain yields and decreasing wheat quality due to foreign material in the grain.

To mitigate the problem, it has been recommended that producers use a crop rotation. Crop rotation has been a successful weed management strategy in winter wheat in other parts of the world. Oklahoma State University researchers have suggested rotating a winter crop with winter wheat because summer crops are economically risky propositions for western Oklahoma due to typically hot dry weather. This study was conducted to determine whether a winter canola - winter wheat crop rotation could compete economically with continuous winter wheat.

Oklahoma State University researchers, Joshua A. Bushong and Thomas F. Peeper, with assistance from personnel and the contribution of land resources from the Oklahoma Agricultural Experiment Station conducted a three year study at four locations (Lahoma, Lake Carl Blackwell, Perkins, and Chickasha). The research objective was to determine and compare crop yields in a continuous winter wheat system to yields in a winter canola-winter wheat system and to determine whether the rotation is economically competitive with continuous monoculture wheat for the region in fields infested with feral rye and Italian ryegrass.

The study found wheat yields following canola are greater than wheat yields experienced in continuous winter wheat and expected net returns are also greater for canola-wheat rotations than for continuous wheat. Glyphosate treatments were strong performers from among the treatments studied due to the relative cost of the glyphosate system and its ability to control a large variety of plant species, but glyphosate treatments were not necessarily found to outperform other herbicide treatments evaluated in the study.

Chapter III

Research and development of lignocellulosic feedstocks for biofuel production have been motivated by the U.S. Energy Independence and Security Act of 2007 (EISA). Switchgrass and forage sorghum have been identified as potential dedicated energy crops for biofuel production. The use of dedicated energy crops such as switchgrass and forage sorghum will require large quantities of land to meet EISA mandates. It is widely accepted that the ethanol industry will be dominated by large capacity biorefineries that are regionally dominant. Due to this regional dominance, large quantities of land near the biorefinery will be necessary to produce an adequate amount of biomass to supply the conversion facility.

Marketing infrastructure for biomass production would be required. Land owners would not enter into biomass feedstock production until a market is available nor would rational investors invest in a biorefinery with no certain feedstock supply. Therefore, the cost to produce, harvest, transport and deliver a feedstock to a biorefinery is integral information to the development of the infrastructure and providing necessary information to decide which feedstock conversion process is most appropriate. This research was designed to determine and compare the cost to deliver a year round flow of biomass to a biorefinery for both a system that uses forage sorghum exclusively and a system that uses switchgrass exclusively.

Scientist at Oklahoma State University with help from Mohua Haque at the Samuel Roberts Noble Foundation designed a mathematical programming model to determine the cost to deliver a steady flow of biomass to a biorefinery using either switchgrass or forage sorghum as the feedstock. The model is designed to determine the optimal location of a biorefinery that requires a flow of 3,630 Mg of biomass per day from among eleven locations, the area and quantity of feedstock harvested in each county by land category, the number of mowing units and baling units necessary for harvest and the cost to produce, harvest, store and transport a continuous flow of biomass to a biorefinery.

The estimated cost to deliver a year round flow of switchgrass to a biorefinery is \$60 Mg^{-1} while the estimated cost for forage sorghum is \$74 Mg^{-1}. The difference in cost is largely due to the extended harvest window for switchgrass relative to forage sorghum as well as switchgrass having more harvestable days in a harvest month. As a result of the extended harvest window and more harvest days, the switchgrass system requires fewer harvest machines and less investment in windrowers, tractors, rakes, balers, and stackers.

CHAPTER I

A COMPARISON OF PERENNIAL POLYCULTURES AND MONOCULTURES FOR PRODUCING BIOMASS FOR BIOREFINERY FEEDSTOCKS[*]

Abstract

Prior to planting millions of ha to switchgrass (*Panicum virgatum* L.) monocultures for producing biomass feedstock for biorefineries, it has been proposed that monocultures be tested against polycultures so, among other issues, the economics of both systems can be compared. This research was conducted to determine the lowest cost lignocellulosic biomass feedstock production system from among four monocultures and four polycultures. Randomized complete block designs with four replications were established at two Oklahoma locations. Plots were managed to represent anticipated production activities if perennial species were established in a low input system and harvested once a year to produce biorefinery feedstock. The four monocultures included switchgrass, sand bluestem (*Andropogon hallii* Hack.), Old World bluestem (OWB) (*Bothriochloa ischaemum* L. Keng), and big bluestem (*Andropogon gerardii* Vitman). The four polycultures included mixtures of four grasses, four grasses and four forbs, eight grasses and eight forbs, and OWB with alfalfa (*Medicago sativa* L.). Plots were harvested

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once a year for three years. For every treatment that included a mix of species, a dominant species emerged by the third harvest, suggesting that over time these treatments may not differ greatly from monocultures with minor representation of other species. The average yield was 4.6 Mg $ha^{-1}yr^{-1}$ for treatments seeded as monocultures at one location compared with 4.0 Mg $ha^{-1}yr^{-1}$ for the treatments seeded as polycultures. At the second location, monocultures averaged 7.9 Mg $ha^{-1}yr^{-1}$ and polycultures 6.5 Mg $ha^{-1}yr^{-1}$. Economics favored monocultures for the location and environmental conditions that occurred during the time period studied.

Introduction

The Energy Independence and Security Act of 2007 (EISA) mandates that 136 billion L yr^{-1} of biofuels be produced in the U.S. by 2022, with 79 billion L yr^{-1} coming from feedstocks other than corn grain (Congress, 2007). Fulfilling this mandate may require the use of several lignocellulosic feedstocks such as forest biomass, urban waste, and biomass from dedicated energy crops.

Development of energy crops was envisioned by the U.S. Department of Energy as a way to convert "idle" marginal land to productive use and at the same time reduce the cost of government commodity and conservation programs that are funded to entice land owners to set aside land from the production of traditional crops. McLaughlin et al. (1999, p. 293) notes that "…the rationale for developing lignocellulosic crops for energy is that …poorer quality land can be used for these crops, thereby avoiding competition with food production on better quality land…." In 2005, Perlack et al. (2005) concluded that 22 million ha of U.S. cropland, idle cropland, and cropland pasture could be seeded to dedicated energy crops and used to produce biomass feedstock for biorefineries.

Switchgrass (*Panicum virgatum* L.) has been identified as a model dedicated energy crop species (Wright 2007). Field trials have been conducted to determine optimal biomass production systems for monocultures of switchgrass (McLaughlin and Kszos, 2005; Parrish and Fike, 2005; Sanderson et al., 2006; Mooney et al., 2009; Haque et al., 2009;). Most dedicated energy crop development research has followed the traditional agronomic paradigm of field trial monocultures. Assessing the economic performance of different species or mixture of species would be necessary to determine the most economically viable and sustainable feedstock production system.

Side-by-side comparisons of biomass yield from monocultures and polycultures are scarce. Johnson et al. (2010) conducted a meta analysis of yield data for cultivated crop and native grasses included in the USDA NRCS web soil survey database. They considered 1,238 sites in Nebraska, Kansas, and Oklahoma and concluded that biomass yield of managed stands of switchgrass monocultures would consistently exceed those of native diverse plant communities. Adler et al. (2009) assessed the potential of CRP and other grasslands to produce biomass and found that as the number of plant species decreased biomass production increased.

Tilman et al. (2001; 2006a; 2006b) conducted a controlled experiment in Minnesota that included plots with one, two, four, eight, and 16 species. In the year prior to seeding, they herbicided and burned, removed 6-8 cm of soil to reduce the seed bank, plowed, and tilled. Plots were seeded in May of the following year and seeded a second time in May of the next year. Species composition was maintained by hand weeding three or four times per year and by the use of selective herbicides in the first three years after seeding. Plots were burned annually in the spring prior to growth. Plots that included 16-species produced more aboveground biomass than monocultures. Tilman et al. (2001, 2006a, 2006b) concluded that the best monoculture did not achieve greater productivity than polycultures and argue that a diverse mixture of plant species would result in a "…more reliable, efficient, and sustainable supply…" of biorefinery feedstock production than could be forthcoming from monocultures (Tilman et al., 2006a, p. 629). Russelle et al. (2007) argued that the activities used by Tilman et al. (2001; 2006a; 2006b) to maintain the polycultures, specifically hand-weeding, would not be feasible in a commercial biomass production system.

The economics of seeding a diverse mixture of perennial species relative to a monoculture for the production of biomass feedstock have not been fully tested and may differ across agronomic conditions. Nyfeler et al. (2009) conclude that the value of diversity may saturate at a low number of species under fertile soil conditions. Species rich plant communities rarely perform well under intense management practices. High frequency of defoliation (mowing) and biomass removal may decrease diversity (Kirchner, 1977; Gough et al., 2000; Weigelt et al., 2009). A realistic test of the economics, performance, and persistence of polycultures relative to the performance of monocultures on a scale required to fulfill EISA mandates would require side by side field trials managed as closely as possible to represent production on a large scale.

The objective of this research is to determine the lowest cost lignocellulosic biomass feedstock production system for western Oklahoma from among seven alternatives at each of two locations. Both sites included treatments of three monocultures and four polycultures. Soil characteristics differed across sites, and species were selected based on recommendations for plantings from Natural Resources Conservation Service experts. Monocultures of switchgrass and Old World bluestem (OWB) (*Bothriochloa ischaemum* L. Keng) were planted at both sites, as was a legume-grass mixture of alfalfa (*Medicago sativa* L.) and OWB. Monocultures of big bluestem (*Andropogon gerardii* Vitman) were planted at one site with sand bluestem (*Andropogon hallii* Hack.) at the second site. Each site included a treatment of (a) four grasses, (b) four grasses and four forbs, and (c) eight grasses and eight forbs. This research differs from previous studies in that the plots were larger and managed to represent production activities expected to be used if perennial species were established on millions of ha and harvested once a year to provide biomass to a biorefinery.

Materials and Methods

Agronomic

The experiments were conducted at the Southern Plains Range Research Station (SPRRS) in northwest Oklahoma (36°25′ N, 99°24′ W). Two fairly different SPRRS sites were selected for the study. SPRRS is operated by USDA-Agricultural Research Service. The Woodward site is a Carey silt loam (fine-silty, mixed, superactive, thermic Typic Argiustoll) and is classified as a Loamy Prairie ecological site. The Fort Supply site is a Grandmore fine sandy loam (fine-loamy, mixed, active, thermic, Typic Haplustalf) and is classified as a Sandy Loam Prairie ecological site.

The experiments were designed as a randomized complete block with four replications. Plot dimensions at the Woodward site were 16 m by 30 m while the dimensions of the plots at the Fort Supply site were 14.6 m by 30 m. The names of the species included in the trial are reported in Table I-1. Plots at both sites had been in crop production for at least the past 50 years and in continuous winter wheat (*Triticum aestivum* L.) for at least 20 years.

The Woodward experiment was initiated in March of 2002 when glyphosate was applied at a rate of 1.12 kg a.i. ha^{-1} to kill existing vegetation. No additional herbicides were used in subsequent years. The plots were not tilled. The Woodward plots were seeded using no-till methods in March of 2002 with a Truax no-till grass drill. Seven planting treatments at Woodward included: (1) monoculture of big bluestem, (2) monoculture of switchgrass, (3) monoculture of OWB, (4) mix of OWB and alfalfa (inoculated alfalfa was seeded in February 2003), (5) mix of four native grasses, (6) mix of four native grasses and four native forbs, and (7) mix of eight native grasses and eight native forbs. Seeding rates for each species and treatment at Woodward are reported in Table I-2.

The experiment at the Fort Supply site was initiated in March of 2004 when glyphosate was applied at a rate of 1.12 kg a.i. ha^{-1} to kill existing vegetation. No additional herbicides were used for the duration of the study. The plots were not tilled. The Truax no-till grass drill was used to seed the plots in March of 2004. Species and seeding rates for each treatment are reported in I-3. The seven Fort Supply treatments were: (1) monoculture of sand bluestem, (2) monoculture of switchgrass, (3) monoculture of OWB, (4) mix of OWB and alfalfa (inoculated alfalfa was seeded in February of 2005), (5) mix of four native grasses, (6) mix of four native grasses and four native forbs, and (7) mix of eight native grasses and eight native forbs.

Yield data were collected at Woodward in 2004, 2005, and 2006 and at Fort Supply in 2005, 2006, and 2007. Monthly precipitation and average monthly temperatures at SPRRS for each of the four years are reported in Table I-4. Herbaceous production was estimated by clipping 10 quadrats (0.3 m x 0.6 m) in each treatment plot in late July of each year. The use of the clipping method allowed each planted species to be collected separately. Thus, yield data for each treatment could be determined for each planted species and for the harvested material that grew on the plots that was not from planted species (weeds). This enabled monitoring of species persistence over time. Recorded biomass yield was from current year production. The Woodward plots were burned in 2004 and 2005 and mowed in 2006 in late winter well before spring greenup to remove standing biomass. The quantity of biomass removed by mowing and burning was not measured. In 2005 the OWB-alfalfa plots at Fort Supply were burned in February prior to alfalfa seeding, however, the other plots at Fort Supply were not mowed or burned prior to greenup in 2005 and none were burned or mowed prior to greenup in 2006. All Fort Supply plots were burned in 2007 in late winter well before spring greenup.

Data were analyzed separately for each location using the SAS Proc Mixed procedure (Lee et al., 2008; SAS, 2008) with treatment and site as fixed effects and year and replication as random effects. Means were compared using the SAS least square means with Tukey adjustment at $P \leq 0.05$ to test comparisons across means.

The Shannon-Wiener index (H) and the Simpson's index of diversity (1-D) were used to compare plant species diversity across treatments (Sanderson et al., 2004). The Shannon-Wiener index, which is described in Pielou (1975), is scaled from zero to approximately 4.6. Values near zero represent little diversity while values near 4.6 indicate substantial diversity. Simpson's (1-D) index of diversity ranges from zero to one where zero represents no diversity and one represents infinite diversity. The Simpson index is described in Magurran (2004).

Species that were included in the study were uniquely identified. However, species that were not included in the study were either classified as other grasses or as other forbs and considered to be weeds. For the purpose of calculating the indices, each of these weed categories was considered to be a single species. The indices were calculated based on the weight of plant material harvested. To further illustrate change in proportion of plant material in the polycultures over time, charts of the proportion of both the dominant species and weeds were prepared.

Economics

Enterprise budgeting was used to compute production costs for each treatment at each site. Budgets were constructed for both establishment (Table I-5) and annual maintenance and harvest (I-6). Average custom operation rates were used to calculate the cost of in-field production operations (Doye and Sahs, 2010). Establishment costs for each of the seven treatments included the application of glyphosate to kill existing vegetation on the plots, seed costs, cost of the no-till grass drill operation, and land rental for the establishment year. It was assumed that the establishment program began with leasing the land and applying glyphosate in March of the establishment year.

Seed costs differed across treatment (Table I-2, Table I-3). Seed cost for the switchgrass treatment was \$31 ha^{-1} at Woodward and \$47 ha^{-1} at Fort Supply. Seed cost for the eight grasses-eight forbs was \$161 ha^{-1} at Woodward and \$196 ha^{-1} at Fort Supply. In an attempt to represent a true low input system, no fertilizer or herbicide other than the glyphosate used in the establishment year was applied. Average custom rates were used to compute harvest costs (Table I-6) that include mowing, raking, baling, and staging (Doye and Sahs, 2010). A staging charge of

$6.61 Mg^{-1} is assessed to account for the cost to collect and load bales to a wagon or truck from the spots on the field where they have been dumped by the baler. The staging charge also accounts for the cost to transport, offload, and stack the bales at a storage location on or near the farm at a distance of no more than 10 km from the field. This enables calculation of a farm gate cost. Mowing and raking costs are assumed to be constant per ha while baling and staging costs vary with biomass yield. An expected stand life of 10 years was used for each treatment (Haque et al., 2009; Mooney et al., 2009). The estimated establishment costs were amortized over the expected life of the stand at a rate of 7%.

Results

Agronomic

Woodward Site

Since the two sites were established in different years the results were analyzed and are presented separately. Based on findings reported by Fuentes and Taliaferro (2002), when not harvested during the establishment year, it is assumed that in the region of the study, switchgrass and other perennial grass species achieve full yield potential in the year after seeding. Thus, total biomass yields were collected beginning with the year after seeding. At the Woodward site yield data were collected in 2004, 2005, and 2006

Figure I-1 includes a chart of the yield by year for each treatment at Woodward. The low yields for 2006 are consistent with the relatively lower rainfall as reported in Table I-4. Aggregate average annual biomass yield across the three years are reported in Table I-7. In general, the mean yields of the plots seeded as polycultures were less than the mean yields of the plots seeded as monocultures. At Woodward, the OWB-alfalfa mixture (which by the third harvest was 98.5% OWB), switchgrass, and OWB monocultures yielded more ($P \leq 0.05$) annual biomass than the mixture of four grasses.

Table I-8 presents the proportions of dry matter for the individual species by year for the Woodward site. It was assumed that a commercial enterprise would harvest all biomass. To determine the persistence of planted species, the harvested biomass was separated into that produced by planted species and that produced by other species. Material from grasses and forbs that were not planted is classified as weeds.

At Woodward, in the OWB with alfalfa treatment, alfalfa decreased from 7.9% of the total dry matter harvested in 2004 to 0.8% in 2006, while the percentage of OWB increased from 73.4% in 2004 to 98.5 % in 2006 (Table I-8). The proportion of weeds (other grasses plus other forbs) decreased from 18.7% to 0.8%.

The four grasses treatment was seeded to a mixture of the native species that would have been dominant on the site without cultivation, big bluestem, little bluestem, sideoats grama, and blue grama. In the first harvest year, 29.8% of the harvested material was from weeds (other grasses, other forbs). By the third harvest year, the proportion of weeds had declined to 10.7% of the harvested dry matter. Each of the four seeded grasses persisted. Yield proportions of little bluestem (7.5% to 29.6%), sideoats grama (40.2% to 44.2%), and blue grama (5.6% to 8.8%) increased from 2004 to 2006 while big bluestem (17.0% to 6.6%) decreased. Figure II-3 includes charts of the dominant species over time and the proportion of weeds over time in each of the four treatments seeded as polycultures at Woodward. By the 2006 harvest, 99% of the material harvested from the OWB-alfalfa seeded plots was from OWB. For the other three polycultures, sideoats grama emerged as the dominant species.

The proportion of weeds in the Woodward four grasses (big bluestem, little bluestem, sideoats grama, blue grama) and four forbs (Illinois bundleflower, Maximilian sunflower, western ragweed, purple prairie clover) plots declined from 17.6% to 4.6% from the first to the third harvest year. The proportion of harvested material from grasses increased from 40.0% to 84.4% and the proportion of harvested forbs decreased from 42.3% to 11.0%.

Consistent with the findings from the four grasses-four forbs treatments, the eight grasses-eight forbs treatment became less diverse over time. For the third harvest year, 89.5% of the harvested material consisted of grasses at Woodward. The mixture at Woodward remained relatively diverse with sideoats grama (24.1%), little bluestem (17.2%), big bluestem (14.7%), Indiangrass (13.8%), and blue grama (13.2%) all contributing more than 10% of the total biomass.

Simpson's (1-D) index of diversity values are reported in Table I-9. Third year index values for the four grasses, four grasses and four forbs, and eight grasses and eight forbs were 0.70, 0.77, and 0.85, respectively. Across the three monocultures big bluestem (0.40) and switchgrass (0.39) plots were more diverse at the time of the third year harvest than OWB (0.00). Shannon-Wiener index values of 0.00 for OWB and 0.10 for OWB-alfalfa indicate little plant diversity in these plots.

Fort Supply Site

The Fort Supply site was seeded in 2004. Yields were collected in 2005, 2006, and 2007. Figure II-2 includes a chart of the yield by year for each treatment at Fort Supply. Harvested biomass yields in 2006 at the Fort Supply site were also lower, consistent with the lower rainfall as reported in Table I-4. Aggregate average annual biomass yield across the three years are reported in Table I-7. In general, the mean yields of the plots seeded to polyculture mixtures were less than the mean yields of the plots seeded as monocultures.

Table I-10 presents the proportions of dry matter for the individual species from the annual harvest for the three harvest years at the Fort Supply site. Alfalfa did not persist in the OWB-alfalfa mix. OWB increased from 81.3% in 2005 to 95.9% in 2007. The proportion of weeds (other grasses and other forbs) decreased from 18.7% to 4.2% of the harvested dry matter over the three years. Consistently over both locations, the proportion of weeds decreased and OWB became the dominate species in the OWB-alfalfa seeded plots.

At Fort Supply, the four grasses treatment was seeded to a mixture of sand bluestem, little bluestem, sideoats grama, and blue grama. In the first harvest year, 25.3% of the harvested material was from weeds. By the third harvest year, the proportion of weeds had declined to 4.7%. The proportion of little bluestem increased from 52.8% in year one to 90.6% in year three, while sand bluestem (9.4% to 1.3%), sideoats grama (5.7% to 0%), and blue grama (7.0% to 3.3%) decreased.

Forbs did not persist in the four grasses (sand bluestem, little bluestem, sideoats grama, blue grama) and four forbs (Illinois bundleflower, sagewort, Indian blanket, purple prairie clover) plots at Fort Supply. The proportion of forbs declined from 2.9% in the first harvest year to 0.6% in the third harvest year. Biomass production from weeds exceeded the biomass production from the planted forbs. Weeds declined from 27.9% to 13.1%, and grasses increased from 69.2% to 86.3%. However, in 2007 77.2% of the total dry matter harvested consisted of little bluestem. The 86.3% grasses from the third harvest year is consistent with the finding of 84.4% grasses at Woodward from the third harvest year. However, the stand at Woodward was more diverse.

Consistent with the findings from the four grasses-four forbs treatments, the eight grasses-eight forbs treatment at both sites became less diverse over time. For the third harvest year, 97.9% of the harvested biomass consisted of grasses at Fort Supply. The third year harvest proportions were less diverse at Fort Supply with switchgrass (46.4%), Indiangrass (38.5%) and little bluestem (12.5%) dominating the stand.

