A Spatially Explicit Watershed Scale Optimization of Cellulosic Biofuels Production

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Abstract:

As environmental deterioration and global warming arouses more and more attention, identifying cleaner and more environmentally friendly energy sources is of interest to society. In addition to environmental concerns, both the high price of gasoline and the fact that the United States has heavy reliance on imports of energy have driven policymakers to find alternative energy sources. Producing biofuels from energy crops is one such alternative with relatively lower greenhouse gas emissions compared to traditional energy sources. Cellulosic feedstocks such as corn stover, perennial grasses and fast growing trees are regarded as promising energy crops and are expected to help with the energy supply.

This study takes a spatially explicit approach to examine fields within a watershed and explores the conditions under which the agricultural land in the watershed can meet the demand of a biorefinery. Costs of two dedicated energy crops, switchgrass and miscanthus, are compared with corn stover. A Matlab program is developed based on a genetic algorithm to minimize production cost subject to biomass production and pollution constraints in the Wildcat Creek Watershed in Indiana, USA. The process of using a genetic algorithm to solve high dimensionality mixed integer optimization problems is discussed. Results indicate that to achieve the required amount of biomass production for a minimum feasible scale thermochemical biorefinery within the watershed, miscanthus must be planted. Miscanthus also helps reduce pollutant levels (total sediment, N and P loadings) when compared to stover removal from continuous corn and corn-soybean rotations. Switchgrass is found to have similar environmental advantages, but is not economically competitive based on preliminary results that require further validation. Corn stover is the lowest cost feedstock considered, however, it results in relatively higher sediment, nitrogen and phosphorus loading than the perennial grasses considered. Relative to the baseline without stover removal, no-till in combination with stover removal results in decreased sediment loading, an increased loading of nitrogen under continuous corn and an increase in phosphorus (except at the 50% removal rate from continuous corn). There is clear tradeoff among cost, production and environmental improvement.

Key Words: cellulosic biofuels; spatially explicit optimization; genetic algorithm; watershed; water pollution; SWAT

Introduction

The United States has high nonrenewable energy consumption and about 55 percent of its consumption of crude oil is imported. As concerns about the security of the energy supply and degradation of the environment have increased, biofuels that can be produced from renewable domestic resources are regarded as a promising energy source with lower greenhouse gas emissions than gasoline. The Renewable Fuel Standard (RFS2) requires production of 16 billion gallons of ethanol-equivalent biofuels using cellulosic feedstocks by 2022 (National Academy of Sciences, 2011).

Previous economic studies have investigated the costs of cellulosic biofuel production and evaluated the feasibility of different potential feedstock sources. Others have focused on the environmental implications of biofuel production. However, few studies have integrated the economic side of biofuel production together with environmental concerns (Secchi et al., 2009; Gramig et al., 2013). The framework established in this research not only provides a practical tool to combine water pollutants and on-farm production of cellulosic feedstocks, but also serves as a novel approach to inform future integrated research on biofuel environmental and cost analysis. Taking a spatially explicit approach, this study examines fields within a watershed and explores the conditions under which the agricultural land in the watershed can meet the demand of a biorefinery. A gap in the literature is filled by taking into account both the economic and the environmental side of biofuel production. Since the area under investigation is an agriculture dominated watershed typical of the Eastern Corn Belt, the results from this study about the tradeoffs between economic and environmental outcomes are generalizable to similar watersheds in other locations. The spatially explicit framework is practical and could be utilized by the biofuels industry to determine cost-minimizing ways to supply a biorefinery over a land area larger than a single watershed.

Three cellulosic feedstocks, corn stover, switchgrass and miscanthus are examined in this study. Corn stover refers to the nongrain portion of the annual crop corn. It is the material remaining in the field after corn grain harvest. Stover consists of husks, shanks, silks, cobs, stalks, tassels, leaf blades and sheaths (Hoskinson, Karlen, Birrell, Radtke, & Wilhelm, 2007). It provides a barrier between topsoil and rain or wind, and thus prevents erosion (Karlen et al., 2011). It also helps maintain soil carbon and fertility. As a byproduct of corn grain, the harvesting of corn stover does not require many extra inputs, hence it is considered a promising feedstock for cellulosic biofuel production.

When stover is removed, the nutrients contained in the stover are also removed. As a result, nutrient replacement is generally required, and this entails additional expenditures on fertilizers and labor. Despite recent studies that have found that the short term productivity of land can be maintained without nutrient replacement (Coulter et al., 2010; Pantoja et al., 2011), long run effect on yields and soil productivity requires further investigation.

Switchgrass (*Panicum virgatum*) is a perennial grass native to North America. It is a warm-season grass and is found throughout the U.S. Currently, it is grown mainly as a forage crop or as ground cover to control erosion for the Conservation Reserve Program and wildlife habitat programs (Gibson & Barnhart, 2007). Because of its rapid growth and winter hardiness (depending on variety), it is regarded as a potential source for biofuel production. Switchgrass is slow to establish. It usually requires two to three seasons to become fully established. Once established, a well-managed switchgrass stand can have a productive life of 10 to 20 years. Swtichgrass can adapt well to different soil and climatic conditions. Its high cellulosic content makes it a promising source for biomass production. The Shawnee cultivar, an upland variety, is used for this study for its high cold tolerance suitable for the Midwest.

Miscanthus, native to eastern Asia, northern India and sub-Saharan Africa, is a warm-season perennial rhizomatous grass. Depending on management, miscanthus stands can last 15 to 20 years. Heaton et al. (2010) noted that the response of miscanthus to fertilization is likely due to the interactions of weather conditions, soil type and agronomic management. Hence, yield response to fertilization may change from field to field or even within the same field from year to year. Typical harvest time for miscanthus is after a killing frost and before the emergence of new shoots in the spring. The sterile hybrid genotype *Miscanthus × giganteus Greef et Deu* is used for this study.

The watershed studied in this project is the Wildcat Creek, which is located in North-Central Indiana. It is approximately 150 km long and drains to the Wabash River, with a drainage area of 2,083 km^2. The watershed is predominantly agricultural with about 70% corn and soybean planted in rotation, 13% urban, 9% forest and 5% pasture area (Cibin, Chaubey, &

Engel, 2012). To facilitate hydrological modeling, the watershed is divided into sub-basins. Sub-basins are further divided into hydrologic response units (HRUs), which are land units that respond in hydrologically similar ways because of their slope, soil type and other physical characteristics. Due to high sediment, nutrients and pesticide (atrazine) loadings in the predominantly agricultural watershed, water quality in the Wildcat Creek has been designated as impaired. The primary water quality concerns are high nutrient concentrations, especially phosphorus and nitrogen concentrations in the streams within the watershed.

Data and methodology

The Soil and Water Assessment Tool (SWAT) model is used to simulate crop yields and pollutant loadings for different bioenergy crop production scenarios and a cost analysis is done to estimate feedstock production and transportation costs. SWAT is a widely used model to examine the impact of land management practices on hydrology and water quality in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch, Arnold, Kiniry, & Williams, 2011). For this study, the SWAT model of the Wildcat Creek watershed was developed, parameterized and validated by members of the Ecohydrology Research Group at Purdue University (Chaubey, 2013). Yields from SWAT output are HRU level biomass production and pollutants are HRU specific aggregated pollutant loadings.

A total of 12 cropping systems with different fertilization and stover removal rates are examined

1. Baseline Corn-Soybean rotation (CS)
2. CSNoTill30 without nutrient replacement (NR)
3. CSNoTill30 with NR
4. CSNoTill50 without NR
5. CSNoTill50 with NR
6. Continuous Corn (CC) NoTill30 without NR
7. CCNoTill30 with NR
8. CCNoTill50 without NR
9. CCNoTill50 with NR
10. Switchgrass (conventional tillage)
11. SwitchgrassNoTill
12. Miscanthus

Baseline corn-soybean (CS) denotes the status quo situation before harvesting cellulosic biomass with corn and soybean grown in rotation; corn is conventionally tilled while soybean is no-tilled. This is the baseline scenario used to make comparisons with the bioenergy cropping systems considered. Scenarios 2 through 5 are continuous no-till scenarios with two sets of stover removal rates (30% and 50%) and nutrient replacement choices (with and without) from a corn-soybean rotation (see Table 1 for additional management details). Scenarios 6 to 9 (see Table 1 for additional management details) are the same stover removal and nutrient replacement choices in continuous no-till continuous corn (CC) cropping systems for comparison with stover collection from a CS rotation. The switchgrass scenarios 10 and 11 are conducted to see the influence of tillage on switchgrass production and water pollutants (see Table 2 for additional management details). The only difference between these two scenarios is the planting method in the establishment year. Conventionally tilled switchgrass means that the field operations, field cultivation and disk-tandem, are done before the seeds are planted; no-till switchgrass costs slightly less because it does not have these field operations. Scenario 12 is to examine the production of miscanthus (see Table 3 for additional management details).

After setting the 12 scenarios, the cost minimization problem is built. It is done in two steps. First, the optimization is under a single constraint on production to find the relationship between production and total cost, and to examine the performance of the algorithm in solving a pure cost minimization problem; second, constraints of required pollutant levels are added to further investigate tradeoffs among cost, production and environmental improvements.

The cost minimization problem is

(1) $\sum_{i=1}^{n=922} Farm-gateCost_i(\$) + HaulingCost_i\ (\$)\ \forall\ i$

$subject\ to$:

$$Total\ Production\ (metric\ ton)\ \geq 1{,}307{,}065\ (metric\ ton)$$

Where the Farm-gate Cost$_i$ = Production Cost$_i$ + Loading-unloading cost$_i$ (for all i) and Hauling Cost$_i$ = Number of Bales * Hauling Distance * Unit Hauling Cost (for all i). All costs are in dollars.

Additional pollution constraints are also considered below, in addition to the production constraint in equation (1) above. The general form of the pollution constraints are that the total amount of a given pollutant loading should be less than or equal to the baseline loading times a reduction rate. The reduction rate is equal to (1-x), where $x \in [0,1]$, so that the baseline pollutant load is not exceeded for $x = 0$ and is reduced by a proportion equal to (1-x) for values of $0<x\leq 1$. Specifically, the pollutant constraints take the form:

$$(2)\ TotalSediment(metric\ ton) \leq BaselineTotalSediment(metric\ ton) * ReductionRate$$

$$TotalN\ (kg) \leq BaselineTotalN(kg) * ReductionRate$$

$$TotalP\ (kg) \leq BaselineTotalP(kg) * ReductionRate$$

The minimum production constraint is set equal to 1,307,065 metric tons per year based on the minimum feasible thermochemical conversion plant size found in the Princeton Environmental Institute study (Kreutz, Larson, Liu, & Williams, 2008). We first consider the economic cost-minimization problem without any pollutant constraint ($x = 0$). Then three individual pollutant constraints are considered ($x>0$), each based on a fixed uniform percentage reduction relative to the baseline. 25% and 50% reduction rates are tested since there is no standard pollutant loading requirement established by law at present.

The total cost is divided into three components: production cost, loading-unloading cost and hauling cost. Production cost includes costs such as planting, collection, and storage; loading-unloading calculates the cost to load the biomass bales onto the truck from on-farm storage and unload them at the biorefinery plant; hauling cost is the cost to haul the bales from farm to plant. Each cost category is calculated separately. Tables 1, 2, and 3 show the cost parameters for each of the feedstocks, and Table 4 lists the parameters for loading-unloading cost. Table 5 is the summary table of farm-gate costs by adding production and loading-unloading cost up.

To get the hauling cost, distances (miles) from each field to the biorefinery are needed. For simplicity, this study locates a hypothetical plant at the centroid of the Wildcat Creek Watershed. ArcGIS 10.1 software is employed to calculate the shortest distance following the actual road path between the centroid of each HRU and the plant. Adding the hauling cost to the farm-gate cost components, total cost of planting each cropping system (scenario) across the watershed is generated and reported in Table 6.

To link the cost of production with the pollution information and achieve the purpose of minimizing cost while maintaining energy crop production under a certain pollution level, the optimization model is built and performed using the global optimization toolbox in Matlab[1]. The optimization is done using a Genetic Algorithm (GA). A GA is a direct, parallel, stochastic method for global search and optimization, which imitates the evolution of living things described by Charles Darwin (Popov, 2005). GAs belong to the group of algorithms known as Evolutionary Algorithms, which imitates the evolutionary process. Three evolutionary processes are mimicked by the GA. First, selection. As all the individuals enter the selection process, the rule of survival of the fittest is applied and the best individuals survive and transfer their genes to the next generation. For this cost minimization application, candidate solutions with lower cost have greater fitness, and thus will have bigger chances for recombination and respectively for generating offspring. The second process is called crossover. The genes of the parents (candidate solutions) are exchanged to form entirely new combinations of practices on different land units in the watershed. Then during the last process—mutation—genes mutate and random changes are introduced to the values.

In the context of this study, each individual candidate solution represents one possible combination of the 12 cropping methods for each HRU and there are 12^{922} possible individuals. Individuals are collected randomly to form an initial population smaller than 12^{922} to enter the optimization. These individuals are evaluated toward each other and best individuals are saved as elite children for the next generation. The rest of the individuals in the initial population undergo crossover and mutation. After these steps are completed, a new generation is formed. This process repeats for multiple, perhaps many, generations until the algorithm converges on a solution that has the lowest cost for a given level of biomass production and pollution. The algorithm then stops and returns the unique set of scenario combinations. Each solution is a spatially explicit allocation of cropping practices for each land unit in the watershed. Whether and where perennial grasses are chosen to be grown alongside corn stover is based on the relative total cost of each feedstock, together with feedstock amount requirement and the pollutant loading constraints imposed.