Figure II-4 includes a chart of the dominant species and weeds for Fort Supply. In both the four grasses and the four grasses and four forbs polycultures that did not include switchgrass, little bluestem emerged as the dominant species. However, for the eight grasses and eight forbs polyculture that included switchgrass, almost half (46.4%) of the harvested biomass in the third year was from switchgrass.

The Simpson’s (1-D) index of diversity values for Fort Supply as reported in Table I-9 show that the eight grasses and eight forbs was the only treatment to maintain substantial diversity throughout all three years with a year three index value of 0.62. By the Simpson index measure all other treatments exhibited low diversity by the third year of production.

Economics

Biomass production cost estimates for Woodward and Fort Supply are reported in Table I-11 and Table I-12, respectively. Costs ($ ha^{-1} and $ Mg^{-1}) are reported for each treatment. Harvest cost includes the cost for mowing, raking, baling the biomass into rectangular solid bales with an average dry matter weight of 681 kg bale^{-1}, and staging. The lowest estimated cost per dry matter unit for a treatment at the Woodward site was for OWB with alfalfa ($61 Mg^{-1}). However, 98.5% of these stands were made up of OWB by the third harvest. Switchgrass had the second lowest estimated cost ($63 Mg^{-1}). The treatments with the highest estimated cost were four grasses ($89 Mg^{-1}) and eight grasses and eight forbs ($83 Mg^{-1}).

The Fort Supply site yielded similar results. The monocultures of switchgrass ($52 Mg^{-1}) and OWB ($53 Mg^{-1}) resulted in the lowest cost. The treatments that include four grasses ($63 Mg^{-1}) and eight grasses and eight forbs ($57 Mg^{-1}) resulted in the highest estimated costs at the Fort Supply location. Across both locations forbs did not persist, which suggests that investment in forb seeds is not economical.

Discussion

These findings differ from those reported by Tilman et al. (2006a). Tilman et al. (2006a) began with a number of species and then randomly assigned species to plots. Monoculture plots could have been seeded to either the most productive or the least productive species. Plots that received multiple species were more likely to include at least one species that was more productive than the average. The Tilman et al. (2006a) design is more likely to result in a positive relationship between the number of species and biomass production. In the current study, the most productive species, based on prior research, were selected for monocultures. These monocultures produced more biomass at lower cost than polycultures.

Diversity may be good in some settings. Polycultures may reduce the risk of disease and pest damage. Society may place a higher value on the variable landscape and other attributes resulting from polycultures relative to monocultures. However, if the objective is to produce massive quantities of biomass for biorefinery feedstock under the constraint that land area is limited, for the conditions that prevailed at these locations during the time of the study, internal economics favored monocultures of productive species. Additional research would be required to determine if society values the external differences between polycultures and monocultures at a level sufficient to overcome the internal production cost differences.

The characteristics that define feedstock quality and that determine the value of biomass to a biorefinery remain to be determined. Desirable feedstock properties may differ depending on which of several competing biomass to bioproducts conversion technologies is used (e.g. biochemical enzymatic hydrolysis; thermochemical/biochemical). Conversion systems that function more efficiently with homogeneous input may discount diverse feedstock or pay a premium for homogeneous material. Differences in the value of biomass across species and treatments are not considered in these cost estimates. Thus, an implicit assumption is that the value of a given quantity of dry matter would be the same across all grass, forb, and weed species.

The plots were managed to represent anticipated production activities for perennial species established in a low input system and harvested once a year to produce biorefinery feedstock. The design resulted in two shortcomings. First, in an attempt to not artificially favor one species or group of species, the plots were not fertilized. However, based on findings from prior research, the cost of producing biomass from a perennial grass such as switchgrass is lower on plots that receive nitrogen fertilizer (Lemus et al., 2008; Haque et al., 2009). Over time if material is harvested year after year prior to senescence, in addition to nitrogen, phosphorus and potassium fertilizers may be required. The cost estimates do not account for the value of elements removed with the biomass. Second, the plots were harvested once a year in late July. Research has found that delivered feedstock costs from switchgrass monoculture can be reduced if the harvest season is extended over many months. Additional research would be required to determine if the harvest strategy used in the study favors one system over another.

Conclusion

This research was conducted to determine the lowest cost lignocellulosic biomass feedstock production system from among several monocultures, one legume-grass mix, and several polycultures. The primary finding is that production costs are lower for monocultures because they produce at least as much, and in some cases more, biomass and have lower seed costs. From among the treatments included, mean biomass production costs are lowest for the alfalfa-OWB mix at Woodward. However, by the third harvest, OWB made up 98.5% of this stand and could be considered a monoculture. Estimated biomass production cost for switchgrass monocultures are \$63 Mg^{-1}. Production costs for the four grass mix are 41% greater than from the switchgrass monoculture at Woodward. Estimated biomass production cost for the switchgrass monoculture is \$52 Mg^{-1} at Fort Supply. Production costs for the four grass mix of \$63 Mg^{-1} are 21% greater than for the switchgrass monoculture.

Additional findings may be summarized as follows. (1) Biomass yields of diverse mixtures were no greater than yields of monocultures. (2) Even though no herbicides were applied and the plots were not weeded, the proportion of weeds declined from the first year to the third year harvest in every treatment at both locations. (3) At both locations, the proportion of weeds decreased, and OWB became the dominate species in the alfalfa-OWB seeded plots. (4) Forbs did not persist. For every treatment that included a mix of species, a dominate grass species emerged by the third harvest. For example, at Woodward the proportion of sideoats grama in the third year harvest was 44.2% of the four grass treatment, 36.3% of the four grass-four forb treatment, and 24.1% of the eight grass-eight forb treatment. At Fort Supply, the proportion of little bluestem in the third year harvest was 90.6% of the four grass treatment, 77.2% of the four grass-four forb treatment, and 12.5% of the eight grass-eight forb treatment. Switchgrass and Indiangrass, species that were included only in the eight grass-eight forb mix, made up 84.9% of the 16 species mix by the third harvest at Fort Supply.

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Table I-1. Species of grasses, forbs, and legumes planted at Woodward and/or Fort Supply

Scientific Name	**Common Name**	**Variety**
Grasses		
Andropogon gerardii Vitman	big bluestem	Kaw
Schizachyrium scoparium (Michx.) Nash	little bluestem	Aldous
Andropogon hallii Hack.	sand bluestem	Woodward
Bouteloua curtipendula (Michx.) Torr.	sideoats grama	El Reno
Bouteloua gracilis (Willd. ex Kunth) Lag. ex Griffiths	blue grama	Alma
Panicum virgatum L.	switchgrass	Blackwell
Sorghastrum nutans (L.) Nash	indiangrass	Cheyenne
Pascopyrum smithii (Rydb.) A. Love	western wheatgrass	Barton
Elymus canadensis L.	Canada wildrye	
Sporobolus cryptandrus (Torr.) A. Gray	sand dropseed	
Buchloe dactyloides (Nutt.) J.T. Columbus	buffalograss	Texoka
Bothriochloa ischaemum (L.) Keng	Old World bluestem	WW-Iron Master
Forbs		
Desmanthus illinoensis (Michx.) MacMill. ex B.L. Rob. & Fernald	Illinois bundleflower	
Helianthus maximilianii Schrad.	Maximilian sunflower	
Ambrosia psilostachya DC.	western ragweed	
Petalostemum purpureum Vent.	purple prairieclover	
Lespedeza capitata Michx.	roundhead lespedeza	
Engelmannia pinnatifida (Raf.) Goodman & C.A. Lawson	Englemann daisy	
Ratibida columnifera (Nutt.) Woot. & Standl.	prairie coneflower	
Salvia azurea Michx. ex Lam.	pitcher sage	
Artemisia campestris L.	sagewort	
Gaillardia pulchella Foug.	indianblanket	
Medicago sativa L.	alfalfa	Cimarron

Table I-2. Species of grasses, forbs, and legumes, and seeding rates used at Woodward by treatment.

Common Name	Pure Live Seed by Treatment (kg ha^{-1})						
Grasses	1[†]	2	3	4	5	6	7[‡]
big bluestem	7.51				1.91	1.35	0.67
little bluestem					1.12	0.78	0.34
sideoats grama					1.23	0.90	0.45
blue grama					0.34	0.22	0.11
switchgrass		2.47					0.22
Indiangrass							0.45
western wheatgrass							0.78
buffalograss							0.34
Old World bluestem			2.24	1.12			
Forbs							
Illinois bundleflower						0.61	0.30
Maximilian sunflower						0.49	0.25
western ragweed						0.83	0.41
purple prairie clover						0.25	0.12
roundhead lespedeza							0.13
Englemann daisy							0.63
prairie coneflower							0.02
pitcher sage							0.12
alfalfa				2.24			
Seed Cost ($ ha^{-1})	132	31	69	51	82	116	161
Total Establishment Cost($ ha^{-1})	300	199	237	241	250	283	328

[†] Big bluestem was the only species seeded in treatment one at Woodward which was intended as a monoculture.

[‡] Eight grasses and eight forbs were seeded in the treatment seven plots.

Table I-3. Species of grasses, forbs, and legumes, and seeding rates used at Fort Supply by treatment.

Common Name	**Pure Live Seed by Treatment (kg ha^{-1})**						
Grasses	1†	2	3	4	5	6	7‡
sand bluestem	13.00				3.25	2.24	1.12
little bluestem					1.68	1.12	0.56
sideoats grama					1.91	1.35	0.67
blue grama					0.56	0.34	0.22
switchgrass		3.70					0.34
Indiangrass							0.78
Canada wildrye							1.23
sand dropseed							0.02
Old World bluestem			1.79	0.90			
Forbs							
Illinois bundleflower						0.34	0.17
sagewort						0.34	0.17
indianblanket						0.17	0.09
purple prairie clover						0.34	0.17
roundhead lespedeza							0.09
Englemann daisy							0.17
prairie coneflower							0.01
pitcher sage							0.17
alfalfa				2.24			
Seed Cost ($ ha^{-1})	429	47	55	44	182	219	196
Total Establishment Cost($ ha^{-1})	597	214	223	234	350	387	364

† Sand bluestem was the only species seeded in treatment one at Fort Supply which was intended as a monoculture.

‡ Eight grasses and eight forbs were seeded in the treatment seven plots.

Table I-4. Monthly precipitation and average monthly temperature at the Southern Plains Research Station (Woodward, Oklahoma) by year

Year	2004		2005		2006		2007	
	Rain (cm)	Temp (°C)	Rain (cm)	Temp (°C)	Rain (cm)	Temp (°C)	Rain (cm)	Temp (°C)
January	3.2	2.6	4.0	1.6	0.9	7.9	2.1	0.2
February	3.4	2.9	2.8	6.1	0.0	3.9	3.6	2.8
March	7.8	11.9	2.8	9.3	3.7	10.4	9.8	13.3
April	5.0	14.6	4.1	14.3	1.3	18.2	5.1	12.1
May	0.1	22.3	2.3	19.4	4.6	21.4	14.1	19.3
June	16.8	23.6	16.3	24.5	4.5	26.6	18.5	22.3
July	4.7	25.6	4.4	26.3	1.0	29.6	7.7	25.1
August	9.5	24.7	13.8	25.4	7.8	27.0	3.6	27.4
September	2.9	22.0	2.4	23.5	3.6	19.9	3.0	22.6
October	8.6	15.4	4.6	15.6	2.0	15.3	1.9	17.2
November	12.0	7.6	0.5	10.6	0.4	9.1	0.1	9.1
December	0.3	4.9	0.5	2.3	11.5	4.1	1.5	1.6
Annual total	74.3		58.5		41.3		71.0	

Source: Oklahoma mesonet data available at: www.mesonet.org.

Table I-5. Estimated establishment costs other than seed.

Item	Unit	Quantity	Cost ($ ha^{-1})
Machinery Operations			
Chemical Application			
Herbicide	ha	1	12.21
Planting			
No-till grass drill	ha	1	22.14
Total machinery cost	ha		34.35
Operating Inputs			
Herbicide (glyphosate)	kg a.i.	1.12	22.05
Land Rental	ha	1	111.15

Table I-6. Estimated harvest costs.

Item	Unit	Price ($)
Harvest Cost		
Mowing	ha	24.98
Raking	ha	9.59
Baling (681kg d.m. bale)	bale	14.64
Staging[†]	bale	4.50

[†] A staging charge is assessed to account for the cost to collect bales from the field, transport a distance of no more than 10 km, and stack them at a storage location.

Table I-7. Mean annual biomass yield for each treatment at both sites.

Site	Treatment	Yield
		(Mg ha^{-1} yr^{-1})
Woodward	4 Old World bluestem-alfalfa	5.5a[†]
	3 Old World bluestem	5.0ab
	2 switchgrass	4.9ab
	6 4 grasses & 4 forbs	4.1abc
	1 big bluestem	4.0abc
	7 8 grasses & 8 forbs	3.5bc
	5 4 grasses	3.0c
Fort Supply	1 sand bluestem	9.0
	2 switchgrass	7.5
	3 Old World bluestem	7.2
	6 4 grasses & 4 forbs	7.1
	7 8 grasses & 8 forbs	6.8
	4 Old World bluestem-alfalfa	6.5
	5 4 grasses	5.6

[†] Means at a site followed by a common letter are not significantly different at $P \leq 0.05$ by the least square means test.

Table I-8. Annual percentages of species by dry matter weight in polyculture treatments harvested at Woodward site.

	Old world bluestem with Alfalfa Harvest Year			4 Grasses Harvest Year			4 Grasses & 4 Forbs Harvest Year			8 Grasses & 8 Forbs Harvest Year		
Species	2004	2005	2006	2004	2005	2006	2004	2005	2006	2004	2005	2006
Big bluestem				17.0	11.4	6.6	5.6	8.7	8.7	4.2	7.8	14.7
Little bluestem				7.5	10.7	29.6	8.1	15.1	22	6.6	20.2	17.2
Sideoats grama				40.2	40.7	44.2	22.9	20.8	36.3	11.8	15.6	24.1
Blue grama				5.6	5.5	8.8	3.4	6.3	17.4	3.2	2.0	13.2
Switchgrass										5.0	4.0	4.4
Indiangrass										15.6	9.9	13.8
Western wheatgrass										0.1	0.7	
Buffalograss											0.1	2.1
Old world bluestem	73.4	83.1	98.5								0.1	
Other grasses	15.8	5.1	0.5	21	11.6	8.8	17.6	6.7	4.6	18.0	2.4	2.8
Illinois bundleflower							3.1	6.5	7.1	1.1	3.7	0.8
Maximilian sunflower							36.1	30.2	3.2	29.6	13.1	2.1
Western ragweed							2.9	2.7	0.4	1.3	4.3	0.5
Purple prairie clover							0.2	0.6	0.3	0.1	0.3	
Roundhead lespedeza										0.6	0.5	
Englemann daisy										0.5	4.5	3.1
Prairie coneflower												
Pitcher sage										2.3		0.6
Other forbs	2.9	6.3	0.3	8.8	20.1	1.9		2.6		0.1	10.8	0.6
Alfalfa	7.9	5.4	0.8									
Total Weeds[†]	18.7	11.4	0.8	29.8	31.7	10.7	17.6	9.3	4.6	18.1	13.2	3.4
Total Planted Grasses	73.4	83.1	98.5	70.3	68.3	89.2	40.0	50.9	84.4	46.5	60.4	89.5
Total Planted Forbs	7.9	5.4	0.8	0.0	0.0	0.0	42.3	40.0	11.0	35.5	26.4	7.1

[†] Total weeds includes the sum of other grasses and other forbs (grasses and forbs that were not planted).

Table I-9. Simpson (1-D) and Shannon-Wiener (H) diversity index values for each treatment and harvest year at both Woodward and Fort Supply.

	Simpson's (1-D) Index of Diversity†						Shannon-Wiener (H) Diversity Index‡					
	Woodward			Fort Supply			Woodward			Fort Supply		
	Harvest Year			Harvest Year			Harvest Year			Harvest Year		
Treatment	2004	2005	2006	2005	2006	2007	2004	2005	2006	2005	2006	2007
Big Bluestem	0.59	0.66	0.40				0.97	1.30	0.59			
Sand Bluestem				0.58	0.22	0.31				0.96	0.42	0.60
Switchgrass	0.38	0.18	0.39	0.22	0.00	0.03	0.68	0.43	0.58	0.44	0.00	0.09
Old World Bluestem	0.20	0.11	0.00	0.34	0.05	0.13	0.40	0.24	0.00	0.64	0.14	0.29
Old World Bluestem - Alfalfa	0.43	0.30	0.03	0.32	0.09	0.08	0.82	0.66	0.10	0.59	0.22	0.19
4 Grasses	0.76	0.76	0.70	0.67	0.68	0.18	1.62	1.68	1.44	1.48	1.39	0.42
4 Grasses & 4 Forbs	0.77	0.82	0.77	0.68	0.65	0.39	1.72	1.99	1.70	1.49	1.38	0.88
8 Grasses & 8 Forbs	0.83	0.88	0.85	0.68	0.68	0.62	2.05	2.33	2.10	1.49	1.36	1.11

† Simpson's (1-D) index of diversity ranges from zero to one where zero represents no diversity and one represents infinite diversity.

‡ The Shannon-Wiener index is scaled from zero (little diversity) to approximately 4.6 (substantial diversity). Values in the midrange of the Shannon-Wiener scale are ambiguous.

Table I-10. Annual percentages of species by dry matter weight in polyculture treatments harvested at Fort Supply site.

	Old world bluestem with Alfalfa Harvest Year			4 Grasses Harvest Year			4 Grasses & 4 Forbs Harvest Year			8 Grasses & 8 Forbs Harvest Year		
Species	2005	2006	2007	2005	2006	2007	2005	2006	2007	2005	2006	2007
Sand bluestem				9.4	16.1	1.3	9.3	14.8	4.1	3.2	2.8	
Little bluestem				52.8	50.7	90.6	51.5	54.4	77.2	6.2	16.2	12.5
Sideoats grama				5.7	14.3		5.0	7.6		1.6	0.7	
Blue grama				7.0	12.7	3.3	3.4	14.0	5.0	0.2	0.3	0.5
Switchgrass										22.6	30.9	46.4
Indiangrass										49.7	44.2	38.5
Canada wildrye										0.1		
Sand dropseed										0.1		
Old world bluestem	81.3	95.2	95.9									
Other grasses	4.7	3.4	3.6	9.2	2.1	4.0	8.1	6.5	12.6	6.4	3.3	0.5
Illinois bundleflower							0.2	0.1	0.6			
Sagewort							0.5	0.8		0.1		
Indianblanket							2.2					
Purple prairieclover										0.1		
Roundhead lespedeza										0.2	0.2	1.5
Englemann daisy												
Prairie coneflower												
Pitcher sage										0.2		
Other forbs	14	1.5	0.6	16.1	4.2	0.7	19.8	1.7	0.5	9.3	1.4	0.2
Alfalfa												
Total Weeds†	18.7	4.9	4.2	25.3	6.3	4.7	27.9	8.2	13.1	15.7	4.7	0.7
Total Planted Grasses	81.3	95.2	95.9	74.9	93.8	95.2	69.2	90.8	86.3	83.7	95.1	97.9
Total Planted Forbs	0.0	0.0	0.0	0.0	0.0	0.0	2.9	0.9	0.6	0.6	0.2	1.5

† Total weeds includes the sum of other grasses and other forbs (grasses and forbs that were not planted).

Table I-11. Estimated cost to produce biomass by treatment at Woodward site.

Treatment	Establishment cost amortized over 10 years at 7% $\$\ ha^{-1}$	Land rental $\$\ ha^{-1}\ yr^{-1}$	Harvest cost $\$\ ha^{-1}$	Average harvested yield $Mg\ ha^{-1}\ yr^{-1}$	Total production cost $\$\ ha^{-1}\ yr^{-1}$	Farm gate cost[†] $\$\ Mg^{-1}$
4 Old World bluestem-alfalfa	34	111	188	5.5	333	61
2 switchgrass	28	111	172	4.9	311	63
3 Old World bluestem	34	111	174	5.0	319	64
6 4 grasses & 4 forbs	40	111	150	4.1	301	73
1 big bluestem	43	111	147	4.0	303	75
7 8 grasses & 8 forbs	47	111	133	3.5	291	83
5 4 grasses	36	111	120	3.0	267	89

[†] The farm gate cost includes a staging charge of $\$6.61\ Mg^{-1}$ assessed to account for the cost to collect bales from the field, transport a distance of no more than 10 km, and stack them at a storage location on or near the farm.

Table I-12. Estimated cost to produce biomass by treatment at Fort Supply site.

Treatment	Establishment cost amortized over 10 years at 7%	Land rental	Harvest cost	Average harvested yield	Total production cost	Farm gate cost[†]
	$ ha^{-1}	$ ha^{-1} yr^{-1}	$ ha^{-1}	Mg ha^{-1} yr^{-1}	$ ha^{-1} yr^{-1}	$ Mg^{-1}
2 switchgrass	31	111	245	7.5	387	52
3 Old World bluestem	32	111	237	7.2	380	53
1 sand bluestem	85	111	287	9	483	54
4 Old World bluestem-alfalfa	33	111	218	6.5	362	56
6 4 grasses & 4 forbs	55	111	234	7.1	400	56
7 8 grasses & 8 forbs	52	111	225	6.8	388	57
5 4 grasses	50	111	192	5.6	353	63

[†] The farm gate cost includes a staging charge of $6.61 Mg^{-1} assessed to account for the cost to collect bales from the field, transport a distance of no more than 10 km, and stack them at a storage location on or near the farm.