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[1] Version used for this study is MATLAB R2012a

Results

Initial Results

As the first trial, the optimization is performed subject to only the production requirement of 1,307,065 metric tons, initial population size is 10,000, with 100 generations. Since the optimization process is purely random, results returned from repeated runs are different, and locations of HRUs allocated to each cropping choice vary while total cost, total biomass production and shares of land area allocated to each practice remain similar. Thus, the model is run 10 times to avoid a single solution being randomly higher cost than other similar solutions. The GA does not return a global optimum. The assumption is that the local optima from multiple runs are in the neighborhood of the global optimum. For each run, total production, production cost and allocation of practices are recorded. The results are then evaluated by taking the 10-run average. Average land shares of each cropping practice together with average values of total production and total cost are calculated.

Figure 1 shows the average percentages of area occupied by each chosen scenario. The Baseline is chosen for 29.27% of the total crop land within the watershed; miscanthus is planted on 35.39% of the land. Area of each of the other scenarios varies from 3% to 4% of the total area. 10-run average total production is 1,318,634 metric tons, with an average total cost of $195,957,875. This is, on average, 11,569 metric tons (0.9%) more than the minimum production constraint imposed. The constraint is not satisfied exactly at the solution because of the discrete nature of the problem.

Simple calculations in Table 6 show how much production results from each individual scenario if that crop were planted alone across the watershed. For example, if miscanthus is the only crop grown across the watershed, it will yield 3,176,365 metric tons of biomass every year, which means that miscanthus alone can meet the minimum production required by the biorefinery at a cost of over $479 million. No other single crop scenario has a yield that is large enough to meet, let alone greatly exceed, the required amount of biomass. Hence, to satisfy the minimum production constraint using only the land inside the watershed, miscanthus must be planted despite its high relative cost. The 35.39% of land devoted to miscanthus shown in Figure 1 equals 1,130,468 metric tons of biomass, which is roughly 86% of the biomass required by the biorefinery. Also, since Baseline CS requires zero production cost, it is the least-cost cropping method in the choice set, and shows up in the simulation result as the second largest share of land (29.27%). The other scenarios combine together to provide the remaining 14% of required biomass and take up the rest of land.

Examining these result using economic intuition alone, only the cheapest method to meet the required production should be chosen to minimize cost. If growing miscanthus alone on about one third of the land area could satisfy the biomass constraint at the lowest cost, then the only other chosen scenario should be the baseline so as to minimize total cost. In addition, since conventional tillage and no-till establishment of switchgrass (Scenarios 10 and 11, respectively) generate the same amount of biomass and no-till is cheaper, no-till and conventionally tilled switchgrass should never be chosen concurrently. The question becomes why scenarios that are apparently economically dominated, and thus should have lower relative fitness in the sense of the evolutionary optimization procedure adopted, are nonetheless chosen when the GA is employed.

A large literature has explored the effectiveness of genetic algorithms since they were first put forward by John Holland (1975). A large number of articles evaluated the optimization outcome of the algorithm given diverse research goals and disciplines. Advantages and disadvantages of the algorithm have been scrutinized in detail; problems have been identified and suggestions and improvements have been made ever since (Angelova & Pencheva, 2011; De Jong & Sarma, 1993; Grefenstette, 1986; Mardle, 1999).

Based on the preceding literature and doing more simulation trial runs, one possible reason why seemingly inferior cropping practices are selected by the GA is the dimensionality of this problem. There are a total of 12^{922} possible combinations of different cropping methods in this study, eliminating the feasibility of a complete enumeration search. The initial population size used for the optimization is 10,000. This population size is almost zero when compared with the actual number of candidate solutions, revealing that a nowhere near exhaustive search is effectively performed given the dimensionality of the applied problem. This clarifies why the result is likely a local minimum instead of the desired global minimum. Knowing the potential problems and limitations, the following changes were explored as ways to improve the initial optimization results: Increase the population size; reduce the dimensionality of the problem; and adjust the default crossover and mutation rates.

Improving Results

Larger initial population sizes of 20,000, 30,000, 40,000, 50,000 and 60,000 were examined. By increasing population sizes, more possible combinations of cropping practices from the theoretical population of candidate solutions can be considered by the GA. The relative improvement—evaluated based on whether lower cost solutions that satisfy the production constraint were found—fluctuated over different population sizes, and there is no sizable or discernable pattern of improvement resulting from increased population sizes. One primary reason for no clear improvement in the solutions is that population size from 10,000 to 60,000 are still a very small share of the total possible combinations.

To reduce the dimensionality of the problem, with and without nutrient replacement cases are compared. Since these are substitutes for a given stover removal rate, and because long run soil productivity is expected to require at least some level of nutrient replacement, the without nutrient replacement cases are removed from the choice set. The 30% and 50% stover removal rates are examined next. Studies indicate that a 30% stover removal rate is more practical and generally preferred to higher removal rates because of impacts on soil properties and erosion (Graham, Nelson, Sheehan, Perlack, & Wright, 2007; Kim & Dale, 2004; Sesmero, Pratt, & Tyner, 2013). As a result, the 50% stover removal scenarios are removed from the choices too. The only difference between the two switchgrass scenarios is the type of tillage when the seed is planted, so the conventional tillage practice (Scenario 10) is removed because it has a higher cost. Because switchgrass cost more than miscanthus and has significantly lower yield it must be removed from the choice set altogether on economic grounds. This process leaves four scenarios to consider: Baseline CS; CSNoTill30 with NR; CC30NoTill with NR; and Miscanthus.

In order to meet the production requirement of biorefinery, it is expected that the Baseline CS and Miscanthus must be planted for their lowest (zero) cost and highest production, respectively. To explore the possibility of further reducing the size of the problem, the remaining 2 scenarios are compared. Relative total cost of each of them is calculated in order to capture and analyze the tradeoffs among yield, farm-gate cost and hauling distance.

To get the relative total cost, assuming each of the two scenarios is planted in the watershed alone to meet the production requirement of 1,307,065 metric tons, the corresponding biorefinery fuelshed sizes are derived. By drawing a hypothetical circle surrounding the fuelshed boundary, radii can be calculated for each candidate feedstock. The average straight-line (as the crow flies) hauling distances are estimated as two thirds of each calculated radius. By comparing total cost of satisfying the production requirement using each remaining candidate feedstock, CCNoTill30 with NR (total cost $108,252,366) is cheaper than CSNoTill30 with NR (total cost $111,374,881). Hence, it is selected as one of the three final candidates and enters the optimization together with the Baseline CS and Miscanthus. The dimensionality of the optimization problem is thus reduced from 12^{922} to 3^{922}.

Based on the reduced dimensionality, a set of 3-scenario optimizations are run to test the sensitivity of the results to changing crossover and mutation rates. Mutation rate, the proportion of non-elite individuals in the population undergoing mutation, is equal to (1– crossover rate), such that all non-elites undergo either crossover or mutation. Through the comparisons, crossover rate 0.7 (mutation rate 0.3) is the best for the 3-scenario optimization in terms of total cost. Under 3 scenarios and crossover rate 0.7, the total cost is $181,144,313, which is about $15 million less than the initial result with 12 scenarios. The land shares are shown in the top panel of Figure 3. Intuitively this makes sense since economically dominated strategies were removed, along with the no nutrient replacement and high removal rate scenarios assumed to be unsustainable in the long term.

Manually Calculated Optimum

After using economic logic together with findings about soil health and erosion from the agronomic literature, only three scenarios remain, and a brute force approach to finding an economic optimum becomes possible. Our methodological interest is in determining whether optimization using the genetic algorithm is capable of identifying solutions that are more optimal than could be arrived at through the application of rational economic thought and manual calculation. By manually sorting all land units and comparing production and cost, it was determined that in order for the watershed to supply the total amount of required biomass, roughly 80% of the total required biomass needs to be provided by miscanthus. Because miscanthus produces eight times as much yield per unit area as CCNoTill30 with NR, minimizing transportation cost will require planting miscanthus on the land nearest to the biorefinery and harvesting stover from the land located farther away. This translates into planting miscanthus within 11.6 miles of the biorefinery and planting the remainder of the watershed in CCNoTill30 with NR. The total production is 1,313,436 metric tons at a total cost of $174,211,751.

Since the production achieved in this way is 6,371 metric tons higher than the requirement, a further reallocation of land, replacing some CCNoTill30 with NR acres with Baseline CS acres, will still meet the production constraint and reduce cost. Following this logic, a minor reallocation that meets the minimum production requirement at a total cost of $173,661,397 was achieved. This manual calculation found a solution that cost $7.48 million less than the solution found from the same choice set by applying the GA above. The land area share of each cropping practice for this least-cost manual solution is shown in Figure 2. Note that this least-cost identified solution is only a rough estimate based on the evaluation that 80% of land area for miscanthus would guarantee biomass production. It is believed to be close to the global optimum, but a reallocation of small HRUs could achieve a minor reduction in the total cost. This would likely mean replacing some miscanthus acres with CCNoTill30 with NR, along with a further reallocation of acres between CCNoTill30 with NR and the no cost Baseline.

In a final effort to improve the GA optimization results, the manual optimum guided by economic logic was used as an input, in addition to reduced dimensionality and using the crossover rate that achieved the best results. The manually calculated optimum (and similar solutions representing marginal HRU reallocations to different practices) was included as a seeded individual (solution) in the initial population. Instead of choosing the initial population completely randomly, a heuristic seed is included by using this best known solution to the optimization problem. The simulation results remained unchanged over 10 runs once seeded; the genetic algorithm is unable to improve upon the seeded manual optimum. It is believed that this is still due to the large dimensionality of the problem and the very small change in value of the objective function that likely results. Different crossover and mutation functions might be capable of achieving improved results given the seeded solutions, but the crossover and mutation processes applied to mixed integer problems in the software package utilized could not improve upon the seeded solution.

Despite this finding, the manually calculated optimum serves as a form of verification for GA as well. Considering the large size of the problem, the 4.3% cost difference (from \$181,144,313 to \$173,661,397) between the 3 scenario GA solution and the manually calculated optimum is small. For the simulation results, the cost can be reduced by moving several HRUs from excess biomass production scenarios to baseline. Furthermore, manual calculation is possible only when there is small number of scenarios. Once the number of scenarios increases or more than one constraint must be satisfied, the brute force approach employed here will be very difficult.

Adding Pollutant Constraints

The total and average per hectare loading information for sediment, N and P when each of the 12 scenarios is planted throughout the entire watershed is provided in Table 7. The table shows that perennial grasses achieve lower loadings for all pollutants compared to stover removal. Among stover removal scenarios, the cropping system with the highest removal rate and lowest amount of continuous residue cover (CSNoTill50 with NR) had the highest sediment contribution, but it is important to note that this was still lower than the Baseline with conventionally tilled corn and no-till soybeans grown in rotation. This is likely due to the fact that we only consider stover removal from no-till corn. For a given rotation and removal rate, N and P loadings are always higher under nutrient replacement than when no nutrient replacement occurs. CCNoTill30 with NR results in the highest N loading and CSNoTill30 with NR results in the highest P loading. In sharp contrast, though the cost per ton of perennial grasses is considerably higher than the stover removal scenarios considered, the three pollutant levels are much lower for switchgrass and miscanthus. In terms of total N, miscanthus generates only about one fifth that of corn stover scenarios. The amount of total P from switchgrass and miscanthus is only about 4% that of corn stover scenarios. These numbers indicate that perennial grasses have significantly different environmental performance compared to corn stover.

In order to simultaneously evaluate economic and environmental sustainability of candidate feedstocks, it is necessary to compare the pollutant outcomes of cost-minimizing solutions to the baseline. Comparing loadings across the Baseline CS, manually calculated optimum and 3 scenario GA optimization results (Table 8), both optimization solutions resulted in improvements in the level of all three pollutant loadings relative to the Baseline. The manual optimum has higher improvement level in total sediment loading while the GA optimization results in lower total N and P. These differences across the two economic optimization results are the result of planting choices. CCNoTill30 with NR contributes higher total N and P loadings and takes up a 24% larger share of the watershed in the manually calculated optimum, while sediment loading is lower in the manually calculated optimum because the lower sediment generating crops miscanthus and CCNoTill30 with NR replace more than 20% of the watershed area allocated to the more intensive tillage Baseline in manually calculated optimum.

To further investigate the effects of pollutant levels on the optimization results, individual constraints for all three pollutants are included in the optimization based on equation (2). Reductions of 25% ($x = 0.25$) and 50% ($x = 0.5$) from the baseline for each pollutant are tested in separate optimizations. The 10 run average land share pie chart that results is shown in Figure 3. As the pollutant constraints are tightened, land share of CCNoTill30 with NR decreases until it is completely replaced by miscanthus and the baseline in the 50% reduction case because of its higher N and P loadings. There is clearly a tradeoff between cost and pollution control requirements. To achieve lower pollutant levels, more miscanthus must be planted at higher total cost, but also higher biomass production.

Watershed vs. Fuelshed

For this study, the total possible biomass production is limited by the physical size of the watershed. Despite the fact that corn stover is less costly to harvest than perennial grasses are to grow, its relatively low yield prevents it from being chosen alone to meet the required minimum production for the assumed biorefinery. In other words, if there is no watershed boundary limitation, corn stover may be a better feedstock than perennial grasses to meet the production requirement in terms of cost. From the perspective of the biorefinery, it is necessary to evaluate production beyond the boundary of a watershed. The relevant question becomes: What is the optimal fuelshed size and feedstock mix to supply the minimum production of a given biorefinery? This section estimates the fuelshed size of each scenario, irrespective of any watershed based on simulated average yield per hectare of each cropping system, and the total cost associated with each fuelshed size.