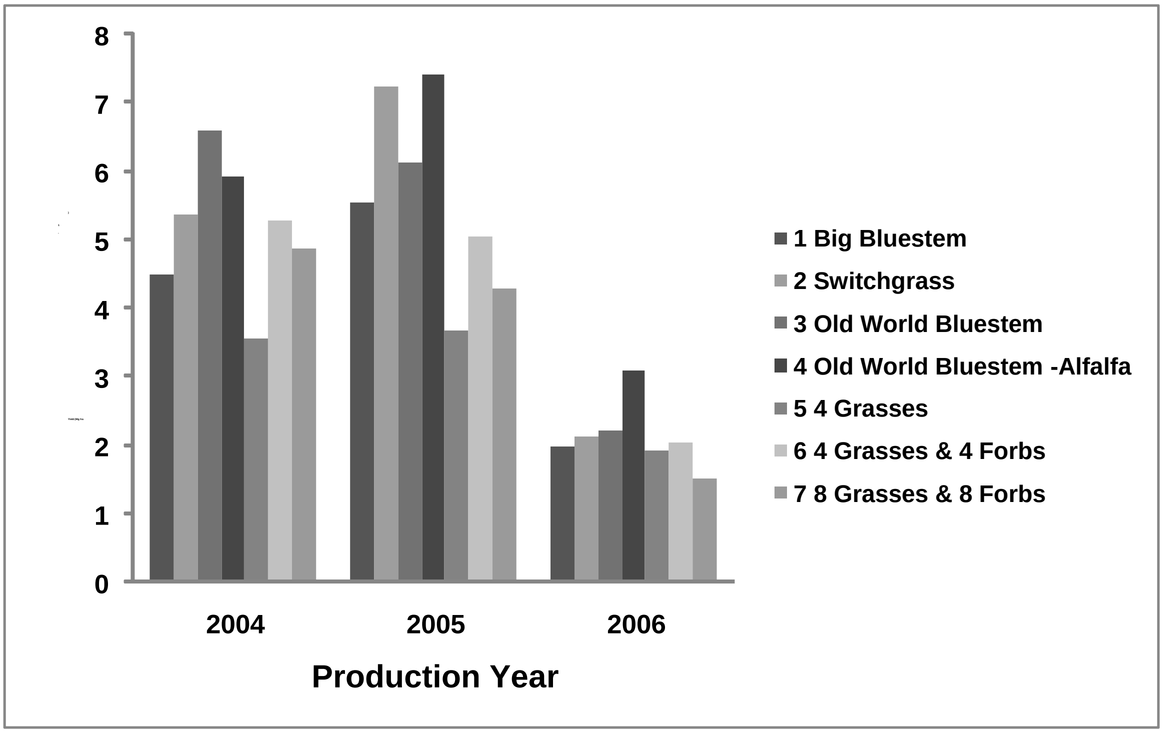

Figure I-1. Average biomass yield across replications for each treatment for each year at the Woodward site.

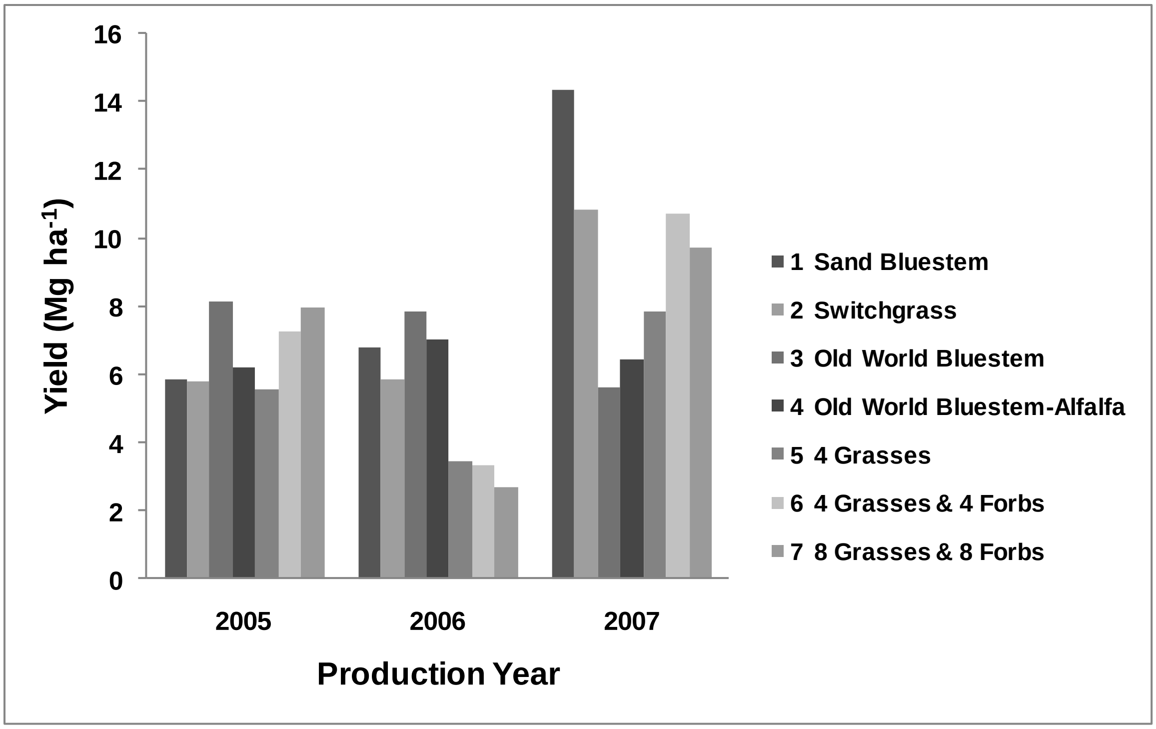

Figure I-2. Average biomass yield across replications for each treatment for each year at the Fort Supply site.

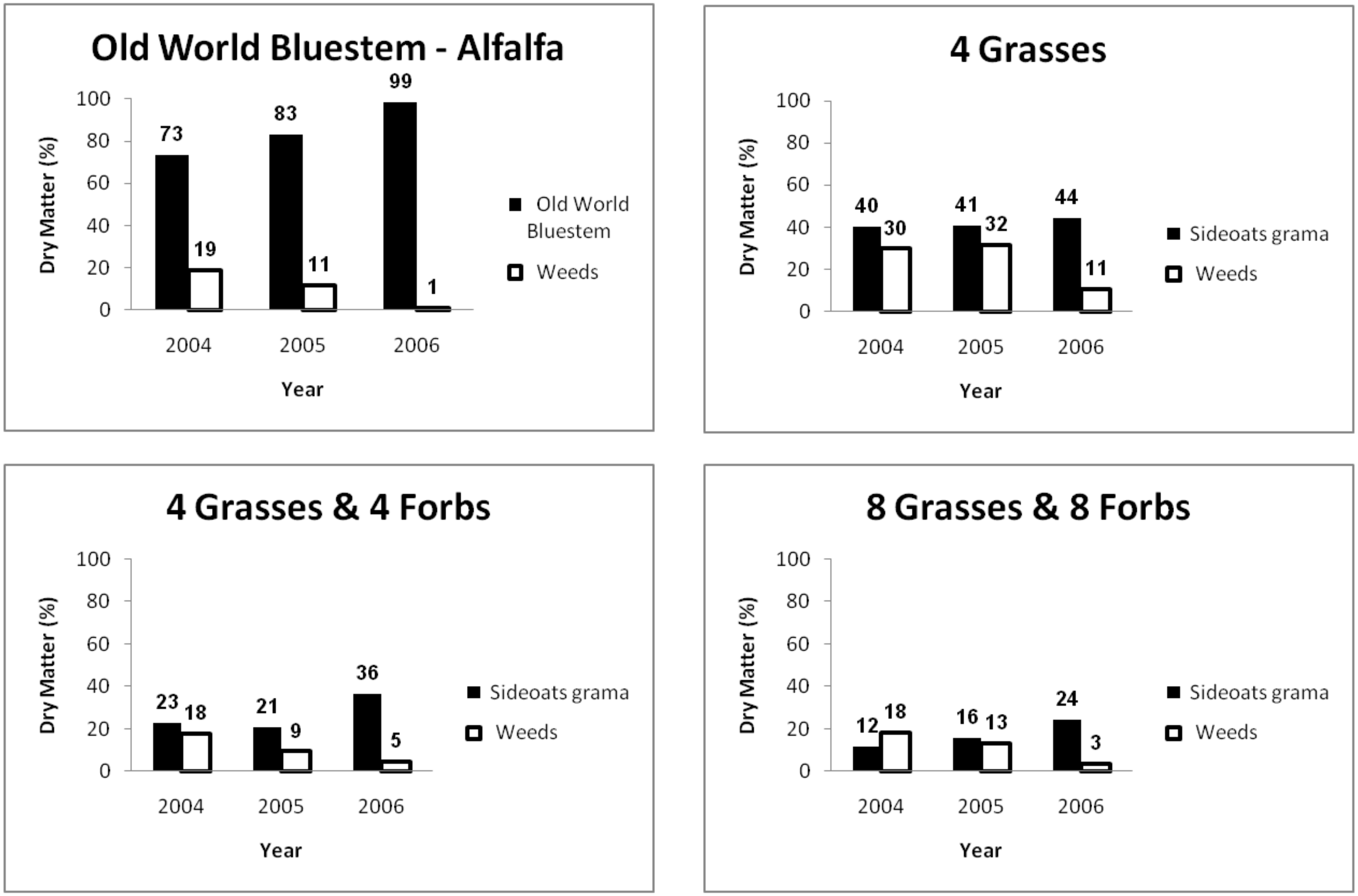

Figure I-3. Changes in proportion of dominant species over time and weeds (species that were not planted) in the polyculture treatments at the Woodward site.

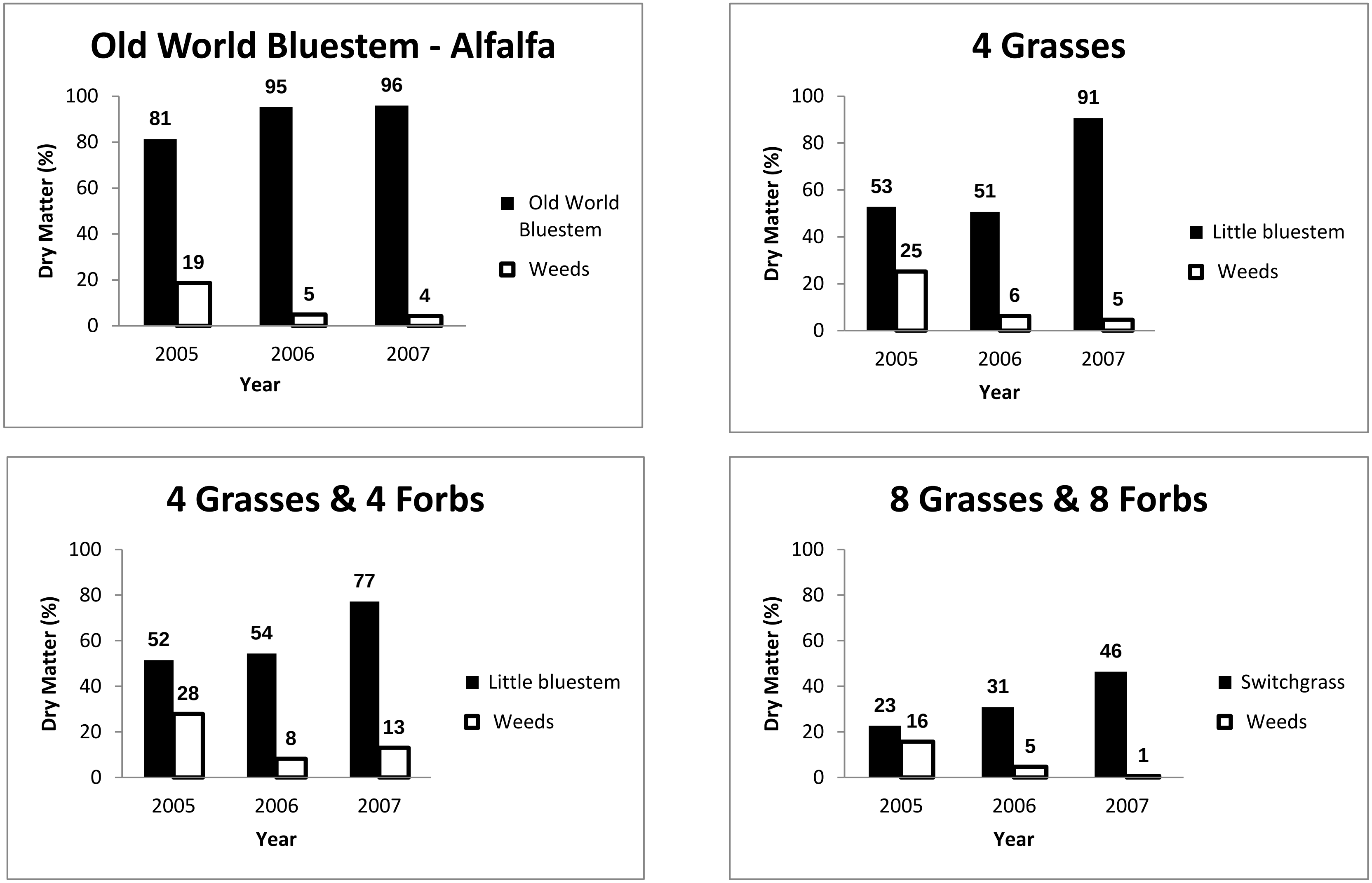

Figure I-4. Changes in proportion of dominant species over time and weeds (species that were not planted) in the polyculture treatments at the Fort Supply site.

CHAPTER II

CONTINUOUS WINTER WHEAT VERSUS A WINTER CANOLA-WINTER WHEAT ROTATION*

Abstract

Difficult to control winter annual grasses that have been used to produce forage, especially Italian ryegrass (*Lolium multiflorum* Lam.) and feral rye (*Secale cereale* L.), have invaded Oklahoma fields traditionally used to produce continuous winter wheat (*Triticum aestivum* L.). This study was conducted to determine whether a winter canola (*Brassica napus* L.) - winter wheat crop rotation could compete economically with continuous winter wheat. The effects of seven herbicide treatments for continuous wheat and 24 herbicide treatments for the canola-wheat rotations were analyzed over a rotation cycle at four Oklahoma locations. Enterprise budgets were prepared to enable economic comparisons across production system and treatments. Wheat yields in year two of the canola-wheat rotations were significantly ($P < 0.05$) greater than wheat yields in year two of continuous wheat across all four locations (10%, 11%, 15%, 22%). Based on the historical relationship between wheat and canola prices, and a wheat price of \$0.21 kg^{-1} and a canola price of \$0.40 kg^{-1}, for the three sites for which net returns could be pooled across herbicide treatment, net returns from the canola-wheat rotation (\$197, \$123, and \$24 $ha^{-1}yr^{-1}$) were significantly ($P < 0.05$) greater than net returns from continuous wheat (-\$46, -\$118, and -

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\$48 $ha^{-1}yr^{-1}$). Based on historical price relationships and the yields produced in the trials, a winter canola - winter wheat crop rotation may improve net returns relative to continuous winter wheat for Oklahoma fields infested with Italian ryegrass and feral rye.

Introduction

Crop rotation is rare on rain fed cropland in western Oklahoma. On average from 2000 to 2010 about 75% of the land planted to annual crops in the state and 86% of the dry land area in the southwest crop reporting district of the state was seeded to winter wheat (*Triticum aestivum* L.). Difficult to control winter annual grasses that have been used to produce forage, especially Italian ryegrass (*Lolium multiflorum* Lam.) and feral rye (*Secale cereale* L.), have invaded Oklahoma fields traditionally used to produce continuous winter wheat (*Triticum aestivum* L.) (Peeper et al., 2000; Barnes et al., 2001; White et al., 2006). Weeds can decrease the value of a wheat crop through direct competition by reducing wheat yields and by decreasing wheat quality due to foreign material in the wheat grain which results in price reductions (Appleby et al., 1976; Justice et al., 1994).

Crop rotations have been a successful strategy in managing weeds in winter wheat in other parts of the world (Daugovish et al., 1999; Lyon and Baltensperger, 1995). Medlin et al. (2003) recommended that producers use a crop rotation to manage the weed problem in Oklahoma. However, they did not identify an economically viable crop rotation option. Biermacher et al. (2006) compared monoculture continuous winter wheat to a crop rotation of soybeans (*Glycine max* L.) followed by winter wheat and double cropped soybeans. The system that included soybeans showed losses in years in which rainfall was consistent with historical averages. For typical weather years the continuous wheat system was more economical. Decker et al. (2009) compared a rotation that included winter wheat and foxtail millet (*Setaria italica* (L.) Beauv.) as a summer hay crop to continuous wheat. They determined that continuous wheat was more economical. As a result of the typically hot dry weather, summer crops are economically risky propositions for western Oklahoma. In 2006, only 81% of the corn (*Zea mays* L.) planted and only 69% of the soybeans planted were harvested.

As a result of the problems with weeds and with the difficulty of growing summer crops in the region, interest has grown in growing winter canola as a rotational crop with winter wheat (Lofton et al., 2010). In the 1990s, attempts to grow fall planted canola in the southern Great Plains were not successful (Unger, 2001). However, breeding programs have been successful in developing winter hardy varieties (Rife and Salgado, 1996; Boyles et al., 2004; Vasilakoglou et al., 2010). Crop rotations of winter canola and winter cereals that provide a number of weed control options have been found to be economically competitive elsewhere (Vasilakoglou et al., 2010).

Conventional cultivars and herbicide resistant cultivars of winter hardy canola are commercially available for Oklahoma. Herbicide alternatives include trifluralin [a,a,a trifluoro-2, 6-dinitro-N, N-dipropyl-p-toluidine], clethodim [2-[1-[[(3-chloro-2-propenyl)oxy]imino] propyl]5-[2-(ethylthio)propyl]-3-hydroxy-2-cyclohexen-1-one], and quizalofop [2-[4-(6-chloroquinoxalin-2-yloxy) phenoxy] propionic acid]. No postemergence herbicides are registered for broadleaf weed control in canola, but herbicide resistant cultivars are available that allow the use of glyphosate [N-(phosphonomethyl) glycine] which can help control many weed species including Italian ryegrass (Grey et al., 2006). Including winter canola in a rotation with winter wheat greatly enhances weed management options. The objective of this research is to determine and compare crop yields in a continuous wheat system to yields in a canola-wheat system and to determine whether the rotation is economically competitive with continuous monoculture wheat for the region in fields infested with feral rye and Italian ryegrass. Twenty-four herbicide treatments are tested for the winter canola – winter wheat rotation and seven herbicide treatments for the continuous winter wheat.

Materials And Methods

Agronomic

The experiments were conducted at four Oklahoma locations: the North Central (Lahoma) (36°39′ N, 98°11′ W), Agronomy (Lake) (36°12′ N, 97°9′ W), Cimarron Valley (Perkins) (35°99′ N, 97°4′ W) and South Central (Chickasha) (35°3′ N, 97°90′ W) Research Stations. The soil at the Lahoma site is a Grant silt loam (fine-silty, mixed, superactive, thermic Udic Agiustoll; pH = 6.4). The soil at the Lake site is a Pulaski sandy loam (coarse-loamy, mixed, superactive, thermic Udic Ustifuvent; pH =6.4). The soil at the Perkins site is a Teller sandy loam (fine-loamy, mixed, active, thermic Udic Agiustoll; pH = 6.3). The soil at the Chickasha site is a Dale silt loam (fine-silty, mixed, superactive, thermic Pachic Haplustoll; pH = 7.9). Monthly rainfall totals are presented in Figure II-1(Oklahoma Mesonet, 2011). The experiments were designed as a randomized complete block with a factorial arrangement of treatments with four replications. Factors included crop grown in the first year (canola or wheat) and the herbicide treatment.

Plots at all four sites had previously been managed as conventionally tilled continuous winter wheat. In November of 2007, the year prior to the initiation of the canola-wheat versus wheat-wheat comparison trials, all four sites were seeded with a mixture of rye (variety not stated), Italian ryegrass cv 'Marshall', and winter wheat cv 'Centerfield' at 17, 11, and 67 kg ha^{-1}, respectively. Fertilizer was applied prior to planting. Seeds were planted into well tilled soil using a conventional grain drill with 18 cm row spacing. The sites were artificially infested with rye and Italian ryegrass to simulate conditions that exist in many Oklahoma wheat fields. Centerfield is an imidazolinone tolerant cultivar and was selected to enable the use of imazomox (2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-(methoxymethyl) -3-pyridinecarboxylic acid) herbicide.

During the setup season of 2007-2008 a third of the plots at each site were treated with imazamox at 35 g a.i. ha^{-1} + MCPA (2-methyl-4-chlorophenoxyacetic acid) at 70 g a.e. ha^{-1} with nonionic surfactant at 0.25 %v v^{-1} and spray grade ammonium sulfate at 18 g L^{-1} of spray solution; a third were treated with pinoxaden [2,2-dimethyl-propanoic acid 8-(2,6-diethyl-4-methylphenyl)-1,2,4,5-tetrahydro-7-oxo-7H-pyrazolo[1,2-d][1,4,5]oxadiazepin-9-yl ester] at 60 g a.i. ha^{-1}; and a third received no herbicide. At the end of this setup season, completed with wheat harvest in June of 2008, conditions similar to those of many Oklahoma wheat fields were assumed to have been established.

In July of 2008, glyphosate at 3100 g ha^{-1} with spray grade ammonium sulfate (NH_4SO_4) at 20.4 g L^{-1} of spray solution was applied to the wheat stubble. In August of 2008, each plot was disked twice in opposite directions within the width of each plot to minimize soil movement between plots. Plots were fertilized prior to planting with 373 kg ha^{-1} of 14-11-11-3 (N-P-K-S) to provide one third of the recommend nitrogen (52 kg ha^{-1}) for a 2800 kg ha^{-1} canola yield goal (Zhang and Raun, 2004).