Setting the required production to the same minimum production requirement of 1,307,065 metric tons, land area needed to grow the required amount is calculated based on the biomass yield per land unit. Assuming the shape of the fuel shed is a circle with a biorefinery at its center, the radius of the fuelshed can be easily calculated for a given land area. Based on the radius of the circle, the average hauling distance from any point in the circle is assumed to be two thirds of the radius. Though a rough estimation, the effect of hauling cost on total cost is captured which is important given the disparity in yield per hectare across feedstocks. For each scenario, total cost is calculated by adding up the total farm-gate cost and hauling cost, given different yields and hauling radii distances for each feedstock. Results (see Song (2013) for full details) show that corn stover scenarios are much less expensive to produce and supply the required production than perennial grasses. A biorefinery is found to be willing to haul corn stover harvested from CCNoTill30 with NR 178 miles before ever contracting for a single metric ton of miscanthus without any hauling costs. Total cost of corn stover production using CCNoTill30 with NR to supply the biorefinery is less than 60% that of miscanthus, even though the required fuelshed size is more than 8 times larger than that required by miscanthus. This means that on high quality farmland, under current conditions, it is not believed that perennial grasses will compete on a strictly economic basis with harvesting corn stover as a biofuel feedstock. If the production requirement were much lower than the one examined in this study, the land area within a watershed may be able to supply the necessary amount of biomass at a lower cost compared with perennials.

Further analysis (see Song (2013) for details) was conducted to more accurately capture the tradeoff between higher farm-gate costs for perennials and the increased hauling cost of transporting corn stover across a many times larger fuelshed. The problem is actually more complex than examining the delivered cost of a marginal ton of candidate feedstocks. This analysis was performed by assuming miscanthus was grown on the closest two miles adjacent of the biorefinery plant, and letting each of the other cropping systems supply the rest of the required production. Intuitively, if the tradeoff between higher hauling cost and lower farm-gate cost is great enough to induce some positive level of miscanthus production in a biorefinery's fuelshed, this production must occur very near the biorefinery given that hauling cost will be many times higher per hectare for miscanthus than for stover due to yield differences between the two crops. Results show that even when miscanthus is grown in the immediate vicinity of the biorefinery, thus reducing the total size of the fuelshed, the total cost of supplying the required production by corn stover alone is less than the combination of miscanthus and any other second feedstock. It is important to continue to bear in mind that if nutrient pollution operates as a constraint on feedstock supply because of concerns about hypoxia or other water quality issues, perennial grasses will be preferred to corn stover unless integrating cover crops or other alternative management practices with corn stover removal can reduce nutrient loading to waterways.

Conclusions

This study evaluated the production and cost of 12 different cropping practices for biomass production. Two perennial grasses examined in this study, switchgrass and miscanthus, have much higher biomass yields than stover harvested from an annual corn crop. Though perennial grasses have large yields, costs associated with their production, loading-unloading operations and hauling are much higher than those of corn stover. These cost differences are largely a result of perennials' large establishment cost and the fact that the cost of growing corn grain is not attributed to corn stover.

Results show that to meet the required production of a biorefinery plant using only cropland within an agriculture dominated 2,083 km^2 watershed, perennial grasses must be planted to ensure enough production. Miscanthus is found to be more promising than switchgrass in this analysis because miscanthus has a longer life span to spread establishment costs over and yields much larger amounts of biomass than any other feedstock considered. The upland switchgrass variety studied has lower yields than lowland varieties considered in other studies and simulated switchgrass yields that are the basis of this are lower than observed experimental plot yields.

Viewed from the perspective of a biorefinery that is not constrained by a watershed boundary in determining its optimal fuelshed size, or if a lower production requirement is established, corn stover is expected to be the only feedstock grown on prime agricultural land. Since corn stover is the byproduct of corn grain, it does not require as much management and labor as perennial grasses, and it has great availability across the Corn Belt.

This analysis focused on a watershed in order to be able to model economic costs together with water pollution outcomes from different candidate feedstocks. From the perspective of environmental quality and pollution control, perennial grasses have many benefits over harvesting corn stover using the most conventional methods, especially where nutrients are concerned. Perennials generate less sediment loading, less nitrogen and phosphorus, as is demonstrated by the SWAT watershed model output that is the basis of this study. There are additional conservation benefits and benefits from reduction of green gas emissions that accompany perennial grasses (National Academy of Sciences, 2011). The tradeoff between perennial grasses and annual crops is mainly about cost and the level and form of environmental improvement desired by society. If environmental degradation is severe and policy makers favor making changes to improve water quality, certain no-till corn production with stover removal systems and perennial grasses are both capable of reducing N, P and sediment loadings to waterways, but if climate change mitigation is another policy objective, then perennial grasses may have the potential to deliver considerably larger benefits from greenhouse gas reductions. Higher cost perennial grasses may be incentivized through appropriately designed private contracts and/or through introduction of public subsidies to defray establishment costs.

In addition to environmental concerns, there is also a debate over “food versus fuel” that surrounds biofuels. Though perennial grasses are environmentally beneficial, they cannot provide food for human beings. Allocating land where food or feed crops were formerly produced for production of biofuels will result in land use changes and could play a role in food shortage as a result of expanding land shares of biofuel energy crops. The loss and gain should not be evaluated simply based on production cost, emissions and water pollutant loadings. Similarly, as demand for biomass production increases, it also puts pressure on forestry. On one hand, farmers may choose to cut forests to meet the high demand and make more profits, and the resulting release of carbon dioxide from converting rainforests, peatlands, savannas, or grasslands to produce biofuels is much higher than the annual greenhouse gas reductions these biofuels could provide by displacing fossil fuels (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008). On the other hand, indirect land change may happen. If there is widespread domestic production of perennial grasses in one country or area, farmers in other parts of the world may clear forests and grassland to new cropland to replace grain diverted to biofuels, such processes increase emissions and pose potential threats to the environment (Searchinger et al., 2008).

A comparison of the cost-minimizing solution from employing a genetic algorithm was not as low as a manually calculated result, but the use of a GA or other computational method was deemed necessary to meet production and pollution constraints simultaneously. Once more than one constraint or objective needs to be balanced, the brute force approach employed here becomes much more difficult. Right now, all the simulations are done using a desktop computer, but with greater computational power better simulation results using the GA approach can be expected. There is much room for improvement in terms of the GA deployed on a desktop computing platform; the best results are only about 4% higher cost than manually calculated optimum. That said, using basic economic logic was capable of finding a lower cost solution than the GA utilized in this study. Greater computational resources will enable larger initial population sizes and more sophisticated search algorithms. Because the application involves a mixed-integer optimization problem, the built-in Matlab GA program offers limited or no access to the core codes for elite selection, crossover functions and mutation functions. If the original codes could be modified directly or original crossover or mutation functions could be developed, better solutions to this class of problem may be possible. No existing methods for global optimization ensure that a global optimum is found, but there is considerable room for improvement and other non-GA stochastic methods could prove better suited to the dimensionality and discrete nature of this problem.

Possible Directions for Future Research

First, currently, the SWAT model cannot simulate the establishment years of perennial grasses, so model results may not accurately reflect the entire lifespan of perennial grasses. This issue is most relevant for pollutant results during the establishment years. Pollutant loadings are highly sensitive to factors such as soil conditions and water flow changes, and thus, efforts can be made to improve not only switchgrass parameterizations, but SWAT output over the entire production cycle of the plant.