The winter canola plots accommodated eight herbicide treatments and the winter wheat plots three herbicide treatments. Canola herbicide treatments included glyphosate (770 g ai ha^{-1}); quizalofop (77 g ai ha^{-1}); clethodim (105 g ai ha^{-1}); trifluralin (1120 g ai ha^{-1}); glyphosate (770 g ai ha^{-1}) followed by glyphosate (770 g ai ha^{-1}); trifluralin (1120 g ai ha^{-1}) followed by quizalofop (77 g ai ha^{-1}); trifluralin (1120 g ai ha^{-1}) followed by clethodim (105 g ai ha^{-1}); and a no herbicide check. Crop oil concentrate at 1 %v v^{-1} was added to clethodim and quizalofop treatments. Wheat treatments included imazamox (35 g ai ha^{-1}) + MCPA (70 g ai ha^{-1}); pinoxaden (60 g ai ha^{-1}); and a treatment with no herbicide. Trifluralin treatments were not included at the Lake site.

Preplant incorporated trifluralin treatments were applied to appropriate canola plots and incorporated within 30 minutes with one pass of an s-tine field cultivator operated 3- to 5-cm deep during the last week of September in 2008. All plots were tilled with this cultivator as a final preplant tillage. A day after application and incorporation of the trifluralin treatments all plots were seeded. Winter canola cv. ‘DKW 41-10’ and wheat cv. ‘Centerfield’ were seeded with a small grain drill at 5.6 and 67 kg ha^{-1}, respectively. The fall herbicide treatments were applied in November of 2008 while the spring herbicide treatments were applied to canola in February of 2009. The remaining quantity of recommended nitrogen was applied with urea top dressed in January of 2009 (105 kg ha^{-1}).

Canola and wheat were harvested with small plot combines in June of 2009. The harvested samples were weighed, scalped using a small commercial seed cleaner, and reweighed. Seed volume weight and moisture content were determined for each sample using standard procedures. Wheat yields were adjusted to 12 percent seed moisture content and canola yields were adjusted to 10 percent moisture. The crop plants remaining along plot edges were harvested using a larger combine.

Plots were disked twice in opposite directions in early July 2009. The final herbicide application occurred in early August 2009, when glyphosate at 770 g a.i. ha^{-1} was applied across all plots other than the checks. The plots were disked twice in mid-August 2009. Plots were fertilized prior to planting with 14-11-11-3 at a rate intended to provide one third of the total anticipated nitrogen required to achieve the yield goal. Winter wheat cv. 'Centerfield' was planted at 67 kg ha^{-1} in November of 2009 to all plots at all sites. Urea was applied as a top dress in February of 2010 to supply the remaining recommended nitrogen. All plots were harvested in June of 2010 using previously described methods.

Canola yield data from 2009 and wheat yield data from 2009 and 2010 were analyzed for each site using the SAS PROC MIXED procedure (Lee et al., 2008; SAS Institute, 2008) with treatment as a fixed effect. Means were compared using the SAS least square means with Tukey adjustment at $P \leq 0.05$ to test comparisons across means.

Economic

The objective function for a risk neutral producer with the choice of producing continuous winter wheat or a winter canola – winter wheat rotation that aspires to maximize net

$$(1) \qquad \max_{\lambda,\boldsymbol{H}} \pi = \max_{\lambda,\boldsymbol{H},} \left[\lambda \left(\sum_{i=1}^{2} (R_i - \boldsymbol{P}'_{\boldsymbol{H}_w} \boldsymbol{H}_w - C_i) \right) + (1-\lambda) \left(\sum_{i=1}^{2} (R_i - \boldsymbol{P}'_{\boldsymbol{H}_k} \boldsymbol{H}_k - C_i) \right) \right]$$

subject to

$$\lambda \in \{0,1\}$$

$$\boldsymbol{H} \in \{0,1\}$$

$$\boldsymbol{i}'\boldsymbol{H} \leq 1$$

where π is net return, λ is an indicator variable for the cropping system which is a discrete choice between continuous wheat (λ = 1) and canola-wheat rotation (λ = 0), R_i is revenue in year i, $\boldsymbol{P}_{\boldsymbol{H}_w}$ is a vector of prices for herbicides used in wheat, H_w is a vector representing the discrete choice between three herbicide applications used in wheat in year one, $\boldsymbol{P}_{\boldsymbol{H}_k}$ is a vector of prices for herbicides used in canola, H_k is a vector representing the discrete choice between eight herbicide applications used in canola in year one, and C_i are other cost associated with production.

Enterprise budgeting was used to compute net returns to land, machinery fixed costs for the machines used to prepare the seedbed and plant, labor, management, and overhead for each crop rotation by herbicide treatment. Budgets were constructed for both continuous wheat and for the canola-wheat rotation.

Companies that provide custom harvest services for small grains have been common in the Great Plains for a number of years (Dhuyvetter and Kastens, 2010). Producers in the region have grown to expect that reliable custom harvest services will be available when needed. These established companies adapted quickly to also provide custom harvest services for canola (Dhuyvetter and Kastens, 2010). Custom application of fertilizer and pesticides is also common in the region. Therefore, average custom machinery rates were used to calculate costs associated with harvest and the application of fertilizer, herbicide, and insecticide (Doye and Sahs, 2010). Herbicide prices for imazamox + MCPA, pinoxaden, glyphosate, quizalofop, clethodim, and trifluralin were obtained from chemical dealers and distributors. Wheat harvest has a base cost of

$40 ha^{-1} with an additional cost of $0.006 kg^{-1} of wheat harvested in excess of 1,345 kg ha^{-1}. The canola harvest is budgeted with a swathing and combining which results in a base cost of $91 ha^{-1}. The excess harvest cost for canola is $0.009 kg^{-1} in excess of 1,680 kg ha^{-1}.

Net returns for 2009 and 2010 for both cropping systems and each of the four locations were calculated for each observation. Historical average Oklahoma hard red winter wheat prices (2007-2010) and canola prices (2009-2010) were used in calculating base case scenario net returns (USDA-NASS, 2011b). Returns were then summed across years, 2009 and 2010, for each observation to obtain the total net return to land, machinery fixed costs for the machines used to prepare the seedbed and plant, labor, overhead, and management for each observation.

Total net returns were analyzed using the SAS PROC MIXED procedure (Lee et al., 2008; SAS Institute, 2008) with treatment as a fixed effect for each of the four sites. Means were compared using the SAS least square means with Tukey adjustment at $P \leq 0.05$ test comparisons across means.

Based on historical prices per kg from 2000 to 2010, canola prices have ranged from 50% to 140% greater than wheat prices (USDA-NASS, 2011a). To evaluate the sensitivity of the results to the budgeted wheat and canola prices, wheat price was held constant and the canola price was increased and decreased by 33%. This resulted in a range for the canola price to be from 30% to 150% greater than the wheat price on a weight basis.

Results

Mean canola and wheat yields for production year 2009 are presented in Table II-1. An F-test was used to determine whether canola yields and wheat yields could be pooled across treatments. Canola yields were pooled at Chickasha ($P = 0.18$), and Perkins ($P = 0.22$) but not Lake ($P = 0.04$) or Lahoma ($P < 0.0001$). Wheat yields were pooled at Chickasha ($P = 0.87$), Lake ($P = 0.23$), Perkins ($P = 0.50$), and Lahoma ($P = 0.35$). The mean canola yield at Chickasha (1939 kg ha^{-1}) was 231% higher than wheat yields at Chickasha (838 kg ha^{-1}). At Perkins, the mean canola yield was 1626 kg ha^{-1} while the mean wheat yield was 1710 kg ha^{-1}. Wheat yields at Lake and Lahoma were 901 kg ha^{-1} and 2459 kg ha^{-1}, respectively. Canola yields at Lake ranged from 1350 kg ha^{-1} for the treatment that received no herbicide in either the setup year or 2009, to 2435 kg ha^{-1} for the treatment receiving imazamox + MCPA in the setup year and quizalofop in 2009. Lahoma canola yields ranged from 1147 kg ha^{-1} for the treatment that received no herbicide in both the setup year and in 2009 to 2316 kg ha^{-1} for the treatments of no herbicide in the setup year and glyphosate in 2009 and pinoxaden in the setup year and glyphosate in 2009.

Table II-2 presents wheat yields for production year 2010 following canola and wheat yields from the continuous wheat treatment. An F-test was used to test whether wheat yields could be pooled across herbicide treatments at each site for both rotations. Wheat yields following canola could be pooled across herbicide treatments for Chickasha ($P = 0.88$), Lake ($P = 0.35$), Perkins ($P = 0.99$), and Lahoma ($P = 0.82$). Likewise, wheat yields in the continuous wheat treatment could be pooled across herbicide treatments for Chickasha ($P = 0.27$), Lake ($P = 0.63$), Perkins ($P = 0.76$), and Lahoma ($P = 0.25$). Wheat yields following canola were found to be significantly greater than wheat yields in the continuous wheat system for all four sites. Wheat yields following canola at Chickasha (2623 kg ha^{-1}) were 15% greater than wheat yields (2290 kg ha^{-1}) in the continuous wheat treatment at the same location while wheat yields following canola at Lake (1815 kg ha^{-1}) were 22% greater than continuous wheat yields (1486 kg ha^{-1}). Wheat yields at Perkins were 1498 kg ha^{-1} for wheat following canola and 1362 kg ha^{-1} for continuous wheat resulting in wheat yields in the canola-wheat system being 10% greater than wheat yields in the continuous wheat system. Similarly, wheat yields following canola (1679 kg ha^{-1}) were 11% greater than wheat yields from the continuous wheat (1510 kg ha^{-1}) treatment at Lahoma. These findings support wheat yields being greater when following canola than wheat yields in a continuous wheat system.

Figure II-1 includes monthly rainfall at each of the four sites from June of 2008 through June of 2010 as well as historical averages per month. The chart illustrates the month-to-month variability in rainfall. It also illustrates differences across locations. For example, in November of 2008 rainfall was substantially above average at Perkins, but substantially below average at Chickasha and Lahoma. In March of 2009 rainfall was near average at Perkins, but substantially below average at Chickasha and Lahoma. In November of 2009 rainfall was substantially below average at all four sites. In April of 2010 rainfall was substantially above average at Perkins but substantially below average at Chickasha. The variability in weather across sites, and differences in soils across sites, lends credence to the robustness of the finding that wheat yield is enhanced by the rotation.

Net returns for the continuous wheat system and the canola-wheat system for Chickasha, Lake, and Perkins are in Table II-3 while net returns for Lahoma are in Table II-4 (Figure1). Table II-3 and Table II-4 also contain a sensitivity analysis of net returns to changes in canola price. An F-test was used to determine whether net returns across herbicide treatments for a cropping system at a site could be pooled. Net returns by cropping systems could be pooled at Chickasha, Lake, and Perkins but only the continuous wheat system could be pooled at Lahoma.

The canola-wheat system resulted in higher expected net returns for all three canola prices analyzed at Chickasha and Lake. Net returns at Chickasha for the canola-wheat system were \$325, \$197, and \$69 ha^{-1} yr^{-1} for canola prices of \$0.53, \$0.40, and \$0.27 kg^{-1}, respectively, while the continuous wheat system resulted in a return of -\$46 ha^{-1} yr^{-1}. The Lake site resulted in net returns of \$251 (\$0.53 kg^{-1}), \$123 (\$0.40 kg^{-1}), and -\$5 (\$0.27 kg^{-1}) ha^{-1} yr^{-1} while the continuous wheat system resulted in a return of -\$118 ha^{-1} yr^{-1}. Net returns at Perkins resulting from canola prices of \$0.53 and \$0.40 kg^{-1} were \$130 and \$24 ha^{-1} yr^{-1}, respectively, which were both significantly greater than the continuous wheat system's return of -\$48 ha^{-1} yr^{-1}, but the return from the continuous wheat system was greater than the canola-wheat system using the low canola price of \$0.27 kg^{-1} and the base wheat price of \$0.21 kg^{-1}.

Wheat treatments at the Lahoma site were pooled, but the canola-wheat treatments could not be pooled. The continuous wheat system at Lahoma resulted in a net return of \$43 ha^{-1} yr^{-1}

which was significantly greater than the treatment that received no herbicide in the setup year and no herbicide in 2009 (-\$103 ha^{-1} yr^{-1}) and the treatment that received imazamox + MCPA in the setup year and no herbicide in 2009 (-\$86 ha^{-1} yr^{-1}) when the canola price was \$0.27 kg^{-1}. When the canola price was increased to \$0.40 kg^{-1} the only three treatments found to have significantly greater net returns than the continuous wheat system were the three treatments that received one application of glyphosate in 2009. The net returns for the glyphosate treatments that received imazamox + MCPA, pinoxaden, or no herbicide in the setup year were \$187, \$181, and \$179 ha^{-1} yr^{-1}, respectively. When the price of canola was increased to \$0.53 kg^{-1} the only canola-wheat treatments that were not significantly greater than the continuous wheat system were the treatments with no herbicide in the setup year and no herbicide in 2009 and the treatment receiving imazamox + MCPA in the setup year and no herbicide in 2009.

These findings suggest the use of a canola-wheat rotation in combination with labeled herbicide in fields infested with Italian ryegrass and feral rye, are expected to produce greater returns than either continuous wheat or a canola-wheat rotation with no herbicide application. Each of the labeled herbicide programs included in the study were equally effective from an economics perspective at the Chickasha, Lake, and Perkins sites.

Canola-wheat treatments receiving one application of glyphosate performed well for the conditions, locations, and years in this study. The success of the glyphosate treatments can be largely attributed to the relative cost of the glyphosate system compared to other herbicides and to the treatments only requiring one herbicide application whereas some of the other canola-wheat treatments required two herbicide applications, an additional tillage procedure for pre-plant incorporation, or both.

Discussion

Continuous winter wheat is commonly produced in the Southern Plains, but continuous winter wheat faces weed problems especially from Italian ryegrass and feral rye. The weed problems have been associated with lower wheat yields and reduced economic returns. It has been proposed that a winter annual crop rotation may alleviate some of the problems faced by continuous winter wheat production. This research was conducted to determine expected wheat yields in a continuous wheat system and wheat yields in a canola-wheat system as well as to determine the expected net returns of continuous wheat produced for grain only and the expected net returns of a canola-wheat rotation.

The primary findings are wheat yields following canola are significantly greater than wheat yields experienced in continuous wheat and expected net returns are greater for canola-wheat rotations than for continuous wheat. From among the treatments included in the study, glyphosate treatments were strong performers due to the relative cost of the glyphosate system and glyphosate's ability to control a large variety of plant species, but glyphosate treatments were not necessarily found to outperform other herbicides used in this study.

An additional finding is that using a herbicide in a canola-wheat rotation is expected to result in a higher net return than not using a herbicide, but it is not known what the effect of alternating herbicides in this rotation would have on net returns. Additional research would be necessary to determine if alternating herbicides from year to year to target weeds not targeted by the previous herbicide and to prevent potential problems such as herbicide resistance would increase net returns.

One shortcoming of the research is that the reason for greater wheat yields following canola was not determined. A number of factors that could influence yield such as differences in disease incidence and differences in soil moisture available after canola relative to the quantity available after wheat were not measured. Additional research would be required to isolate the causes for the yield differences.

An additional limitation of the study is that it was not extended over several sequences of the rotation. It will take time for insects, diseases, and weeds to adapt. Repeating the experiment over a number of years would be required to obtain a full accounting of the costs and benefits of the winter canola-winter wheat rotation relative to continuous winter wheat. Given the variability in weather across the four sites, along with the differences in soil type across the four sites, the consistency in findings across sites, namely that wheat yield is enhanced by the rotation, and that the rotation is more economical than continuous wheat, appear to be relatively robust. However, additional research would be required to confirm the findings and to determine long run consequences on yields, income, and variability of yields and income.

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Table II-1. Mean canola and wheat yields by site for production year 2009.

Crop	Site	Setup year (2008) herbicide	2009 herbicide	Yield
				(kg ha^{-1})
Canola	Chickasha	Pooled across treatments[†]		1939
	Perkins	Pooled across treatments		1626
	Lake			
		No herbicide	No herbicide	1350b[‡]
		No herbicide	Glyphosate	1803ab
		No herbicide	Glyphosate fb.[§] Glyphosate	1765ab
		No herbicide	Quizalofop	2093ab
		No herbicide	Clethodim	2048ab
		Pinoxaden	No herbicide	1830ab
		Pinoxaden	Glyphosate	1788ab
		Pinoxaden	Glyphosate fb.[§] Glyphosate	1765ab
		Pinoxaden	Quizalofop	2148ab
		Pinoxaden	Clethodim	1760ab
		Imazamox + MCPA	No herbicide	2078ab
		Imazamox + MCPA	Glyphosate	2184ab
		Imazamox + MCPA	Glyphosate fb.[§] Glyphosate	2203ab
		Imazamox + MCPA	Quizalofop	2435a
		Imazamox + MCPA	Clethodim	2305ab
	Lahoma			
		No herbicide	No herbicide	1147b
		No herbicide	Glyphosate	2316a
		No herbicide	Glyphosate fb.[§] Glyphosate	2273a
		No herbicide	Quizalofop	2106a
		No herbicide	Clethodim	2160a
		No herbicide	Trifluralin	2074a
		No herbicide	Trifluralin fb. Quizalofop	2191a
		No herbicide	Trifluralin fb. Clethodim	2217a
		Pinoxaden	No herbicide	1736ab
		Pinoxaden	Glyphosate	2316a
		Pinoxaden	Glyphosate fb. Glyphosate	2311a
		Pinoxaden	Quizalofop	2269a
		Pinoxaden	Clethodim	2234a
		Pinoxaden	Trifluralin	2253a
		Pinoxaden	Trifluralin fb. Quizalofop	2249a
		Pinoxaden	Trifluralin fb. Clethodim	2309a
		Imazamox + MCPA	No herbicide	1355b
		Imazamox + MCPA	Glyphosate	2263a

		Imazamox + MCPA	Glyphosate fb. Glyphosate	2243a
		Imazamox + MCPA	Quizalofop	2161a
		Imazamox + MCPA	Clethodim	2162a
		Imazamox + MCPA	Trifluralin	2098a
		Imazamox + MCPA	Trifluralin fb. Quizalofop	2192a
		Imazamox + MCPA	Trifluralin fb. Clethodim	2271a
Wheat	Chickasha	Pooled across treatments		838
	Lake	Pooled across treatments		901
	Perkins	Pooled across treatments		1710
	Lahoma	Pooled across treatments		2459

† Used an F-test to determine whether yields could be pooled across treatments.

‡Means followed by a common letter are not significantly different at $P \leq 0.05$ by the least square means test.

§Followed by.

Table II-2. Mean wheat yield for each site for production year 2010†.

	Wheat Yield (kg ha^{-1})‡			
Rotation§	Chickasha	Lake	Perkins	Lahoma
C-W	2623a	1815a	1498a	1679a
W-W	2290b	1486b	1362b	1510b

† Used an F-test to determine whether yields could be pooled across treatments.
‡Means in the same column followed by a common letter are not significantly different at $P \leq 0.05$ by the least square means test.
§ Canola-wheat (C-W) and wheat-wheat (W-W) rotations.

Table II-3. Sensitivity of mean net returns over two production years to changes in canola prices for Chickasha, Lake and Perkins.

		Net return ($\$$ ha^{-1} y^{-1})[†‡]		
Rotation[§]	Canola price	Chickasha	Lake	Perkins
C-W	$\$0.53$ kg^{-1}	325a	251a	130a
C-W	$\$0.40$ kg^{-1}	197b	123b	24b
C-W	$\$0.27$ kg^{-1}	69c	-5c	-83d
W-W		-46d	-118d	-48c

[†] Expected net returns to land, machinery fixed costs for the machines used to prepare the seedbed and plant, labor, overhead and management and a wheat price of $\$0.21$ kg^{-1}.
[‡] Means in the same column followed by a common letter are not significantly different at $P \leq 0.05$ by the least square means test.
[§] Canola-wheat (C-W) and wheat-wheat (W-W) rotations.

Table II-4. Sensitivity of mean net returns over two production years to changes in canola price for Lahoma.

			Net return (\$ ha^{-1} y^{-1})[†‡]		
			Canola price		
Rotation[§]	Setup year herbicide	2009 herbicide	\$0.27 kg^{-1}	\$0.40 kg^{-1}	\$0.53 kg^{-1}
C-W	No herbicide	No herbicide	-103c	-28d	48cd
C-W	No herbicide	Glyphosate	26abc	179a	332a
C-W	No herbicide	Glyphosate fb.[¶] Glyphosate	2abc	152abc	302a
C-W	No herbicide	Quizalofop	-11abc	129abcd	268ab
C-W	No herbicide	Clethodim	-4abc	139abc	282ab
C-W	No herbicide	Trifluralin	-13abc	124abcd	261ab
C-W	No herbicide	Trifluralin fb. Quizalofop	-10abc	135abc	280ab
C-W	No herbicide	Trifluralin fb. Clethodim	-10abc	137abc	283ab
C-W	Pinoxaden	No herbicide	-25abc	89abcd	204abc
C-W	Pinoxaden	Glyphosate	28ab	181a	334a
C-W	Pinoxaden	Glyphosate fb. Glyphosate	12abc	165ab	318a
C-W	Pinoxaden	Quizalofop	16abc	166ab	316a
C-W	Pinoxaden	Clethodim	19abc	167ab	315a
C-W	Pinoxaden	Trifluralin	31ab	142abc	254ab
C-W	Pinoxaden	Trifluralin fb. Quizalofop	-1abc	148abc	297a
C-W	Pinoxaden	Trifluralin fb. Clethodim	-2abc	151abc	304a
C-W	Imazamox + MCPA	No herbicide	-86bc	4cd	94bcd
C-W	Imazamox + MCPA	Glyphosate	37ab	187a	336a
C-W	Imazamox + MCPA	Glyphosate fb. Glyphosate	22abc	170ab	319a
C-W	Imazamox + MCPA	Quizalofop	5abc	147abc	290a
C-W	Imazamox + MCPA	Clethodim	21abc	164ab	307a
C-W	Imazamox + MCPA	Trifluralin	-7abc	132abc	271ab
C-W	Imazamox + MCPA	Trifluralin fb. Quizalofop	-21abc	124abcd	269ab
C-W	Imazamox + MCPA	Trifluralin fb. Clethodim	-3abc	147abc	297a
W-W	Pooled across treatments		43a	43bcd	43d

[†] Expected net returns to land, machinery fixed costs, labor, overhead and management.
[‡] Means in the same column followed by a common letter are not significantly different at $P \leq 0.05$ by the least square means test.
[§] Canola-wheat (C-W) and wheat-wheat (W-W) rotations.
[¶] Followed by.