Second, the centroid of the watershed was chosen as the location for a biorefinery for purely illustrative purposes. If the optimization model were adapted for use as model to select biorefinery location, the location could be selected that takes into account both cost and feasibility. More knowledge about logistics can be useful in finding the optimal biorefinery location. In reality, large machinery or trucks cannot enter some of the HRUs where road conditions are bad. More accurate characterization of farm fields together with transportation costs would improve the realism of the logistics dimension of this analysis. A closer look at details such as shortest ways to avoid city centers, whether or not to take toll roads, and what the actual speed limits of different trip segments over different hauling routes are would also be useful.

Third, real farmers may behave differently than modeled farmers when making choices. In practice it may be difficult to convince farmers to make changes that are not based on their own circumstances or persuade them to grow certain types of crops. Strategic responses by farmers facing policy changes could also complicate implementation and possibly increase costs. Therefore the optimal solutions could be changed accordingly. Besides, complexities of administrative tasks to manage pollutants and yields should be emphasized. Much work is needed to develop policies and programs that can encourage farmer participation. In addition, different farmer participation rates can be tested to show the extent to which decentralized farmer decisions about whether or not to supply biomass has an influence on the cost minimizing spatial allocation of crops and practices. This also serves as one way to compare the difference between a watershed and using a larger fuelshed for the scale of analysis. So far, the results can be identified down to the HRU level, which is already of importance for watershed management. If actual farm field scale data were available, the results would be even more accurate.

Though cellulosic biofuels have the potential for providing net environmental benefits compared to using petroleum-based fuels, many site specific factors influence environmental effects. It also depends on the type of feedstocks produced, the management practices used to produce them, prior land use, and any land-use changes that their production might induce (National Academy of Sciences, 2011). Hence, studies should be done taking into account the characteristics of specific sites.

Last but not least, Linden et al. (2000) pointed out that only long-term studies can assess management options over a wide variety of climatic inputs. By continuing treatments over a long period, soils approach equilibrium conditions based on a particular management scheme. Since research on some perennial grasses and stover removal began only in recent years, it is necessary to accumulate more knowledge and experience to better understand their potentials and problems.

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Table 1 Parameters for Corn Stover Removal Scenarios

Parameter		**Value**	**Source**
Stover to Corn grain Ratio		0.8:1	Linden et al. (2000), Pordesimo et al. (2004), Edgerton (2010), Purdue University WQFS (2012)
Stover Yield (dry ton/acre)		Location and Crop Rotation Specific (Table 5)	SWAT Output
Removal Rate		30%	Author's Assumptions
		50%	
Bale Size	Length (feet)	5	Perlack & Turhollow (2002)
	Diameter (feet)	6	
Bale Weight (dry lb/bale)		1270	
Raking ($/acre)		7.23	Miller (2012)
Round Baling with Wrap ($/bale)		12.08	
Moving to Storage ($/bale)		5.91	
Storage Area (acre/bale)		0.0008	Author's Calculation
Land Cost ($/acre)		182	Dobbins & Cook (2011)
Storage Loss		6%	Ji (2012)
N Application (lb/dry ton removed)		16.6	
P Application (lb/dry ton removed)		5.2	
K Application (lb/dry ton removed)		30.3	
NH_3 Price ($/lb)		0.55	2013 Purdue Crop Cost and Return Guide
P_2O_5 Price ($/lb)		0.62	
K_2O Price ($/lb)		0.53	

Table 2 Parameters for Switchgrass Scenarios

Parameter		**Value**	**Source**
Switchgrass Biomass Yield (dry ton/acre)		3.51	SWAT Output
Seeding Rate (lb/acre)		6	Purdue University WQFS
Seed Price ($/lb)		5	Sharp Bros. Seed Company
Reseeding Probability		25%	Duffy & Nanhou (2001), Khanna et al. (2008), Brummer et al. (2002)
Life Span (year)		15	Author's Assumption
Discount Rate		5%	
Bale Size	Length (feet)	5.5	Popp & Hogan (2007)
	Diameter (feet)	5	
Bale Weight (dry lb/bale)		1000	
Storage Area (acre/bale)		0.0008	Author's Calculation
Storage Loss		7%	Khanna et al. (2008)
Land Cost ($/acre)		182	Dobbins & Cook (2011)
Field Cultivation ($/acre)		11.55	Miller (2012)
Disk-tandem ($/acre)		12.32	
Mowing and Conditioning ($/acre)		15	
Raking ($/acre)		7.23	
Round Baling with Wrap ($/bale)		12.08	
Moving to Storage ($/bale)		5.91	
Nitrogen Application: Production Years (lb/acre)		50	Purdue University WQFS
Lime Application: Establishment Year (ton/acre)		2	Ji (2012)
Atrazine Application (qt/acre): Establishment and Re-establishment Year		1.25	
2,4-D Application (pt/acre): Establishment and Re-establishment Year		1.25	
Urea (45% Nitrogen) Price ($/lb)		0.65	2013 Purdue Crop Cost and Return Guide
Lime Price ($/ton)		19	
Atrazine Price ($/gallon)		16.54	University of Arkansas Extension 2012
2,4-D Price ($/gallon)		17.15	
Opportunity Cost ($/acre average net revenue from corn-soybean rotation)		457	2013 Purdue Crop Cost and Return Guide

Table 3 Parameters for Miscanthus

Parameter		**Value**	**Source**
Miscanthus Biomass Yield (dry ton/acre)		10.49	SWAT Output
Rhizome Density (number of rhizome/acre)		3919	
Rhizome Price ($/rhizome)		0.45	Yoder (2010)
Life Span (year)		15	Author's Assumption
Discount Rate		5%	
Bale Size	Length (feet)	5.5	
	Diameter (feet)	5	
Bale Weight (dry lb/bale)		1000	
Storage Area (acre/bale)		0.0008	Author's Calculation
Storage Loss		7%	Khanna et al. (2008)
Land Cost ($/acre)		182	Dobbins & Cook (2011)
Chisel Plow ($/acre)		14.52	Miller (2012)
Disk-tandem ($/acre)		12.32	
Mowing and Conditioning ($/acre)		15	
Raking ($/acre)		7.23	
Round Baling with Wrap ($/bale)		12.08	
Moving to Storage ($/bale)		5.91	
Nitrogen Application: Production Year (lb/acre)		50	Purdue University WQFS
Phosphorus Application: Production Year (lb/ton removed)		0.666	Khanna et al. (2008), James et al. (2010), Yoder (2010)
Potassium Application: Production Year (lb/ton removed)		9.21	
Lime Application: Establishment Year (ton/acre)		1.82	
Atrazine Application (qt/acre): Establishment Year		1.25	
2,4-D Application (pt/acre): Establishment Year		2.61	
Urea (45% Nitrogen) Price ($/lb)		0.65	2013 Purdue Crop Cost and Return Guide
P_2O_5 Price ($/lb)		0.62	
K_2O Price ($/lb)		0.53	
Lime Price ($/ton)		19	
Atrazine Price ($/gallon)		16.2	University of Arkansas Extension 2012
2,4-D Price ($/gallon)		16.8	
Opportunity Cost ($/acre average net revenue from corn-soybean rotation)		457	2013 Purdue Crop Cost and Return Guide

Table 4 Loading and Unloading Cost for Large Round Bales

Activity	Time (hrs)	Hourly Wage ($/hr)	Corn ($/bale)	SG & Mxg ($/bale)	Source
Loading			1.31	1.31	Petrolia (2006)
Unloading			1.31	1.31	
Truck Wait	1.329	19.15	0.85	0.85	Berwick & Farooq (2003), Thompson (2011)
Oversize Permit			0.02	0.02	Author’s Estimate
Total			3.70	3.70	

Table 5 Summary of Farm-gate Costs

		Yield (DM ton/ac)	$/acre	$/ha	$/DM ton	$/metric ton
Scenario 1	Baseline CS	0	0	0	0	0
Scenario 2	CSNoTill30 without NR	1.28	21.98	54.29	18.29	20.12
Scenario 3	CSNoTill30 with NR	1.29	41.81	103.27	34.47	37.91
Scenario 4	CSNoTill50 without NR	2.13	40.23	99.36	20.09	22.10
Scenario 5	CSNoTill50 with NR	2.17	73.77	182.22	36.24	39.87
Scenario 6	CCNoTill30 without NR	1.30	44.80	110.66	36.57	40.23
Scenario 7	CCNoTill30 with NR	1.31	84.94	209.79	68.93	75.83
Scenario 8	CCNoTill50 without NR	2.16	81.37	200.97	40.14	44.15
Scenario 9	CCNoTill50 with NR	2.18	148.74	367.40	72.45	79.70
Scenario 10	Switchgrass	3.51	773.95	1911.66	236.84	260.52
Scenario 11	SwitchgrassNoTill	3.51	770.86	1904.02	235.89	259.48
Scenario 12	Miscanthus	10.49	1268.42	3133.00	130.03	143.03

Table 6 Total Cost of Each Cropping Scenario if Planted Across Entire Watershed

		Total Production (metric ton)	Farm-gate Cost	Hauling Cost	Total Cost
Scenario 1	Baseline CS	0	0	0	0
Scenario 2	CSNoTill30 without NR	192,552	7,887,313	1,152,345	9,039,658
Scenario 3	CSNoTill30 with NR	194,322	15,002,429	1,166,530	16,168,959
Scenario 4	CSNoTill50 without NR	320,698	14,433,617	1,918,219	16,351,836
Scenario 5	CSNoTill50 with NR	326,075	26,471,387	1,952,212	28,423,600
Scenario 6	CCNoTill30 without NR	392,465	16,076,178	2,348,771	18,424,950
Scenario 7	CCNoTill30 with NR	394,760	30,476,956	2,364,556	32,841,512
Scenario 8	CCNoTill50 without NR	649,417	29,195,752	3,884,974	33,080,726
Scenario 9	CCNoTill50 with NR	657,718	53,372,566	3,939,230	57,311,796
Scenario 10	Switchgrass	1,064,042	277,709,355	8,182,752	285,892,107
Scenario 11	SwitchgrassNoTill	1,064,050	276,600,142	8,182,752	284,782,894
Scenario 12	Miscanthus	3,176,365	455,136,117	24,307,703	479,443,821

Table 7 Total and Average per Hectare Pollutant Loadings for Each Cropping Scenario

	Total Sediment (metric tons)	Sediment (metric ton/ha)	Total N (kg)	N (kg/ha)	Total P (kg)	P (kg/ha)
Baseline CS	587,227	5.676	3,374,119	26.851	337,538	2.890
CSNoTill30 without NR	563,157	5.433	3,021,438	23.323	366,947	3.002
CSNoTill30 with NR	563,498	5.436	3,152,386	24.311	375,571	3.073
CSNoTill50 without NR	583,394	5.628	2,92,0571	22.513	346,757	2.830
CSNoTill50 with NR	583,987	5.632	3,094,668	23.820	361,331	2.949
CCNoTill30 without NR	524,295	5.044	3,471,210	26.565	340,284	2.791
CCNoTill30 with NR	526,039	5.060	4,038,052	31.014	357,245	2.930
CCNoTill50 without NR	551,336	5.304	2,889,451	22.079	299,888	2.451
CCNoTill50 with NR	554,876	5.335	3,599,485	27.633	328,014	2.681
Switchgrass	2,946	0.029	1,453,251	10.526	14,511	0.108
SwitchgrassNoTill	2,945	0.029	1,453,073	10.525	15,247	0.114
Miscanthus	2,671	0.026	681,210	4.795	13,135	0.096

Table 8 Pollutant Level Details for Key Spatial Allocations of Practices Meeting the Full Production

	Total Sediment (metric ton)	Total N (kg)	Total P (kg)	Percentage of Baseline		
				Total Sediment	Total N	Total P
Baseline	587,227	3,374,119	337,538	N/A	N/A	N/A
Manually Calculated Optimum	353,475	2,968,415	244,435	60.2%	88%	72.4%
3 Scenarios Optimization Results	378,187	2,741,018	238,313	64.4%	81.2%	70.6%

Figure 1 Share of Land Area for Each Chosen Scenario. 12 Scenarios, Population Size 10,000