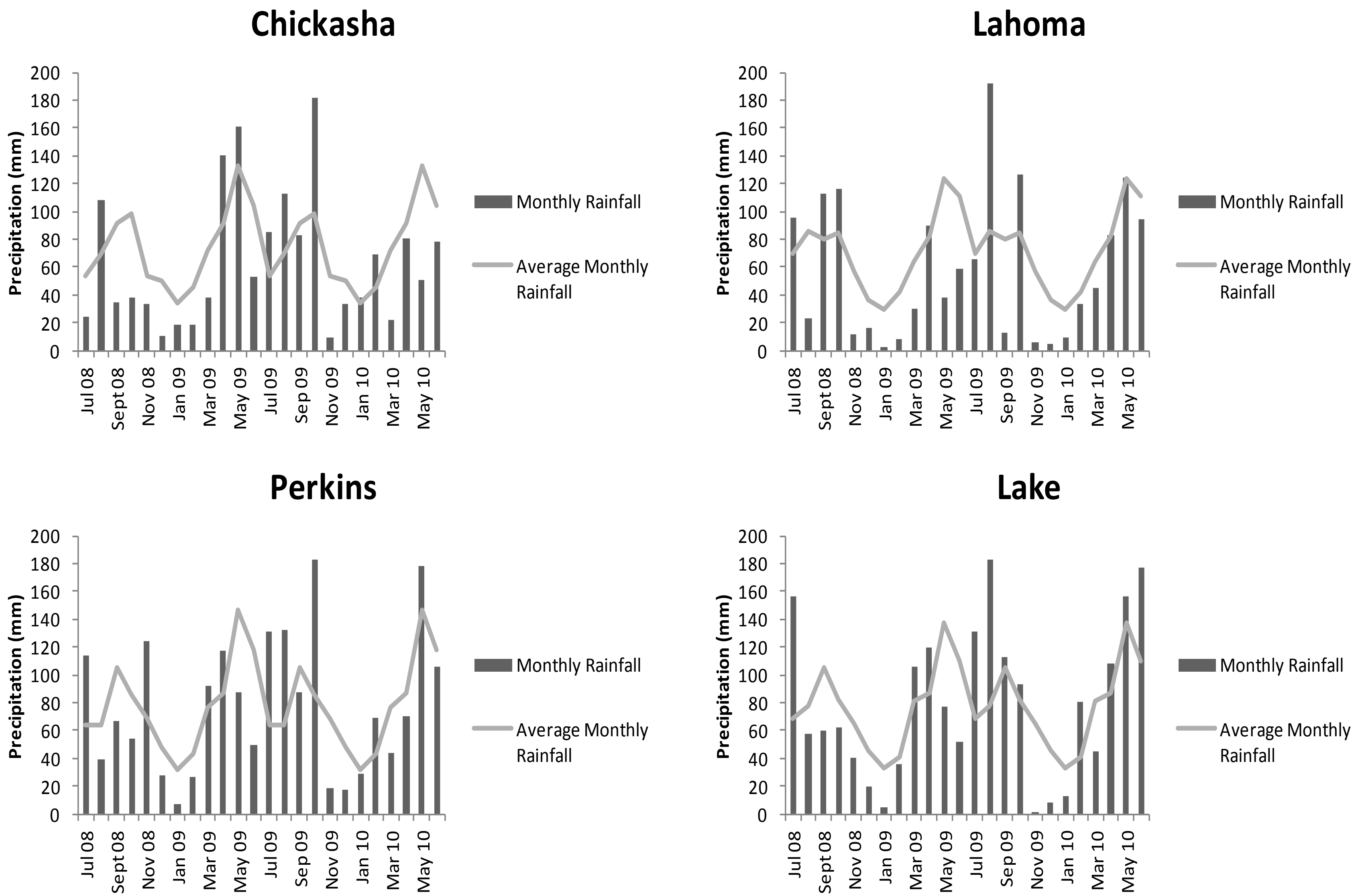

Figure II-1. Rainfall totals by month for Chickasha, Lake, Perkins, and Lahoma for production years 2009 and 2010.

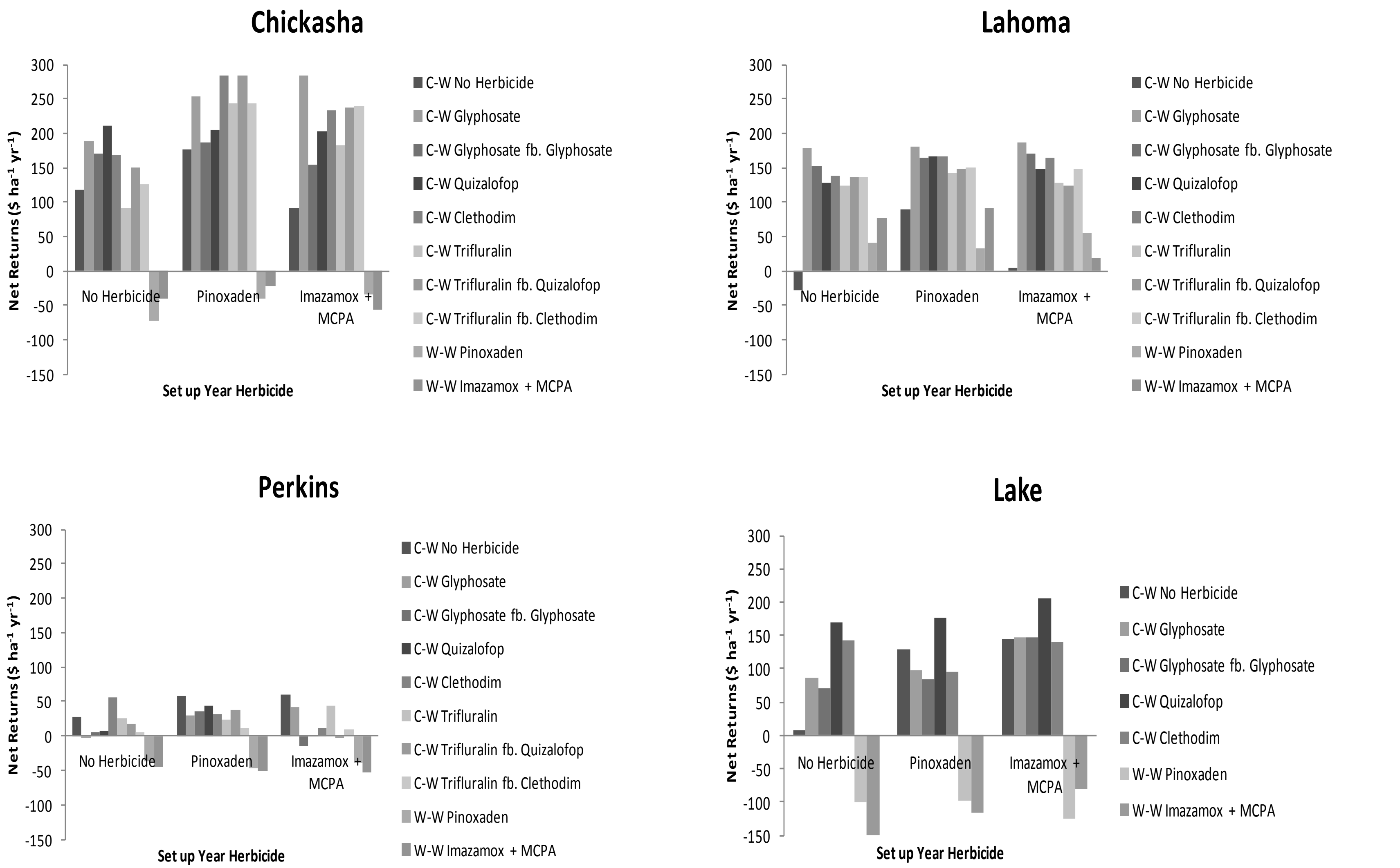

Figure II-2. Net returns for canola-wheat rotation and continuous wheat for each of four sites by setup year herbicide and herbicide used in production year 2009.

CHAPTER III

PRODUCING CELLULOSIC FEEDSTOCK FOR A BIOREFINERY: FORAGE SORGHUM VERSUS SWITCHGRASS

Abstract

Many resources have been devoted to the research and development of lignocellulosic feedstocks such as switchgrass for biofuel production. Switchgrass and forage sorghum have both been identified as high yielding dedicated energy crops. This research was conducted to determine and compare the cost to deliver a year round flow of biomass to a biorefinery for a system using forage sorghum exclusively and a system using switchgrass exclusively. A multi-region, multi-period, monthly time-step, mixed integer mathematical programming model was used to determine the cost to deliver a steady flow of biomass to a biorefinery. The model is designed to determine the optimal location of a biorefinery requiring a flow of 3,630 Mg of biomass per day from among eleven locations, the area and quantity of feedstock harvested in each county by land category, the number of mowing units and baling units necessary for harvest and the cost to produce, harvest, store and transport a continuous flow of biomass to a biorefinery. The estimated cost of land rent, establishment, maintenance, fertilizer, harvest, storage and transportation is \$60 Mg^{-1} for switchgrass and \$74 Mg^{-1} for forage sorghum. The difference in cost between switchgrass and forage sorghum is primarily due to harvest costs which are estimated to be \$13 Mg^{-1} greater for forage sorghum. Harvest costs for forage sorghum are greater than for switchgrass because the forage sorghum system requires 37 more cutting units

and 83 more raking-baling-stacking units than the switchgrass system. Based on the assumptions used in the study for Oklahoma conditions, the switchgrass system is economically preferable to the forage sorghum system for producing and delivering a year round flow of biomass to a biorefinery.

Introduction

Much attention and many resources have been devoted to the research and development of lignocellulosic feedstocks for biofuel production. The U.S. Energy Independence and Security Act of 2007 (EISA) mandates that U.S. retailers sell 136 billion L yr^{-1} of biofuels by the year 2022 if they are produced, with 79 billion L yr^{-1} expected to be forthcoming from lignocellulosic feedstocks such as urban waste, forest biomass, and biomass from dedicated energy crops (Congress, 2007). Switchgrass (*Panicum virgatum* L.) is a potential dedicated energy crop that has received considerable attention and that may need to be produced at some level to meet EISA mandates (Duffy and Nanhou, 2001; Sanderson et al., 2006; Perrin et al., 2008). Switchgrass is considered a potential dedicated energy crop in Oklahoma because it has higher yields than other warm season grasses such as kleingrass (*Panicum coloratum* L.), johnsongrass (*Sorghum halepense* L. Pers), and bermudagrass (*Cynodon dactylon* L. Pers) among others (Rogers et. al, 2012) as well as yielding more biomass than other potential dedicated energy crops in other parts of the United States.

Another crop that has been proposed for evaluation as a potential dedicated energy crop is forage sorghum (*Sorghum bicolor* L. Moench). Sorghum has broad genetic diversity which provides the opportunity to develop biomass sorghum adapted to diverse climates (McCutchen et al., 2008). Rooney et al. (2007, pg. 149) state that "…several independent factors … clearly designate sorghum as a superior choice for bioenergy production." The factors that Rooney et al. (2007) specify include sorghum's yield potential and composition, water-use efficiency and drought tolerance, established production systems, and the potential for genetic improvement using traditional and genomic approaches. McCutchen et al. (2008, pg. 120) add that “Sorghum is of particular interest because it is the only annual, high-tonnage dedicated energy crop with the potential for being produced on large acreages, and it already has an existing agronomic (e.g. seed) infrastructure.” Hallam et al. (2001) found that in Iowa forage sorghum produced more biomass than alternatives including reed canarygrass (*Phalaris arundinacea* L.), switchgrass, big bluestem (*Andropogon gerardii* Vitman), alfalfa (*Medicago sativa* L.), and corn (*Zea mays* L.).

There are fundamental differences in production practices of switchgrass and forage sorghum. Switchgrass is a perennial planted once every ten or more years while forage sorghum is an annual that would require planting every year. Forage sorghum and switchgrass may be established using conventional tillage practices to till the soil and prepare a seed bed. Conventional tillage practices conducted annually on a field increase the risk of soil erosion relative to that of a perennial grass that requires reseeding no more than once per decade. Annual crops such as forage sorghum increase the risk of soil erosion relative to that of perennial grasses such as switchgrass.

Land use decisions also differ between annual and perennial crops. A perennial crop would require the biorefinery to engage in long term leases either for production or for land to manage. The biorefinery may have to pay a premium to obtain long term leases that reduce the land owner’s future options. However, a long term lease may be prudent to insure that that biorefinery has a source of feedstock for the life of the facility. Another fundamental difference between switchgrass and forage sorghum produced for biofuel is that they have different fertilizer requirements (Thomason et al., 2004) (Table III-1).

Although forage sorghum has the potential to have greater yields than perennial dedicated energy crops such as switchgrass, its economic competitiveness with switchgrass is less concrete. Switchgrass production costs are well documented using both enterprise budgeting (Duffy and Nanhou, 2001; Hallam et al., 2001; Perrin et al., 2008) and mathematical programming models (Graham et al., 2000; Tembo et al., 2003; Mapemba et al., 2008; Haque, 2010; Epplin and Haque, 2011). Conversely, the production costs of forage sorghum for biomass are not as well documented. Most previous forage sorghum research has been designed to determine the most economical production practices for producing livestock forage. Much of this prior work has focused on forage sorghum used as silage for livestock (Dumler et al., 2009; Colombini et al., 2010). Depending on the end use of forage sorghum and thus the desired characteristics of the crop at harvest, cultural practices for production may differ. For instance, forage sorghum used for livestock feed benefits from a high protein level for nutritive reasons. Conversely, a high protein level may be undesirable for a biorefinery feedstock (Kruse et al., 2005).

This research attempts to compare the economic competitiveness of forage sorghum relative to switchgrass as a biorefinery feedstock. Due to the limited information of the most economically efficient method of converting switchgrass and forage sorghum to biofuel and due to the lack of information with regards to costs associated with the facilities required for conversion, switchgrass and forage sorghum are modeled and analyzed separately. Though the costs of conversion, desired feedstock quality attributes and the necessary facilities are unknown, it is possible to calculate the cost to produce and deliver a steady supply of feedstock to a biorefinery.

For a dedicated energy crop production system to be feasible, the crop and the conversion process must be economically competitive with alternatives. The objective of this research is to determine and compare the cost to deliver a year round flow of biomass to a biorefinery for both a system that uses forage sorghum exclusively and a system that uses switchgrass exclusively. This information will be useful to determine the cost of delivering a flow of forage sorghum biomass to a biorefinery throughout the year relative to the cost of delivering a flow of switchgrass.

Conceptual Framework

Annual crops such as corn and soybeans had well established production and marketing infrastructure as food and feed sources, prior to their use as feedstocks for ethanol and biodiesel.

Infrastructure to produce and deliver lignocellulosic feedstocks such as switchgrass and forage sorghum does not exist. In 2011 U.S. farmers planted nearly 129.2 million ha to major crops which included 37.4 million ha of corn and a little over 30.4 million ha of soybeans (USDA-NASS, 2011). To meet the mandate of 79 billion L yr^{-1} of biofuels from lignocellulosic sources by 2022, with a conversion rate of 334 L Mg^{-1} of biomass, 237 million dry Mg of biomass would be required (Epplin and Haque, 2011). If a crop such as switchgrass or forage sorghum is used to meet the mandate yields 6.7 dry Mg ha^{-1} yr^{-1} then 27.1 million ha would be required; a crop yield of 15.7 Mg ha^{-1} yr^{-1} would require 11.7 million ha be planted to the dedicated energy crop (Epplin and Haque, 2011).

To meet the mandate, a lignocellulosic biorefinery must procure biomass feedstock. The Conservation Reserve Program (CRP) had an enrollment of approximately 12.6 million ha in 2011 and is an example of procuring large quantities of cropland (USDA-FSA, 2011). The development of an economically viable biofuels program using lignocellulosic feedstocks produced on cropland would have a sizable impact on U.S. land use. The U.S. Billion-Ton Update reasoned that 16 to 24 million ha of cropland and pasture could be displaced by energy crops (U.S. Department of Energy, 2011), but it does not address the logistics that would be required to provide a continuous flow feedstock to a biorefinery throughout the year

The optimal size of a cellulosic biorefinery is not known, but economies of scale suggest the industry will "be characterized by regionally dominant, large capacity biorefineries" (Carolan et al., 2007, p. 7). Kazi et al. (2010) and Wright et al. (2010) budgeted for 2,000 dry Mg per day. Larger biorefineries are possible and could require as much as 4,000 dry Mg per day. Regardless of the average feedstock yield, a substantial quantity of land would be necessary to fulfill the needs of a 2,000 to 4,000 dry Mg per day biorefinery that operates year round. The most economically efficient method for obtaining the quantity of land required in the vicinity of a biorefinery remains to be determined. Rational land owners would not enter into biomass feedstock production until a market is available nor would a rational investor invest in a biorefinery that did not have a certain supply of feedstock for the life of the plant (Epplin and Haque, 2011).

A biorefinery could attempt to acquire feedstock for the daily needs of a plant that operates year round through: (1) a spot market, (2) a vertically coordinated system in which a biorefinery either contracts with individual farmers (Epplin et al., 2007; Larson et al., 2008) or contracts with a cooperative to produce, harvest, store and transport feedstock (Jensen et al., 2011) or (3) creating a vertically integrated system where the biorefinery leases land and performs all the duties of production, harvest, storage and transportation (Tembo et al., 2003; Mapemba et al., 2008).

Since an infrastructure for producing and marketing biomass feedstock does not exist and since biomass feedstock has few alternative uses, it would be very risky for a biorefinery to rely on a spot market. A vertically coordinated system in which the biorefinery contracts with individual producers or with a cooperative could develop (Hayenga et al. 1996). Contracts could be designed to entice farmers to establish dedicated energy crops such as switchgrass or forage sorghum. Contract provisions could address issues such as drought, flooding, or wildfires.

The third option for a biorefinery to obtain biomass is through a vertically integrated system. Weyerhaeuser Company which is in the timberland management, wood products, cellulose fiber, containerboard and real estate business is an example of vertical integration of a company that uses lignocellulosic feedstock. Through either ownership or leases, Weyerhaeuser has rights to millions of hectares of timber land. Due to the geographical concentration of landholdings and through long-term relationships, Weyerhaeuser creates a cost advantage by contracting timber harvest and using the timber in one of their many business segments (Weyerhaeuser, 2012). Studies suggest a biobased products industry can be efficiently organized with a vertically integrated business plan (Rosenthal, 2006; Chan and Reiner, 2011). A biorefinery could obtain land through long-term leases and then produce, harvest, store and transport a dedicated energy crop to the biorefinery to produce biobased products. One potential advantage of a vertical integrated biorefinery system is that similar to the integrated timber companies, production, harvest, storage, and delivery of feedstock could be centrally managed and coordinated. This system has the potential to quickly identify and reduce bottlenecks and achieve cost efficiencies by managing quality throughout the field to products chain. Acquiring land use rights through long term leases would allow the biorefinery to coordinate production, harvest, storage and transportation of feedstock to the biorefinery to meet the year round daily demand of biomass to run the conversion facility at full capacity.

Fewell et al. (2011) conducted a stated choice survey to determine farmers' willingness to grow a dedicated energy crop in three different regions in Kansas under several different contractual arrangements. One of those contractual arrangements was based on the required net returns above CRP rental rates that would be necessary for a farmer to grow a dedicated energy crop. Assuming an adequate quantity of land can be obtained by paying more than the market rental rate (Fewell et al., 2011) then production, harvest, storage and transportation are the other factors to be coordinated. A number of studies have estimated production, harvest, storage and transportation cost of switchgrass (Epplin, 1996; Perrin et al., 2008; Brechbill et al., 2011) and production and harvest cost of forage sorghum (Hallam et al., 1997; McCorkle et al., 2007; Dumler et al. 2009). Many of these cost estimates were budgeted similar to traditional crops with a narrow harvest window (one time period), usually when dry matter yield is at a maximum. Yield per hectare would be maximized in this system, but it does not guarantee the system is the most efficient for delivering a year round flow of biomass to a biorefinery (Epplin and Haque, 2011).

The harvest window for obtaining maximum yield from a single annual harvest may be relatively narrow. For a given annual biomass requirement, the number of required harvest machines will depend on the length of the harvest window, the weather, and the number of harvest days. A vertically integrated system designed to maximize profit would include the most economically efficient plan for producing, harvesting, storing, and delivering a flow of feedstock to an optimally located conversion facility year round. Therefore, a vertically integrated firm may spread harvest over many time periods (months). Extending the harvest window could reduce the investment required in harvest machines necessary to supply the biorefinery as well as reduce the amount of storage space needed. Extending the harvest window would require additional land for growing feedstock due to the lower average yield that is expected with an extended harvest window. Harvesting before dormancy could also require more nitrogen for feedstocks such as switchgrass because studies have determined that if harvest is delayed until after senescence some proportion of the nutrients translocate from the foliage to the crown and rhizomes (Reynolds et al., 2000; Vogle et al., 2002). However, annuals such as forage sorghum do not translocate nutrients to the root system to the same degree that is experienced with switchgrass (USDA-NRCS, 2009).

A biorefinery has a daily demand of feedstock to meet full capacity. Centrally managed feedstock transportation systems could be designed to enhance the probability of timely delivery of feedstock.

A mathematical programming model designed to maximize the net present value of a biomass feedstock production and biofuel processing, field-to-fuel system was constructed and solved by Tembo (2000). Mapemba (2005) enhanced several aspects of the Tembo (2000) model most notably by including the number of harvest machine as a choice integer variable. This followed from the coordinated harvest unit system designed by Thorsell et al. (2004). Hwang (2007) enhanced the Mapemba (2005) model by using historical weather data to determine distributions of suitable harvest days by month. In most months, the number of suitable mowing days exceeds the number of suitable baling days. Hwang (2007) built separate integer mowing unit and integer raking-baling-stacking unit activities.

Haque (2010) modified the Hwang (2007) version of the model by incorporating estimates of switchgrass yield response to fertilizer for alternative harvest months based on data from a multiyear field trial. Switchgrass harvested in July results in a lower expected yield and a greater expected nitrogen requirement than switchgrass harvested in October. Haque (2010) also rebuilt the model equations used to estimate feedstock transportation costs following a method developed by Wang (2009). In addition, Haque (2010) included improved pasture land along with cropland so switchgrass could compete for both land types.

The first extension to previous work that this study institutes is that it analyzes both a forage sorghum system exclusively and a switchgrass system exclusively whereas the previous studies did not include forage sorghum. Secondly, land rental rates for cropland and improved pasture land were calculated using the Fewell et al. (2011) estimate of the required premium above average county CRP rental rates (Table III-2) that would be required to lease sufficient quantities of land. Lastly, county level switchgrass yields were updated and forage sorghum yields were added to the model based on revisions produced by Oak Ridge National Laboratory (Jager et al., 2010; U.S. Department of Energy, 2011).

The model includes all 77 Oklahoma counties as individual production regions as well as 11 potential biorefinery locations across the state. Switchgrass and forage sorghum biomass yield estimates for each production region were obtained from Oak Ridge National Laboratory (Jager et al., 2010; U.S. Department of Energy, 2011) (Table III-2, Figure III-1). Yields for cropland and improved pasture land are not differentiated (U.S. Department of Energy, 2011). Switchgrass was modeled as having a harvest window starting in July and ending in March with no harvest expected in April, May or June due to potential damage to future year's plant growth. Forage sorghum production was modeled to be continuously cropped on the same land year after year with harvest modeled to start in October and end in February. Forage sorghum harvest is delayed until October because it is a later maturing species than switchgrass and because it has a high moisture content which makes it difficult to dry forage sorghum to a low enough moisture content to safely bale. Forage sorghum is assumed to be baled in this study instead of chopped because when a feedstock is chopped it is more difficult and costly to store and transport than when baled. Secondly, the moisture content of forage sorghum may be in excess of 60% when chopped which results in transporting large amounts of water weight which increases transportation costs. For some conversion processes, high moisture feedstocks are less efficient for conversion resulting in expensive drying required before conversion (Schnepf, 2010). Forage sorghum harvest is modeled to end in February because it has a higher incidence of lodging which makes it more difficult to harvest (Marsalis and Bean, 2010).

The model is constructed so switchgrass can be produced on both cropland and improved pasture land whereas forage sorghum production is only modeled for cropland. Forage sorghum is limited to cropland due to soil erosion concerns on marginal lands. Erosion concerns associated with annual crops being produced on marginal lands were verified in screening trials (Wright and Turhollow, 2010). Hallam et al. (2001) argue the potential for erosion may preclude forage sorghum from use on sloping soils. Soil erosion for annuals such as sorghum was found to be five times greater than for perennials such as switchgrass (Hallam et al., 2001; Wright and Turhollow, 2010). Switchgrass was allowed on both cropland and improved pasture land because perennial grasses such as switchgrass reduce soil loss on sloping lands while providing an opportunity to produce crops on erosive land (Wright and Turhollow, 2010).

The model limits biomass production in a production region by restricting area usage to no more than 10% of a county’s cropland and no more than 10% of a county’s improved pasture land. The restriction on a county’s area usage is based on data from the Census of Agriculture (USDA, 2002). It was assumed that cropland could be acquired for a long-term lease rate above average CRP rental rates (Data.gov, 2010). The long-term lease rate for cropland for each county was calculated by adding a fixed amount of \$49 ha^{-1} to the average CRP rental rate for that county as described in Fewell et al. (2011). Long term lease rates for improved pasture land were derived by adding \$76 ha^{-1} to the 2010 average county pasture rental rate (USDA-NASS, 2010). The rental rate assumptions used in the model are designed to exceed the opportunity costs of alternative production options and to account for increased land-lease rates that would likely occur due to the construction of a biorefinery in near proximity to that land and thus attract landowners to enter into long-term leases for biofuel feedstock production.

Biomass harvest and storage costs are derived from the integrated harvest unit concept developed by Thorsell et al. (2004) and later revised by Hwang (2007). Machinery requirements for harvest include machines for mowing, raking, baling, and stacking. The machinery complements for a mowing unit include a self-propelled windrower (140 kW) with a 4.9 m rotary header and a laborer. The harvest unit modeled for raking, baling, transport and stacking consists of three wheel rakes, three 40 kW tractors, three balers, three 147 kW tractors, a field transporter and seven laborers. A single wheel rake consists of two 3 m rakes pulled in tandem. A baler constructs a 1.2 m × 1.2 m × 2.4 m solid rectangular bale. The mowing unit and harvest unit are included in the model as integer variables.

The balers used in the model construct large rectangular bales. The moisture content of the biomass should be no more than 15% when baled because the higher the moisture content when baled, the higher the incidence of mold, premature fermentation, and potential spontaneous combustion. The moisture content restriction was a major determinant in modeling the number of days per month safe for baling both switchgrass and forage sorghum. It is assumed forage sorghum requires twice as many days as switchgrass to reach a moisture content safe for baling because it has a higher moisture content relative to switchgrass. For most months, the number of mowing days exceeds the number of safe baling days, and in addition, the number of mowing days and baling days differs across counties because harvest largely depends on weather (Hwang et al., 2009).

Eleven potential plant locations are considered in the model: Blaine, Canadian, Carter, Garfield, Grady, Kay, Okmulgee, Payne, Pontotoc, Washington and Woods. The potential biorefinery sites were selected considering biomass relative density and availability of road infrastructure.

Material And Methods

Building on and extending the work of Tembo et al. (2003), Hwang (2007), Mapemba et al. (2008), Haque (2010), and Epplin and Haque (2011), a multi-region, multi-period, monthly time-step, mixed integer mathematical programming model was used to determine the cost to deliver a steady flow of biomass to a biorefinery using either switchgrass or forage sorghum as the feedstock. The model is designed to determine the optimal location of a biorefinery that requires a flow of 3,630 Mg of biomass per day from among eleven locations, the area and quantity of feedstock harvested in each county by land category, the number of mowing units and baling units necessary for harvest and the cost to produce, harvest, store and transport a continuous flow of biomass to a biorefinery. The objective function is constructed to maximize the net present value (*NPV*) of the system:

$$\max_{\substack{Q_{jm},A_{ilm},XT_{ijkm}XSIP_{ikm},X_{ilm},XP_{jkm},\\ XSI_{ikm},XSN_{ikm},XSJ_{jkm},HUM,HUB}} NPV = \left\{\sum_{m=1}^{M}\left(\sum_{j=1}^{J}\rho Q_{jm} - \sum_{i}^{I}\sum_{k}^{K}\delta_k\sum_{l=1}^{L}A_{ilm} - \sum_{i}^{I}\sum_{k}^{K}\eta_{ik}\sum_{l=1}^{L}A_{ilm} - \sum_{i}^{I}\sum_{k}^{K}\nu_{ik}\sum_{l=1}^{L}A_{ilm} - \sum_{i=1}^{I}\sum_{l=1}^{L}\alpha_{lm}A_{ilm} - \sum_{i=1}^{I}\sum_{l=1}^{L}\gamma_{lm}A_{ilm} - \sum_{i}^{I}\sum_{j}^{J}\sum_{k}^{K}\tau_{ij}XT_{ijkm} - \sum_{i=1}^{I}\sum_{k=1}^{K}\Gamma_k XSIP_{ikm}\right) - \sum_{j=1}^{J}\sum_{f=1}^{F}OMC_f\beta_j - \omega HUM - \varpi HUB\right\} * PVAF - \sum_{j=1}^{J}\sum_{f=1}^{F}AFC_f\,\beta_j \tag{1}$$

where tables III-3, III-4 and III-5 include descriptions of set member elements, parameters, and variables respectively.

$$\text{PVAF} = \frac{(1+r)^T - 1}{r(1+r)^T} \tag{2}$$

$$\alpha_{lm} = P^{\,n} * NIT_{lm} \tag{3}$$

$$\gamma_{lm} = P^{P} * PIT_{lm} \tag{4}$$

Equation (1) is maximized subject to a set of constraints. Equation (5) restricts total planted switchgrass or forage sorghum in each county on cropland to not exceed a set proportion of the quantity of available cropland. In this study, *BIPROP* was set to 10% and therefore limiting the quantity of cropland bid from traditional crops to produce dedicated energy crops to 10% of total cropland in the county.

$$\sum_{m=1}^{M} A_{ilm} - BIPROP * POTACRE_{il} \leq 0, \quad \forall_i, l = \text{cropland} \tag{5}$$

Similar to cropland, equation (6) restricts total planted switchgrass on improved pasture land in each county. Improved pasture land in each county was limited by setting *BIPROP*1 to 10%. Therefore, the total quantity of improved pasture land in a county that are permitted to be bid from current use and placed in switchgrass production was set to 10%.

$$\sum_{m=1}^{M} A_{ilm} - BIPROP1 * POTACRE_{il} \leq 0, \quad \forall_i, l = \text{improved pasture land} \tag{6}$$

Equation (7) is a yield balance equation used to calculate the amount of biomass produced on harvested lands.

$$\sum_{l=1}^{L} X_{ilm} - \sum_{l=1}^{L} A_{ilm} \, BYLD_{il} YAD_{km} = 0, \qquad \forall_{i,k,m} \tag{7}$$

Due to potential damage to switchgrass plants and lodging in forage sorghum, equation (8) limits harvest months. The model sets YAD_{km} equal to zero in the months of April, May, and June for switchgrass and the months of March through September for forage sorghum, resulting in no harvest during the respective months.

$$\sum_{l=1}^{L} A_{ilm} = 0 \; if \; YAD_{km} = 0, \qquad \forall_{i,k,m} \tag{8}$$

The sum of biomass transported to the plant location from each county in addition to stored biomass is set to be equivalent to the sum of current production and the usable portion of stored biomass at the source county for each month by equation (9).

$$\sum_{l=1}^{L} X_{ilm} + \theta I_k XSI_{ikm-1} - \sum_{j=1}^{J} XT_{ijkm} - XSI_{ikm} = 0, \quad \forall_{i,k,m} \tag{9}$$

Equation (10) equates total biomass quantity transported to the biorefinery plus the storage loss to quantity harvested.

$$\sum_{l=1}^{L}\sum_{m=1}^{M} X_{ilm} - \sum_{j=1}^{J}\sum_{m=1}^{M} XT_{ijkm} - (1-\theta I_k)\sum_{m=1}^{M} XSI_{ikm} = 0, \quad \forall_{i,k} \tag{10}$$

The total quantity of harvested biomass plus the quantity of biomass removed from field storage each month is set equal to the amount of biomass transported from each county to the biorefinery plus the amount of biomass placed in storage at the biorefinery (Equation 11)

$$\sum_{i=1}^{I}\sum_{l=1}^{L} X_{ilm} - \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K} XT_{ijkm} + \sum_{i=1}^{I}\sum_{k=1}^{K} XSIN_{ikm} - \sum_{i=1}^{I}\sum_{k=1}^{K} XSIP_{ikm} = 0, \ \forall_{m} \tag{11}$$

Equation (12) limits monthly biorefinery processing capacity for each location.

$$Q_{jm} - CAPP\ \beta_j \leq 0, \quad \forall_{j,m} \tag{12}$$

Equation (13) limits monthly storage capacity at biorefinery locations.

$$\sum_{k=1}^{K} XSJ_{jkm} - CAP\ \beta_j \leq 0, \quad \forall_{j,m} \tag{13}$$

Equation (14) restricts the quantity of biomass transported to the biorefinery in a month minus the quantity processed at the biorefinery in a month to be equal to the change in biomass storage inventory during the month at the biorefinery.

$$\sum_{i=1}^{I} XT_{ijkm} + \theta J_k XSJ_{jkm-1} - XSJ_{jkm} - XP_{jkm} = 0, \quad \forall_{j,k,m} \tag{14}$$

Total quantity of biomass delivered from each production region to the biorefinery is equated to the total quantity of processed biomass plus losses due to storage loss at the biorefinery in equation (15).

$$\sum_{i=1}^{I}\sum_{m=1}^{M} XT_{ijkm} - (1-\theta J_k)\sum_{m=1}^{M} XSJ_{jkm} - \sum_{m=1}^{M} XP_{jkm} = 0, \quad \forall_{j,k} \tag{15}$$

A minimum biomass inventory at the biorefinery is imposed in equation (16).

$$\sum_{k=1}^{\mathrm{K}} XSJ_{\mathrm{jkm}} - BINV\,\beta_j \geq 0, \forall_{j,m} \tag{16}$$

Equation (17) restricts ethanol production in each month to not exceed the capacity of the biorefinery.

$$Q_{jm} - \sum_{k=1}^{K} \lambda_k\, XP_{jkm} \leq 0, \quad \forall_{j,m} \tag{17}$$

The number of endogenously determined mowing harvest units in any month is restricted to not exceed the available number of mowing units (equation 18).

$$\sum_{i=1}^{I} XHUM_{im} - HUM \leq 0, \quad \forall_m \tag{18}$$

The number of raking-baling-stacking harvest units used in any month is restricted by equation (19) to not exceed the total number of raking-baling-stacking harvest units endogenously determined by the model.

$$\sum_{i=1}^{I} XHUB_{im} - HUB \leq 0, \quad \forall_m \tag{19}$$

Equations (20), (21), (22), and (23) ensure that each month's harvested biomass is less than the harvesting capacity of the total number of mowing harvest units and raking-baling-stacking harvest units.

$$CAPHUM_{im} = FWD_{im} DCAMHU_m \quad \forall_{i,m} \tag{20}$$

The monthly capacity of a mowing harvest unit is calculated by multiplying the capacity of a mowing harvest unit in month *m* by the number of field days.

$$\sum_{l=1}^{L} X_{ilm} - XHUM_{im}CAPHUM_{im} \leq 0, \quad \forall_{i,m} \tag{21}$$

$$CAPHUB_{im} = BWD_{im}DCABHU_{m} \quad \forall_{i,m} \tag{22}$$

$$\sum_{l=1}^{L} X_{ilm} - XHUB_{im}CAPHUB_{im} \leq 0, \quad \forall_{i,m} \tag{23}$$

Equation (24) equates the raking-baling-stacking capacity in each production region and each month with the mowing capacity.

$$XHUM_{im}CAPHUM_{im} - XHUB_{im}CAPHUB_{im} = 0, \quad \forall_{i,m} \tag{24}$$

Equation (25) lists non-negative decision variables. The number of mowing harvest units (*HUM*) and the number of raking-baling-stacking harvest units (*HUB*) are set to be non-negative integer values.

$$Q_{jm}, A_{ilm}, XT_{ijkm}, X_{lim}, XP_{jkm}, XSI_{ikm}, XSIP_{ikm}, X_{ilm}, XSIN_{ikm}, XSJ_{jkm}, XHUM, \tag{25}$$

and $XHUB \geq 0$

Equation (26) restricts the biorefinery location variable to be binary.

$$\beta_j \in \{0,1\} \tag{26}$$

Results

<u>Enterprise budgets</u>

The traditional way to estimate production costs is to use an enterprise budget (Griffith et al., 2010). Tables III-6 and III-7 contain cost estimates using enterprise budgets for switchgrass establishment and maintenance respectively while table III-8 contains cost estimates for forage sorghum production. It was assumed that both crops are established using conventional tillage. Local custom rates are used to reflect cost of budgeted machine operations (Doye and Sahs, 2010). These cost estimates depend on the assumption that a sufficient quantity of custom operators could be hired to perform the operations in a timely manner.

Forage sorghum and switchgrass were assumed to have dry matter yields of 14.2 and 10 Mg ha^{-1} respectively. The estimated cost to harvest and deliver switchgrass was \$72 Mg^{-1} while the estimated cost to deliver forage sorghum was \$75 Mg^{-1}. One major limitation of using enterprise budgets to estimate feedstock production cost is that the logistics are ignored. Implicitly, the budgets assume that all biomass needed for the year could be harvested and transported to the biorefinery during a very narrow window of time. The mathematical programming model can be used to address the production cost issues while considering the logistics of producing, harvesting, storing, and transporting massive quantities of biomass to an optimally located biorefinery throughout the year.

Base scenario

The model determined that the biorefinery would be optimally located in Blaine County. A summary of estimated costs, number of harvest units, harvested ha, and quantity of harvested feedstock for supplying the biorefinery with 3,630 Mg of feedstock per day from switchgrass and forage sorghum is provided in Table III-9. The estimated cost to deliver a steady flow of forage sorghum to a biorefinery is approximately \$14 Mg^{-1} greater than the estimated cost to deliver switchgrass. The estimated cost of land rent, establishment, maintenance, fertilizer, harvest, storage, and transportation is \$60 and \$74 Mg^{-1} for switchgrass and forage sorghum respectively (Table III-9; Figure III-2). The cost difference between switchgrass and forage sorghum is primarily a result of differences in harvest costs which are estimated to be \$13 Mg^{-1} greater for forage sorghum than for switchgrass.

Estimated harvest costs for forage sorghum are substantially greater than for switchgrass because the forage sorghum feedstock system requires 37 more harvest units for cutting and 83 more harvest units for baling which increases machinery ownership costs. The optimal number of harvest units for cutting switchgrass is 34 units while it is estimated that 71 units are needed for forage sorghum. The optimal number of harvest units for baling is 27 (81 40 kW tractors; 81

wheel rakes; 81 147 kW tractors; 81 balers; 27 field stackers) for switchgrass and 110 (330 40 kW tractors, wheel rakes, 147 kW tractors, and balers; 110 field stackers) for forage sorghum. The forage sorghum system requires more harvest units than the switchgrass system because approximately 1.31 million Mg of forage sorghum must be mowed, dried in the field to no more than fifteen percent moisture, and harvested in a five month window to supply a year round flow of feedstock to a biorefinery. Switchgrass has a nine month harvest window and requires fewer days to dry after cutting prior to baling. For four of the five forage sorghum harvest months at least twice as much forage sorghum is scheduled to be harvested as compared to switchgrass (Figure III-3).

An advantage of the forage sorghum system compared to the switchgrass system is that fewer ha of land are needed to supply a biorefinery year round. The forage sorghum system requires 92,387 ha of cropland to produce the required biomass to supply a biorefinery, but the switchgrass system requires 128,581 ha (78,636 ha of cropland and 49,944 ha of improved pasture land) to fully supply a biorefinery with biomass. Forage sorghum requires fewer ha of land is because it has a yield advantage over switchgrass. The average forage sorghum yield is 14.2 Mg ha^{-1} while switchgrass averages about 10 Mg ha^{-1} for the production regions selected. A second less prominent reason forage sorghum requires fewer ha of land is due to less yield loss from leaving biomass standing in the field (Table III-1).

<u>Sensitivity to changes in fuel price</u>

Table III-10 reports estimated costs, number of harvest units, harvested ha, and megagrams of harvested feedstock for supplying a biorefinery in Blaine County with feedstock from switchgrass and forage sorghum when the fuel price is doubled. The cost to deliver switchgrass increases to \$73 Mg^{-1} while the cost to deliver forage sorghum increases to \$87 Mg^{-1}. Under the base scenario it cost \$14 Mg^{-1} more to deliver forage sorghum than switchgrass, and similarly when the fuel price doubled, forage sorghum cost \$14 Mg^{-1} more to deliver to a biorefinery than switchgrass. When the fuel price increases and thus increases transportation cost, switchgrass production shifts from improved pasture land that is further from the biorefinery to cropland nearer the biorefinery (Figure III-4). The shift from improved pasture land to cropland occurs because the increased transportation cost exceeds the increased rental rate that comes with the shift from improved pasture land to cropland production and this shift in land use will continue until the rental rate for cropland exceeds the change in transportation cost. When the fuel price is doubled, the amount of improved pasture land under biomass production decreases from 49,944 ha to 48,261 ha while cropland in biomass production increases from 78,636 ha to 81,366 ha (Table III-9, Table III-10).

An increase in fuel price has little effect on how forage sorghum production is distributed across counties. The shifts in production that do occur are primarily due to cropland rental rates differing across counties and expected yields varying across counties. Feedstock production in one county shifts to counties with higher rental rates but that are closer to the biorefinery because the higher transportation costs experienced in the more distant county exceeds the land rental rate encountered in the county closest to the biorefinery when fuel prices increase. For example, production in Ellis County(expected yield of 13.2 Mg ha^{-1} and a rental rate of \$132 ha^{-1}) decreases from 5,100 ha to no production while production in Garfield County (expected yield of 12.1 Mg ha^{-1} and a rental rate of \$145 ha^{-1}) increases by more than 2,300 ha and production in Logan County (expected yield of 11.9 Mg ha^{-1} and a rental rate of \$142 ha^{-1}) increases by more than 4,100 ha. Another factor that causes production to shift when fuel price increases is if a county with a higher rental rate that is closer to the biorefinery has greater expected yields which could result in leasing fewer ha of land to supply the biorefinery.

<u>Sensitivity to changes in land rent</u>

The conceptual framework for the model is that a centrally managed biorefinery could engage in long term leases with land owners in the vicinity of the biorefinery location to lease up to 130,000 ha of land. The land lease rates reported in Table III-2 were doubled and the model solved to determine how results may change. The optimal biorefinery location remains in Blaine County (Table III-11). The estimated cost to deliver switchgrass to the biorefinery increases by \$12 Mg^{-1} from \$60 Mg^{-1} (base scenario) to \$72 Mg^{-1} when the land rental rate is doubled while the cost to deliver forage sorghum increases by \$9 Mg^{-1} from \$74 Mg^{-1} (base scenario) to \$83 Mg^{-1} when the land rental rate is doubled.