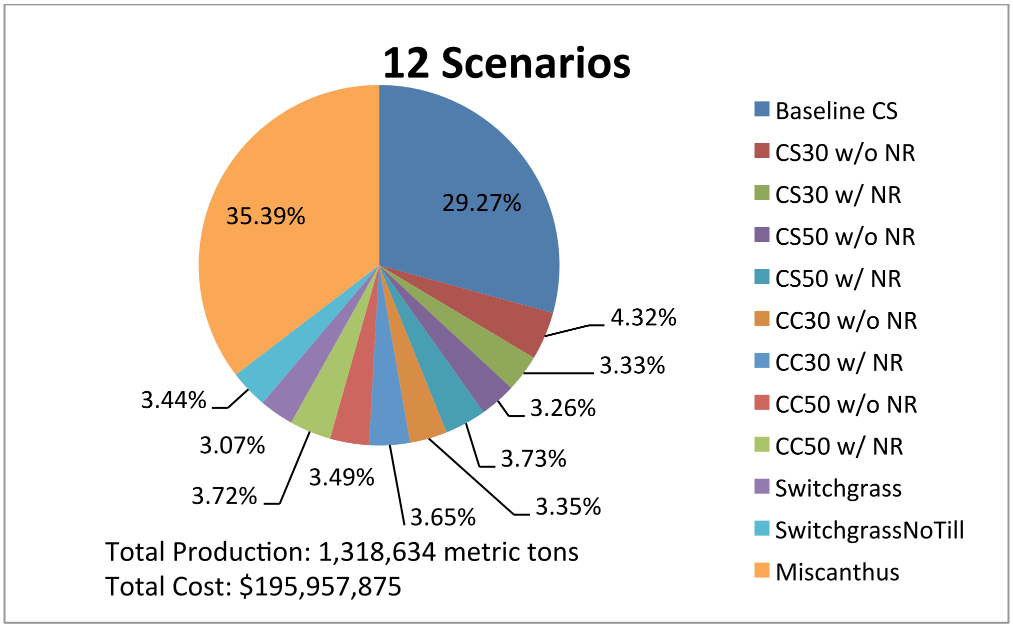
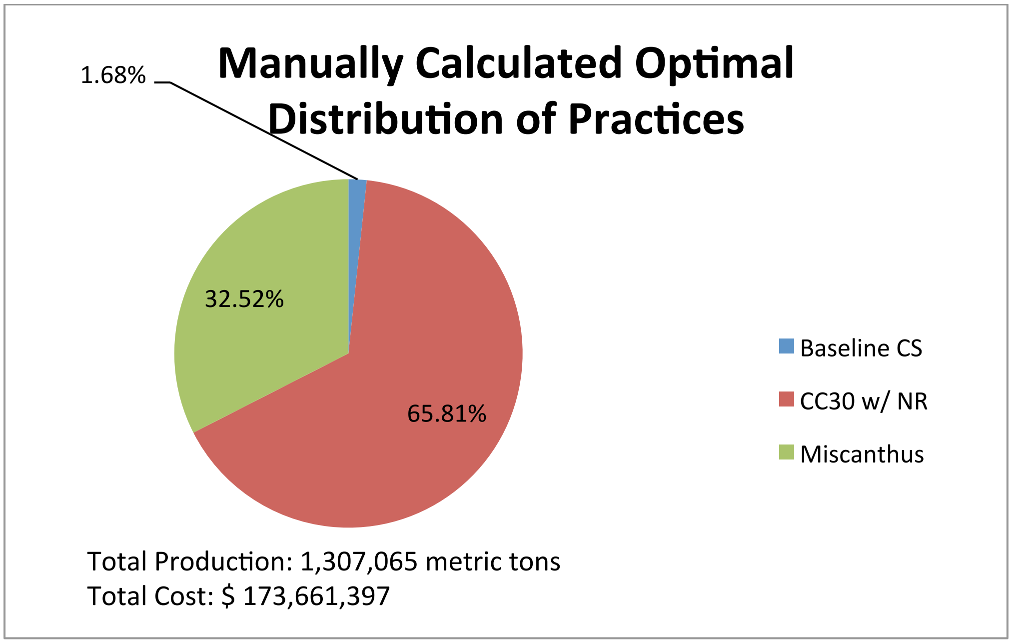
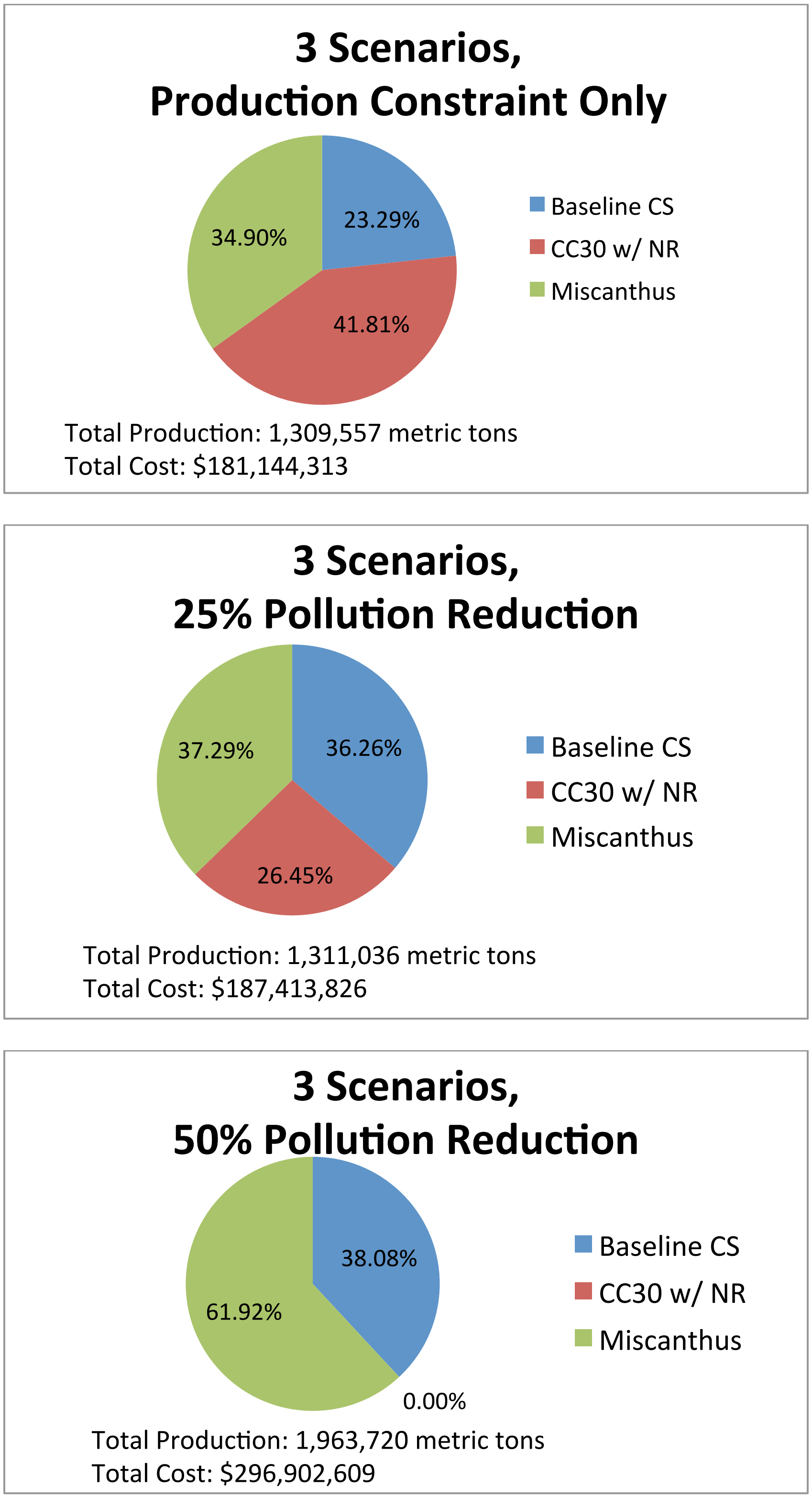


Figure 2 Share of Each Cropping Practice for the Manually Calculated Optimal Solution



Total Production: 1,307,065 metric tons
Total Cost: $ 173,661,397

Figure 3 Land Share of Different Scenarios under Only Production and under Both Production and Pollutant Constraints (25% and 50% Reduction in Each Pollutant Level)



3 Scenarios,
Production Constraint Only

Total Production: 1,309,557 metric tons
Total Cost: $181,144,313

3 Scenarios,
25% Pollution Reduction

Total Production: 1,311,036 metric tons
Total Cost: $187,413,826

3 Scenarios,
50% Pollution Reduction

Total Production: 1,963,720 metric tons
Total Cost: $296,902,609