As would be expected, increasing the land rental rate increases the land rent per Mg of feedstock delivered (Table III-11, Figure III-2), but what is less obvious is that the estimated transportation cost of switchgrass increases more than the transportation cost of forage sorghum. Estimated transportation cost for switchgrass increases due to a shift in the type of land under production and where that land is located. Since switchgrass can be produced on both cropland and improved pasture land, an increase in the land rental rate decreases the amount of cropland and increases the amount of improved pasture land in feedstock production (Figure III-4). Figure III-4 illustrates how the production region encompasses a larger geographical region as well as demonstrating how fewer ha of cropland are used for switchgrass production and how more ha of improved pasture land are under production when the land rental rate increases.

The shift in production from cropland to improved pasture land that is further from the biorefinery is due to land rental rates of cropland exceeding the additional transportation costs that are experienced when production takes place in more distant counties. If we assume cropland and improved pasture land rental values increase proportionally then the geographical area of the switchgrass production region will continue to increase as land rental values increase and the amount of cropland in production will continue to decrease while the amount of improved pasture land in production will continue to increase.

Sensitivity to increased forage sorghum yield

A summary of estimated costs, number of harvest units, harvested ha, and quantity of harvested feedstock for switchgrass and forage sorghum with forage sorghum yields and fertilizer requirements are doubled is provided in Table III-12. When forage sorghum yields are doubled the difference in estimated cost to harvest and deliver a steady flow of forage sorghum versus switchgrass decreases from \$14 Mg^{-1} (base scenario) to \$2 Mg^{-1}. The estimated cost of land rent, establishment, maintenance, fertilizer, harvest, storage and transportation are \$60 and \$62 Mg^{-1} for switchgrass and forage sorghum respectively (Table III-12; Figure III-2).Harvest cost for forage sorghum are \$14 Mg^{-1} greater than for switchgrass, but forage sorghum has cost advantages in land rent, transportation, and establishment and maintenance. Lower costs are experienced in land rent and establishment and maintenance because only 47,063 hectares of land are required to supply the biorefinery which means fewer hectares of land to lease and fewer hectares of energy crops to establish and maintain. Transportation cost declines because the leased land is closer to the biorefinery and the feedstock does not have to travel as far from the field to the conversion facility.

Sensitivity to number of baling days

Safe baling requires that the mowed biomass contains no more than 15% moisture. Hwang et al. (2009) used historical weather data and forage dry-down models to determine probability distributions of the number of days per month that switchgrass could be safely baled in Oklahoma. Similar information is not available for forage sorghum. For the base model it was assumed that forage sorghum would require twice as long to dry to safe baling moisture levels and thus baling days for forage sorghum were set at half the level as for switchgrass. The number of required harvest machines and the estimate of harvest cost depend critically on this constraint on the number of forage sorghum harvest days per month. To test the sensitivity of the findings the number of harvest days for forage sorghum was set equal to the number of days modeled for switchgrass.

Table III-13 reports estimated costs, number of harvest units, harvested ha, and Mg of harvested feedstock for supplying a biorefinery with feedstock from switchgrass and forage sorghum when the constraint for available number of baling days for forage sorghum is relaxed to be the same as switchgrass. The cost to harvest and deliver forage sorghum decreases from \$74 Mg^{-1} to \$65 Mg^{-1}. Under the base scenario it cost \$14 Mg^{-1} more to deliver forage sorghum than switchgrass, but when the number of available baling days constraint is relaxed for forage sorghum, it cost \$5 Mg^{-1} more to deliver forage sorghum to a biorefinery than switchgrass. Relaxing the constraint on the number of baling days for forage sorghum reduces harvest cost from \$29 Mg^{-1} (base scenario) to \$20 Mg^{-1}. Harvest costs are reduced by \$9 Mg^{-1} because 54 fewer raking-baling-stacking units are needed to harvest the forage sorghum.

Discussion

Based on the assumptions included in the model, the switchgrass system is economically preferable to the forage sorghum system for producing and delivering a year round flow of biomass to a biorefinery. Though forage sorghum has a yield advantage over switchgrass and the forage sorghum system requires less nitrogen fertilizer per Mg, switchgrass has the advantage of a longer harvest window, more harvest days in a harvest month and the ability to be produced on both cropland and improved pasture land.

The longer harvest window is one reason switchgrass is economically preferred to forage sorghum as a feedstock to supply a biorefinery. Results confirm land and fertilizer requirements are greater for switchgrass than for forage sorghum, but the investment required for harvest machines is greater for forage sorghum than for switchgrass. The harvest machinery investment for forage sorghum is more than three times the harvest machinery investment for switchgrass (base scenario). The investment in harvest machines estimated to supply a year round flow of forage sorghum to a biorefinery is greater than the harvest machinery investment for switchgrass. The higher machinery investment for forage sorghum is the primary reason the cost to harvest and deliver forage sorghum is 54% greater than the cost to harvest and deliver switchgrass. This finding demonstrates the importance of longer harvest windows to reduce the cost to harvest biomass and that feedstocks produced in regions that enable longer harvest windows have an economic advantage over feedstocks produced in regions with relatively short harvest windows.

Forage sorghum having fewer harvestable days per month than switchgrass is another reason forage sorghum requires a larger investment in harvest machinery. Forage sorghum has a high moisture content which causes it to have a longer dry down period before it can be safely baled. With fewer days per month to harvest, more baling units are required to supply a biorefinery which increases harvest machinery costs. Therefore, there is an economic advantage for feedstocks that can reach a safe moisture content for baling more quickly if the harvest system being used requires baling and storing biomass. Forage sorghum is cost competitive with switchgrass when the number of safe baling days is the same for both feedstocks.

A third component that is capable of creating an economic advantage is the ability for the feedstock to be produced on both cropland and improved pasture land. This advantage is important when land rental rates are changing or when transportation costs change and the feedstock being produced can be shifted from one type of land to another. When rental rates for cropland increase relative to those for improved pasture land, production optimally shifts to improved pasture land until the cost to transport the biomass exceeds the change in the land rental price. Likewise, if transportation costs increase, then production on improved pasture land will decrease and production on cropland closer to the biorefinery will increase, and this shift will occur until the difference in rental rate and transportation costs are equal.

Conclusions

Switchgrass and forage sorghum have been identified as potential dedicated energy crops for cellulosic ethanol production. To determine and compare the cost to deliver a year round flow of biomass to a biorefinery, a multi-region, multi-period, monthly time-step, mixed integer mathematical programming model was developed for both switchgrass and forage sorghum. The model determines the optimal biorefinery location, the area and quantity of feedstock harvested in each county by land category, the number of mowing units and baling units necessary for harvest. The model also provides an estimate of the cost to produce, harvest, store and transport a continuous flow of biomass to a biorefinery. Based on the programming model the estimated cost to deliver a year round flow of switchgrass to a biorefinery is \$60 Mg^{-1} while the estimated cost for forage sorghum is \$74 Mg^{-1}. The advantage switchgrass has over forage sorghum is harvest costs due to both a longer harvest window and more suitable baling days per month. The greater baling days is due to smaller stems drying out faster after rain. Based on enterprise budgets that ignore the logistics of providing a flow of feedstock throughout the year, the estimated cost to deliver switchgrass is \$72 Mg^{-1} while the estimated cost for forage sorghum is \$75 Mg^{-1}. For the Oklahoma conditions modeled, assuming no difference in quality, switchgrass is economically preferable as a feedstock when compared to forage sorghum.

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Table III-1. Switchgrass and forage sorghum yield proportion and fertilizer requirements by harvest month

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Proportion of Potential Yield by Harvest Month[a]											
Switchgrass	0.80	0.75	0.70				0.79	0.86	1.00	1.00	0.90	0.85
Forage Sorghum	0.80	0.75								1.00	0.90	0.85
	Level of Nitrogen (kg N ha^{-1}) by Harvest Month											
Switchgrass	71	71	71				90	83	77	71	71	71
Forage Sorghum	101	101								101	101	101
	Level of Phosphorus (kg P_2O_5 ha^{-1}) by Harvest Month											
Switchgrass	0	0	0				11	11	11	0	0	0
Forage Sorghum	50	50								50	50	50

[a] Switchgrass harvest is not permitted in April, May, and June. Forage sorghum harvest is not permitted from March through September.

Table III-2. County yields for switchgrass and forage sorghum and county land rental rates.

	Biomass Yields[a] (dry Mg ha^{-1})		Land Rental Rates($ ha^{-1})		
County	Switchgrass	Forage Sorghum	CRP Rate[b]	Cropland[c]	Improved Pasture Land[d]
Adair	16.0	15.2	160	210	122
Alfalfa	12.1	13.5	100	149	111
Atoka	11.7	16.0	95	144	103
Beaver	12.8	0.0	78	127	95
Beckam	12.2	19.4	79	128	106
Blaine	12.3	18.5	79	128	104
Bryan	11.0	16.0	98	147	115
Caddo	11.8	16.3	89	138	109
Canadian	12.2	15.4	81	131	114
Carter	10.7	16.0	79	128	94
Cherokee	14.3	15.2	149	198	107
Choctaw	11.4	14.7	99	148	111
Cimarron	12.0	0.0	71	120	93
Cleveland	11.9	15.8	82	131	106
Coal	11.7	16.0	92	141	98
Comanche	11.2	16.1	76	126	106
Cotton	9.7	13.6	74	123	107
Craig	14.4	14.5	114	163	115
Creek	12.8	13.9	92	141	109
Custer	12.4	17.2	87	136	104
Delaware	15.2	14.5	130	179	119
Dewey	12.9	18.5	91	140	101
Ellis	13.2	17.5	82	132	95
Garfield	12.2	16.8	96	145	105
Garvin	11.3	16.3	78	128	106
Grady	11.8	14.5	68	117	110
Grant	12.2	13.5	103	153	106
Greer	10.8	13.6	80	129	103
Harmon	10.3	16.6	77	127	99
Harper	12.4	14.2	82	131	99
Haskell	12.4	14.3	120	170	104
Hughes	12.2	17.5	99	148	101
Jackson	9.8	13.6	76	126	103
Jefferson	10.0	16.0	82	132	105
Johnston	11.2	16.0	87	136	99
Kay	12.6	13.5	102	152	109
Kingfisher	11.7	13.5	80	130	111
Kiowa	11.2	16.6	88	137	103
Latimer	13.4	14.6	111	161	106

Table III-2. County yields for switchgrass and forage sorghum and county land rental rates.

Le Flore	13.6	14.1	116	166	105
Lincoln	12.3	13.5	88	137	100
Logan	11.9	13.5	93	142	104
Love	10.4	16.0	81	130	103
Major	12.0	18.8	88	138	103
Marshall	10.6	16.0	86	135	100
Mayes	13.7	13.5	128	177	120
McClain	11.8	14.0	80	129	104
McCurtain	13.2	14.7	106	155	101
McIntosh	12.5	13.8	99	149	111
Murray	11.7	16.0	82	131	103
Muskogee	12.6	16.2	119	168	117
Noble	12.3	13.5	98	147	107
Nowata	13.8	15.2	112	162	114
Okfuskee	12.5	13.9	92	141	101
Oklahoma	12.1	15.2	87	136	104
Okmulgee	12.8	16.6	88	138	103
Osage	13.2	15.2	105	154	112
Ottawa	15.0	15.5	95	145	136
Pawnee	12.7	14.5	99	149	104
Payne	12.6	14.7	93	142	109
Pittsburg	12.5	15.2	103	152	101
Pontotoc	12.0	16.0	89	138	100
Pottawatomie	11.9	14.3	91	140	101
Pushmataha	13.0	14.6	103	152	105
Roger Mills	13.0	18.5	75	125	96
Rogers	13.5	14.5	116	165	111
Seminole	11.9	13.9	94	143	101
Sequoyah	13.4	15.8	143	182	107
Stephens	11.1	14.0	76	126	107
Texas	12.6	0.0	84	124	95
Tillman	9.7	14.2	85	135	105
Tulsa	13.1	14.5	101	151	101
Wagoner	12.9	15.2	120	166	107
Washington	13.3	14.5	107	158	110
Washita	11.8	18.8	87	135	106
Woods	12.2	13.5	84	140	98
Woodward	12.8	13.5	82	135	96

[a] Biomass yields are expected county yields obtained from Oak Ridge National Laboratory (Jager et al., 2010; U.S. Department of Energy, 2011).
[b] County average Conservation Reserve Program (CRP) rental rates for 2010 (Data.gov, 2010).

[c] Land rental rates for cropland were calculated using Fewellet al.'s (2011) required return above average county Conservation Reserve Program (CRP) rental rates (Data.gov, 2010). The calculated cropland rental rate used is \$49 ha^{-1} greater than the CRP rental rate.

[d] Improved pasture rental rates were calculate using USDA-NASS (2010) county cash rental rates for pasture plus a return above the county cash rental rate for pasture (Fewell et al., 2011). The calculated improved pasture rental rate used is \$76 ha^{-1} greater than the USDA-NASS (2010) pasture rental rate.

Table III-3. Descriptions of set member elements

Index	Description
M	Months: m = {Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec}
J	Prospective biorefinery locations: j = {Blaine, Canadian, Carter, Garfield, Grady, Kay, Okmulgee, Payne, Pontotoc, Washington, Woods}
I	Biomass source counties: i = {77 Oklahoma counties}
F	Facilities: f = {processing, storage}
K	Switchgrass or forage sorghum production system: k = {established on cropland, established on improved pasture land}
L	Land class: l = {cropland, improved pasture land}

Table III-4. Descriptions of parameters.

Parameter	Description
ρ	Price of ethanol ($ L^{-1})
P^n	Price of nitrogen ($ kg^{-1})
P^P	Price of P_2O_5 ($ kg^{-1})
δ_k	Cost of producing switchgrass or forage sorghum with system *k* excluding cost of fertilizer, and harvest ($ ha^{-1})
η_{ik}	Establishment cost for county *i* by production system *k* ($ ha^{-1})
ν_{ik}	Land rent for county *i* by production system *k* ($ ha^{-1})
α_{lm}	Cost of applied nitrogen to land class *l* harvested in month *m* ($ ha^{-1})
γ_{lm}	Cost of applied P_2O_5 to land class *l* harvested in month *m* ($ ha^{-1})
τ_{ij}	Round-trip cost of transporting biomass from county *i* to biorefinery located at *j* ($ Mg^{-1})
Γ_k	Cost of storing biomass in the field with production system *k* ($ Mg^{-1})
ω	Annual cost of a mowing unit ($ per unit)
ϖ	Annual cost of a raking-baling-stacking unit ($ per unit)
θI_k	Usable proportion of biomass from production system *k* stored in field (1 – storage loss %)
θJ_k	Usable proportion of biomass from production system *k* stored at biorefinery (1 – storage loss %)
λ_k	Quantity of ethanol produced from a ton of biomass from production system *k* (L Mg^{-1})
$BIPROP$	Proportion of cropland in each county available for producing biomass
$BIPROP1$	Proportion of improved pasture land in each county available for producing switchgrass
NIT_{lm}	Nitrogen applied to land class *l* when harvested in month *m* (kg ha^{-1})
PIT_{lm}	P_2O_5 applied to land class *l* when harvested in month *m* (kg ha^{-1})
$POTACRE_{il}$	Hectares of land class *l* in county *i*
YAD_{km}	Biomass yield adjustment factor for production system *k* harvested in month *m*
$BYLD_{il}$	Biomass yield from production in county *i* on land class *l* (Mg ha^{-1} yr^{-1})
OMC_f	Biorefinery operating and maintenance cost for facility of type *f* ($ yr^{-1})
AFC_f	Biorefinery investment cost for facility of type *f* made once in year 0 ($)
$PVAF$	Present value of annuity
T	Plant life (years)
r	Discount rate (%)
$BINV$	Minimum biomass inventory for the plant (Mg per month)
$CAPP$	Processing capacity of the biorefinery (L of ethanol per month)
CAP	Storage capacity of the biorefinery (Mg of biomass)
FWD_{im}	Field work days suitable for mowing in county *i* in month *m*
$DCAMHU_m$	Daily capacity of a mowing harvest unit in month *m*
$CAPHUM_m$	Capacity of mowing harvest unit in month *m*
BWD_{im}	Field work days suitable for raking-baling-stacking in county *i* in month *m*
$DCABHU_m$	Daily capacity of a raking-baling-stacking harvest unit in month *m*
$CAPHUB_m$	Capacity of raking-baling-stacking harvest unit in month *m*

Table III-5. Description of variables

Variable	Description
NPV	Net present value of the system ($)
Q_{jm}	Quantity of ethanol produced in month *m* by a biorefinery at location *j* (L)
A_{ilm}	Land harvested in month *m* from land class *l* in county *i* (hectares)
XSI_{ikm}	Biomass stored in field in month *m* from system *k* in county *i* (Mg)
$XSIP_{ikm}$	Biomass placed into storage in month *m* from system *k* in county *i* (Mg)
XT_{ijkm}	Biomass transported from county *i* in month *m* from system *k* to a biorefinery at location *j* (Mg)
HUM	Integer variable representing the total number of mowing harvest units
HUB	Integer variable representing the total number of raking-baling-stacking harvest units
X_{ilm}	Biomass harvested in month *m* from land class *l* in county *i* (Mg)
XP_{jkm}	Biomass processed in month *m* from system *k* at location *j* (Mg)
XSI_{ikm}	Biomass stored as source *i* from system *k* in month *m* (Mg)
XSJ_{jkm}	Biomass stored in month *m* from system *k* at location *j* (Mg)
$XSIN_{im}$	Biomass removed from field storage in month *m* and county *i* (Mg)
$XHUM_{im}$	Proportion of a harvest unit for mowing used in month *m* in county *i*
$XHUB_{im}$	Proportion of a harvest unit for raking-baling-stacking used in month *m* in county *i*
β_j	Binary variable for biorefinery location *j* (1 if built, 0 otherwise)

Table III-6. Conventional tillage switchgrass establishment budget

Item	Unit of Measure	Price per unit	Quantity	Value
"Cash" Costs				
Land Rental[a]	ha	$148.26	1	148.26
Switchgrass Seed	kg PLS	$13.23	5.6	74.13
Phosphorus (P_2O_5)	kg	$1.17	22	26.19
Fertilizer Application	ha	$10.23	1	10.23
Chisel Plow	ha	$27.18	1	27.18
Discing	ha	$24.71	3	74.13
Cultipacking (firming seedbed)	ha	$22.24	1	22.24
Seeding	ha	$33.11	1	33.11
Rotary mowing (cutting tops of tall weeds)	ha	$8.65	1	8.65
Herbicide (Roundup PowerMax (glyphosate))	L	$7.78	1.3	10.23
Herbicide (broadleaf, post emerge)	ha	$11.12	1	11.12
Herbicide Application	ha	$12.21	2	24.41
Annual Operating Capital	$	$0.07	469.89	32.89
Total "Cash" Costs	ha			$502.78
Establishment Prorated over 10 years	annual	$502.78	7%	$71.58

[a] The assumed land rental rate is from Griffith et al. (2010).

Table III-7. Switchgrass maintenance for biomass production budget

Item	Unit of measure	Price per unit	Quantity	Value
Harvested yield (dry matter)	Mg ha^{-1}		10	
"Cash" costs				
Establishment prorated over 10 years	ha	$71.58	1	71.58
Land rent[a]	ha	$148.26	1	148.26
Nitrogen	kg	$1.01	71	71.61
Fertilizer application	ha	$10.23	1	10.23
Swathing	ha	$32.49	1	32.49
Raking	ha	$9.59		9.59
Baling (large square bales 4x4x8)(544 kg)	bale	$14.60	18.4	268.22
Hauling	bale	$4.50	18.4	82.67
				347.33
Annual operating capital	$	7.00%		24.31
Total "cash" costs	ha			$718.97
Total cost of delivered feedstock	$ Mg^{-1}			$71.90

[a] The assumed land rental rate is from Griffith et al. (2010).

Table III-8. Forage sorghum for biomass production budget

Item	Unit of measure	Price per unit	Quantity	Value
Harvested yield (dry matter)	Mg ha^{-1}		14.2	
"Cash" costs				
Land rent[a]	ha	$148.26	1	148.26
Sorghum seed	kg	$3.00	4.5	13.50
Nitrogen	kg	$1.01	101	102.30
Phosphorus (P_2O_5)	kg	$1.17	50	58.93
Fertilizer application	ha	$10.23	1	10.23
Chisel Plow	ha	$27.18	1	27.18
Discing	ha	$24.71	3	74.13
Cultipacking (firming seedbed)	ha	$22.24	1	22.24
Seeding	ha	$33.11	1	33.11
Swathing	ha	$32.49	1	32.49
Raking	ha	$9.59		9.59
Baling (large square bales 4x4x8)(544 kg)	bale	$14.60	26.1	381.10
Hauling	bale	$4.50	26.1	117.46
				515.26
Annual operating capital	$	7.00%		36.07
Total "cash" costs	ha			$1,067
Total cost of delivered feedstock	$ Mg^{-1}			$75.11

[a] The assumed land rental rate is from Griffith et al. (2010).

Table III-9. Comparison of estimated costs, number of harvest units, harvested hectares, and Megagrams of harvested biomass from switchgrass and forage sorghum as a feedstock for a biorefinery (Base scenario)

		Feedstock Source Comparison	
Category	Units	Switchgrass	Forage Sorghum
Land rent	$ Mg^{-1}	12.22	9.52
Establishment and maintenance cost	$ Mg^{-1}	7.61	6.26
Cost of nitrogen	$ Mg^{-1}	7.64	7.20
Cost of phosphorus	$ Mg^{-1}	0.46	4.15
Total field cost	$ Mg^{-1}	15.71	17.62
Harvest cost	$ Mg^{-1}	15.73	28.85
Field storage cost	$ Mg^{-1}	0.48	1.22
Transportation cost	$ Mg^{-1}	16.06	16.57
Total cost of delivered feedstock	$ Mg^{-1}	60.20	73.78
Harvest units for cutting	no.	34	71
Harvest units for baling	no.	27	110
Biomass harvested from cropland	Mg	795,997	1,312,184
Biomass harvested from improved pasture land	Mg	493,262	
Total biomass harvested	Mg	1,289,259	1,312,184
Cropland harvested	ha	78,636	92,387
Improved pasture land harvested	ha	49,944	
Total land harvested	ha	128,581	92,387

Table III-10. Comparison of estimated costs, number of harvest units, harvested hectares, and Megagrams of harvested biomass from switchgrass and forage sorghum as a feedstock for a biorefinery (Fuel price doubled)

		Feedstock Source Comparison	
Category	Units	Switchgrass	Forage Sorghum
Land rent	$ Mg^{-1}	12.47	9.72
Establishment and maintenance cost	$ Mg^{-1}	7.69	6.36
Cost of nitrogen	$ Mg^{-1}	7.70	7.31
Cost of phosphorus	$ Mg^{-1}	0.46	4.21
Total field cost	$ Mg^{-1}	15.86	17.88
Harvest cost	$ Mg^{-1}	18.92	33.21
Field storage cost	$ Mg^{-1}	0.48	1.22
Transportation cost	$ Mg^{-1}	25.39	25.35
Total cost of delivered feedstock	$ Mg^{-1}	73.13	87.38
Harvest units for cutting	no.	35	73
Harvest units for baling	no.	27	113
Biomass harvested from cropland	Mg	820,642	1,311,402
Biomass harvested from improved pasture land	Mg	468,144	
Total biomass harvested	Mg	1,288,787	1,311,402
Cropland harvested	ha	81,366	93,737
Improved pasture land harvested	ha	48,261	
Total land harvested	ha	129,627	93,737

Table III-11. Comparison of estimated costs, number of harvest units, harvested hectares, and Megagrams of harvested biomass from switchgrass and forage sorghum as a feedstock for a biorefinery (Land rent doubled)

		Feedstock Source Comparison	
Category	Units	Switchgrass	Forage Sorghum
Land rent	$ Mg^{-1}	24.08	18.67
Establishment and maintenance cost	$ Mg^{-1}	7.54	6.20
Cost of nitrogen	$ Mg^{-1}	7.57	7.13
Cost of phosphorus	$ Mg^{-1}	0.45	4.11
Total field cost	$ Mg^{-1}	15.56	17.43
Harvest cost	$ Mg^{-1}	14.39	28.90
Field storage cost	$ Mg^{-1}	0.48	1.22
Transportation cost	$ Mg^{-1}	16.86	17.07
Total cost of delivered feedstock	$ Mg^{-1}	72.32	83.29
Harvest units for cutting	no.	35	72
Harvest units for baling	no.	26	110
Biomass harvested from cropland	Mg	760,958	1,312,160
Biomass harvested from improved pasture land	Mg	528,216	
Total biomass harvested	Mg	1,289,173	1,312,160
Cropland harvested	ha	74,938	91,414
Improved pasture land harvested	ha	52,673	
Total land harvested	ha	127,611	91,414

Table III-12. Comparison of estimated costs, number of harvest units, harvested hectares, and Megagrams of harvested biomass from switchgrass and forage sorghum as a feedstock for a biorefinery (Forage sorghum yield doubled)

		Feedstock Source Comparison	
Category	Units	Switchgrass	Forage Sorghum
Land rent	$ Mg^{-1}	12.22	4.79
Establishment and maintenance cost	$ Mg^{-1}	7.61	3.19
Cost of nitrogen	$ Mg^{-1}	7.64	7.34
Cost of phosphorus	$ Mg^{-1}	0.46	4.23
Total field cost	$ Mg^{-1}	15.71	14.76
Harvest cost	$ Mg^{-1}	15.73	29.66
Field storage cost	$ Mg^{-1}	0.48	1.22
Transportation cost	$ Mg^{-1}	16.06	11.61
Total cost of delivered feedstock	$ Mg^{-1}	60.20	62.04
Harvest units for cutting	no.	34	73
Harvest units for baling	no.	27	113
Biomass harvested from cropland	Mg	795,997	1,311,490
Biomass harvested from improved pasture land	Mg	493,262	
Total biomass harvested	Mg	1,289,259	1,311,490
Cropland harvested	ha	78,636	47,063
Improved pasture land harvested	ha	49,944	
Total land harvested	ha	128,581	47,063

Table III-13. Comparison of estimated costs, number of harvest units, harvested hectares, and Megagrams of harvested biomass from switchgrass and forage sorghum as a feedstock for a biorefinery (Number of baling days are the same for both switchgrass and forage sorghum)

		Feedstock Source Comparison	
Category	Units	Switchgrass	Forage Sorghum
Land rent	$ Mg^{-1}	12.22	9.55
Establishment and maintenance cost	$ Mg^{-1}	7.61	6.27
Cost of nitrogen	$ Mg^{-1}	7.64	7.21
Cost of phosphorus	$ Mg^{-1}	0.46	4.16
Total field cost	$ Mg^{-1}	15.71	17.65
Harvest cost	$ Mg^{-1}	15.73	20.16
Field storage cost	$ Mg^{-1}	0.48	1.22
Transportation cost	$ Mg^{-1}	16.06	16.10
Total cost of delivered feedstock	$ Mg^{-1}	60.20	64.68
Harvest units for cutting	no.	34	72
Harvest units for baling	no.	27	56
Biomass harvested from cropland	Mg	795,997	1,311,640
Biomass harvested from improved pasture land	Mg	493,262	
Total biomass harvested	Mg	1,289,259	1,311,640
Cropland harvested	ha	78,636	92,508
Improved pasture land harvested	ha	49,944	
Total land harvested	ha	128,581	92,508

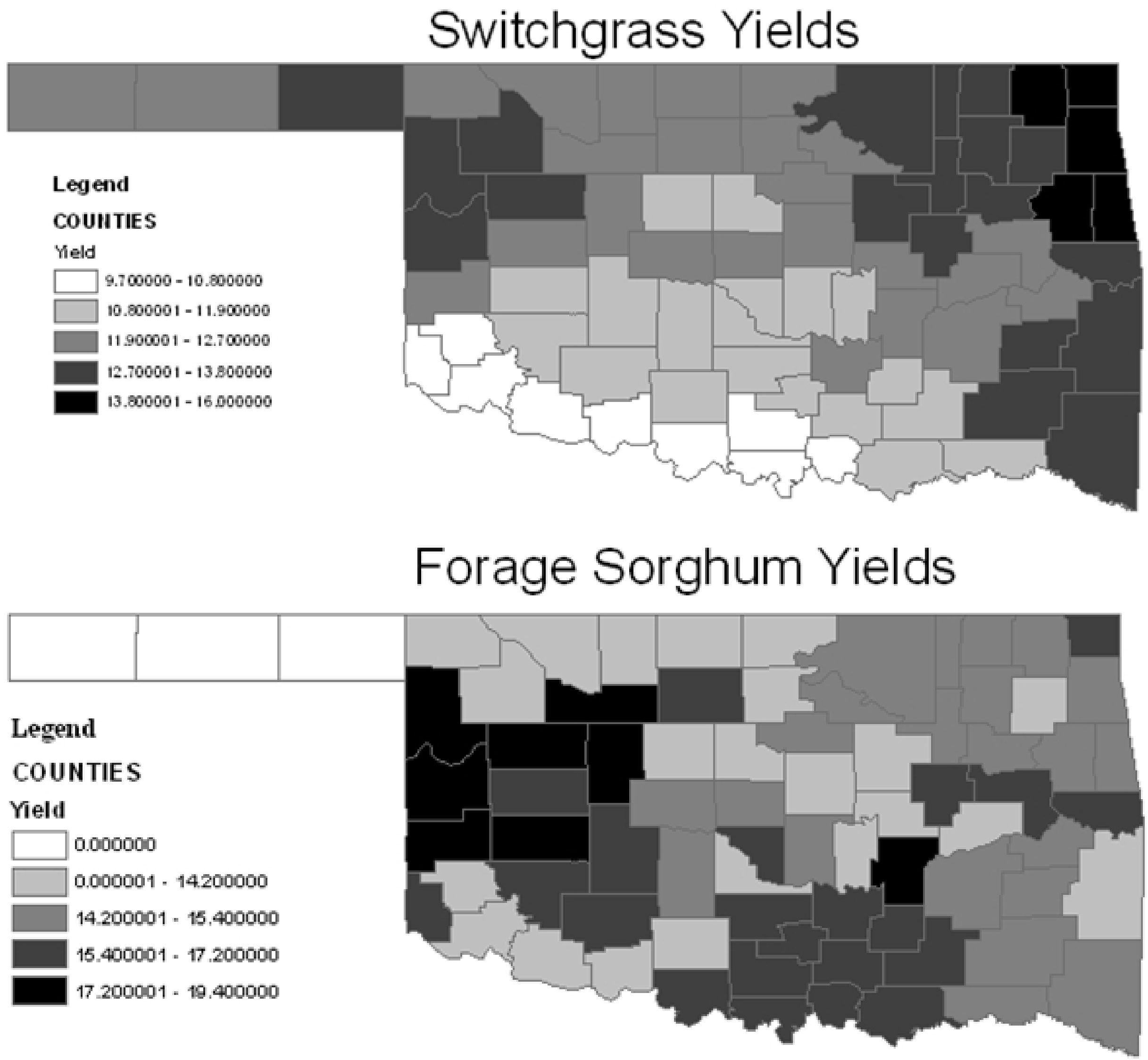

Figure III-1. Switchgrass and forage sorghum yields (Mg ha^{-1}) by county.

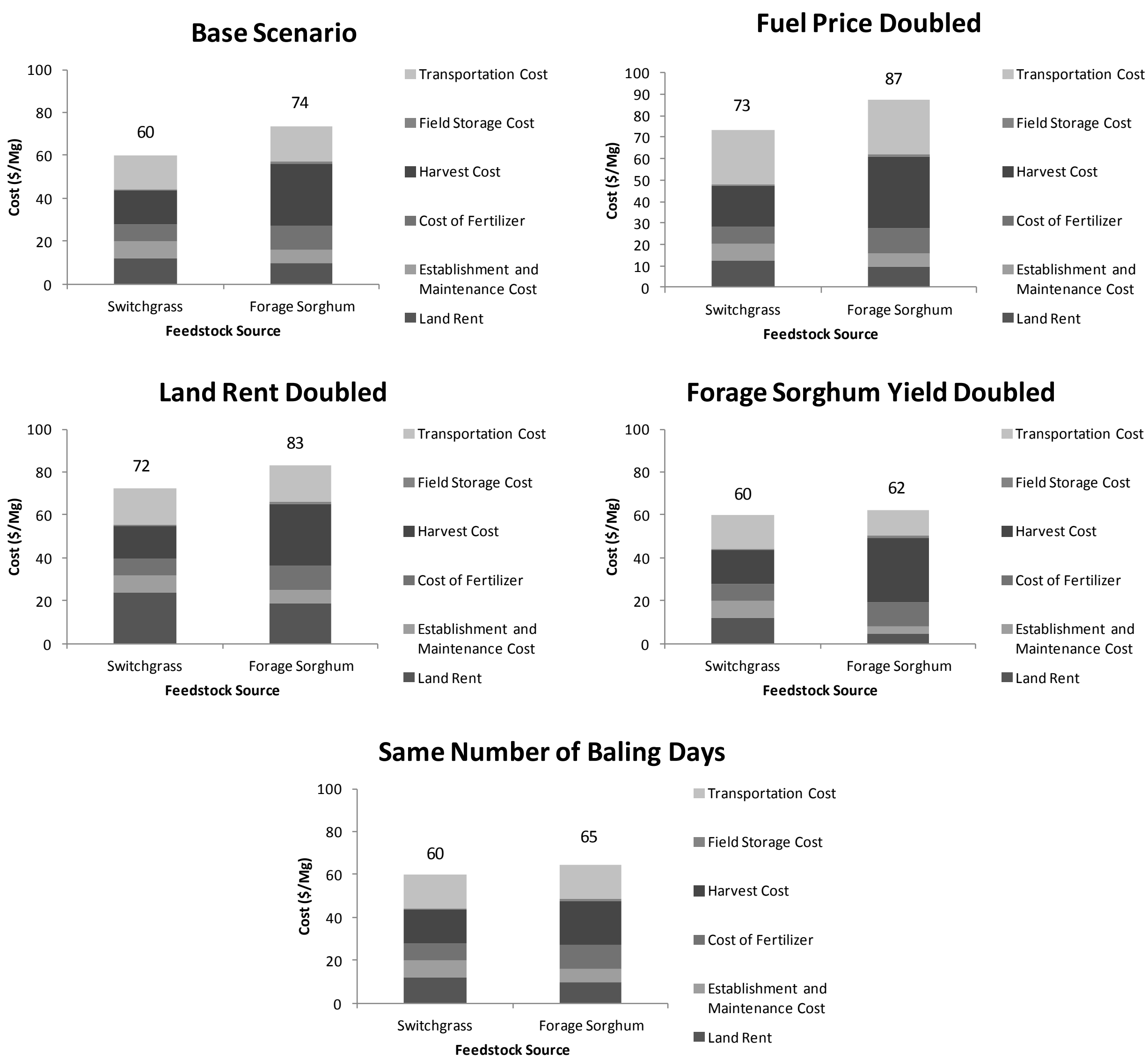

Figure III-2. Estimated costs ($ Mg^{-1}) to provide a flow of feedstock throughout the year to a biorefinery for both switchgrass and forage sorghum.

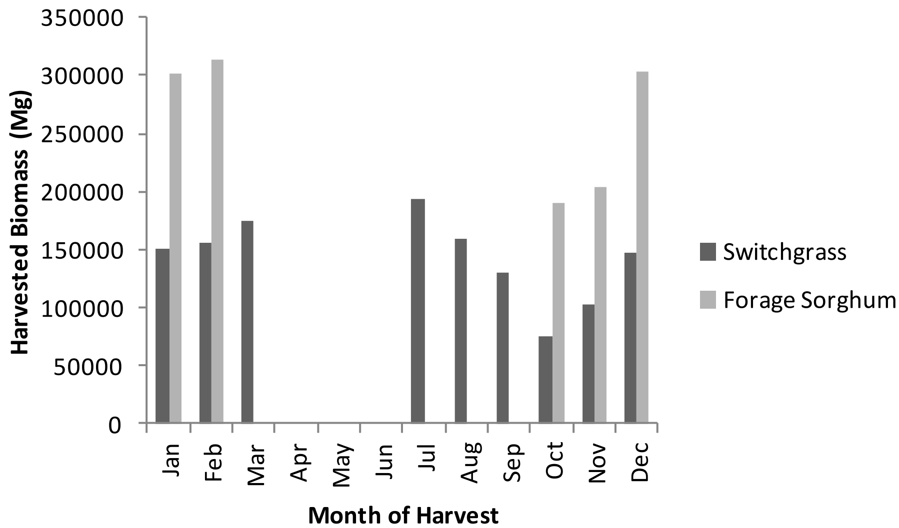

Figure III-3. Monthly harvest of biomass for switchgrass and forage sorghum for the base scenario.

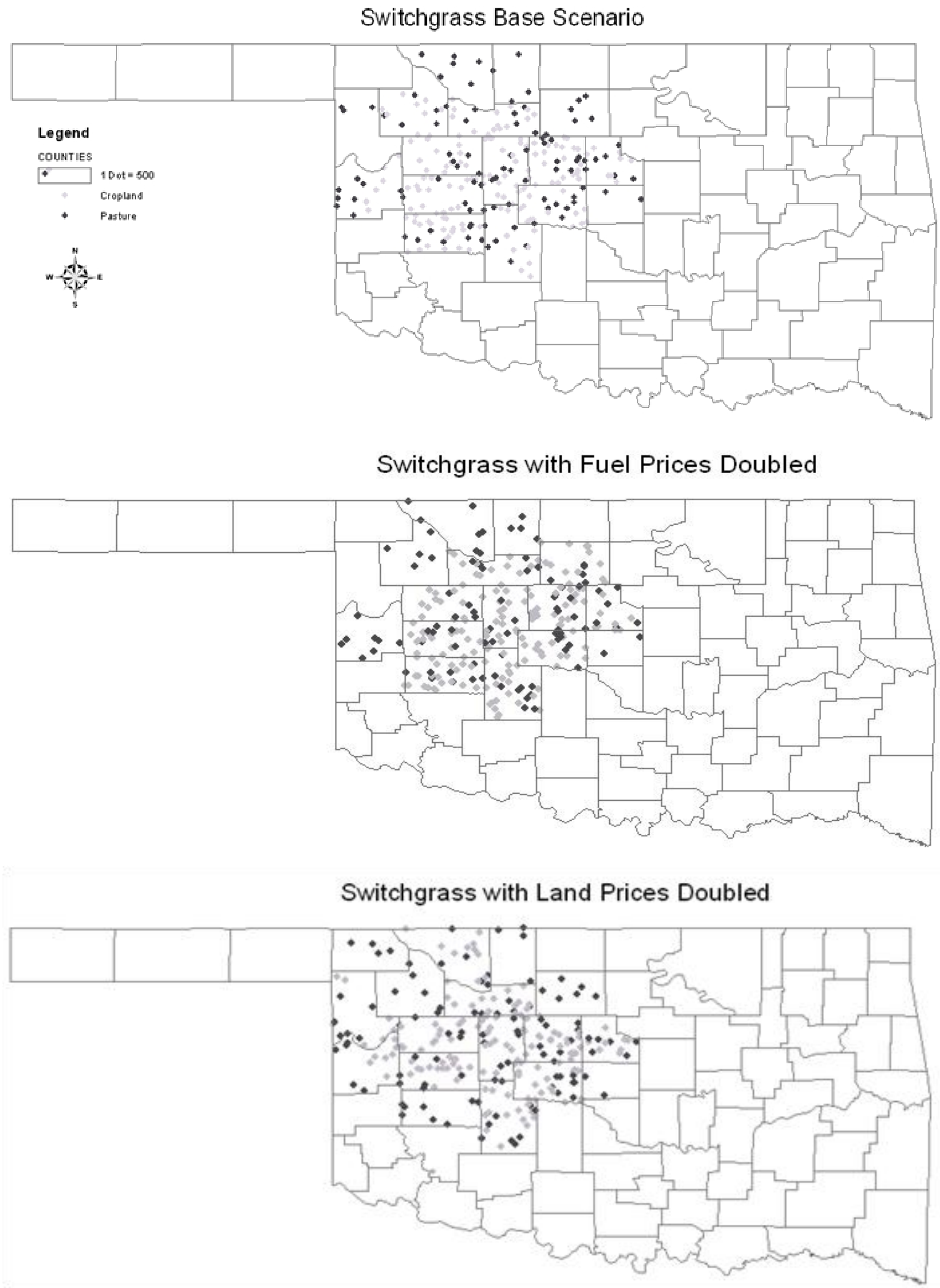

Figure III-4. Cropland and improved pasture land usage for switchgrass under the base scenario, when fuel prices are doubled and when land prices are doubled. (One dot represents 500 ha. Dots are randomly assigned within a county).

VITA

Andrew P. Griffith

Candidate for the Degree of

Doctor of Philosophy

Thesis: PRODUCTION ECONOMICS OF POTENTIAL PERENNIAL AND ANNUAL BIOMASS FEEDSTOCKS

Major Field: Agricultural Economics

Biographical:

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Completed the requirements for the Doctor of Philosophy in Agricultural Economics at Oklahoma State University, Stillwater, Oklahoma in May, 2012.

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8/09-Present	Graduate Research Assistant and USDA National Needs Fellow, Department of Agricultural Economics, Oklahoma State University
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Name: Andrew P. Griffith Date of Degree: May, 2012

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: PRODUCTION ECONOMICS OF POTENTIAL PERENNIAL AND ANNUAL BIOMASS FEEDSTOCKS

Pages in Study: 102 Candidate for the Degree of Doctor of Philosophy

Major Field: Agricultural Economics

Scope and Method of Study: The first essay determines the lowest cost lignocellulosic biomass feedstock production system for western Oklahoma from among seven alternatives at each of two locations. Field experiments were conducted at the Southern Plains Range Research Station to test production of monoculture (one species) and diverse plantings (many species). The second essay compares crop yields in a continuous wheat system to yields in a canola-wheat system and determines whether the rotation is economically competitive with continuous monoculture wheat for the region in fields infested with feral rye and Italian ryegrass. Field trials were conducted at Lahoma, Lake Carl Blackwell, Chickasha, and Perkins using 24 different treatments for the canola-wheat rotation and eight treatments for continuous wheat. The third essay determines and compares the cost to deliver a year round flow of biomass to a biorefinery for both a system that uses forage sorghum exclusively and a system that uses switchgrass exclusively. A multi-region, multi-period, monthly time-step, mixed integer mathematical programming model was used to determine the cost to deliver a steady flow of biomass to a biorefinery

Findings and Conclusions: The first essay found biomass yields of diverse mixtures were no greater than yields of monocultures. If the objective is to produce massive quantities of biomass for biorefinery feedstock under the constraint that land area is limited, for the conditions that prevailed at the western Oklahoma locations during the time of the study, internal economics favored monocultures of productive species. The second essay found wheat yields following canola are significantly greater than wheat yields experienced in continuous wheat and expected net returns are greater for canola-wheat rotations than for continuous wheat. A canola-wheat rotation may be an economically viable and effective crop production system for fields traditionally seeded to continuous winter wheat, especially if those fields are infested with feral rye and Italian ryegrass. The third essay found, that given the assumptions used in the study, a switchgrass system would be economically preferable to a forage sorghum system for producing and delivering a year round flow of biomass to a biorefinery. Though forage sorghum has an expected yield advantage over switchgrass and the forage sorghum system is expected to require less nitrogen fertilizer per ton produced, switchgrass has the advantage of a longer harvest window, more harvestable days in a harvest month, and the ability to be produced on both cropland and improved pasture land. By these measures, a flow of switchgrass biomass could be delivered to a biorefinery throughout the year at a lower cost than forage sorghum biomass.

ADVISER'S APPROVAL: Dr. Francis M. Epplin