Supply of Cellulosic Biofuel Feedstocks and Regional Production Pattern

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Interest in cellulosic biofuels has grown due to recent concerns about the impact of expanding production of corn ethanol on food prices and the greater potential of cellulosic biofuels to mitigate climate change. The Energy Independence and Security Act (EISA) of 2007 limits the production of corn ethanol to 56 billion liters after 2015 and mandates the production of at least 80 of the 136 billion liters of ethanol from non–corn starch–based cellulosic feedstocks by 2022. The Biomass Research and Development Act of 2000 had established an even more ambitious goal of using biomass to replace the equivalent of 30% of current petroleum consumption by 2030 and estimated that this would require 1 billion dry (short) tons of biomass annually (U.S. Department of Energy [USDOE 2003]). Biomass can be obtained from several different sources, including forest resources, crop residues, woody biomass, and perennial grasses. A USDA/USDOE report (Perlack et al. 2005) examined the technical feasibility of sustaining this supply of biomass and the land resources that would be required under alternative scenarios with yield-enhancing and other technological changes in conventional crops and perennial bioenergy crops. The study estimated that 0.54 to 1 billion dry tons of agricultural crop-based biomass could be obtained annually from cropland, idle cropland, and cropland pasture with moderate to high productivity gains in crop productivity, residue collection, and tillage practices.

The extent to which this technical potential is economically viable and the biomass price can be realized will depend on the incentives for agricultural producers to harvest and deliver crop residues and to switch land from conventional crops to perennial grasses. These incentives include the price offered for biomass, which must cover the cost of harvesting, storing, and transporting the biomass. In the case of perennial grasses, it must also cover their cost of establishment and the opportunity cost of land.

This paper has two purposes. First, we seek to examine the economically viable supply of agricultural biomass at various biomass prices and the mix of cellulosic feedstocks that will be produced at these prices. We examine this relationship under alternative assumptions about costs of production of these feedstocks, productivity of perennial grasses, and availability of land. Second, we examine the regional pattern of production of various cellulosic feedstocks and the spatial mix of feedstock production. The supply of various feedstocks and location of biomass production is determined simultaneously with the most profitable use of the land given the demands for food, feed, fuel, and livestock production at various biomass prices. This incorporates the competition for land among perennial grasses, food/feed and livestock production, and the effect of the profitability of producing conventional crops on the supply of crop residues.

We undertake this analysis by applying a dynamic, multimarket equilibrium, nonlinear mathematical programming called Biofuel and Environmental Policy Analysis Model (BEPAM). This model endogenously determines land allocation, crop production, and prices in markets for fuel, biofuel, food/feed crops, and livestock in the United States at annual time scales over 2007–2030. The dynamic model incorporates changes in yields and costs of production of perennial grasses
over their life cycle. The model considers the 295 Crop Reporting Districts (CRDs) in forty-one states as the spatially heterogeneous decision units and reports on their simulated crop production and land allocation decisions for 2030.

Simulation Model

BEPAM includes major row crops and livestock and considers biomass from two crop residues, corn stover and wheat straw, and two perennial grasses, switchgrass and miscanthus. Demand functions for domestic consumption and for exports and imports of tradable commodities are specified for individual commodities, including crop and livestock products. These demand functions are shifted upward over time at exogenously specified rates to allow for increasing demand for food and feed over time. The supply of crops and livestock to meet demand for food and feed is endogenously determined based on their costs of production and yields that vary across CRDs. The crop and livestock sectors are linked to each other through the supply and use of feed and also through the competition for land (because pastureland needed by the livestock sector has alternative crop uses). Exogenously set biomass prices trigger incentives for reallocation of land among various row crops and bioenergy crops until a new equilibrium is achieved in all markets. Market equilibrium is simulated by maximizing the sum of producers’ and consumers’ surplus across all the markets subject to various material balance and technological and land availability constraints (for details, see Chen et al. 2010).

We consider two types of land, existing cropland and idle land/pastureland. A change in crop prices triggers change at the extensive margin and leads to a shift in acreage between cropland and idle land/pastureland. Cropland can be used for crops or bioenergy crops. Bioenergy crops can also be grown on the remaining idle land/pastureland but with a conversion cost. In the absence of an empirically based estimate of the ease of conversion of marginal land for perennial grass production, we assume a CRD specific conversion cost equal to the returns the land would obtain from producing the least profitable annual crop in the CRD. This ensures consistency with the underlying assumption of equilibrium in the land market, in which all land with nonnegative profits from annual crop production is utilized for annual crop production. As annual crop prices increase, the cost of conversion increases; the “supply curve” for idle marginal land is, therefore, upward sloping. The perennial nature of bioenergy crops requires farmers to make planting decisions for a long-term planning horizon based on price expectations. However, these decisions can be revisited over time if actual price realizations differ from their expectations. We incorporate these considerations using a rolling horizon approach where producers make decisions for a ten-year planning period, revise these following the realization of the market equilibrium in the first year, and make decisions for the next ten years. The biomass price is kept constant over the 2007–2030 period. Crop production is assumed to meet the demand for food, feed, and, in the case of corn, biofuel; the latter is determined by the mandate for corn ethanol under EISA and maintained at the 56 billion liter level after 2022. Land allocation across several crop rotation and tillage practices is determined endogenously by net returns; this allocation differs across space and over time and influences the availability of crop residues. The model simultaneously determines the quantity of biomass produced from each feedstock and the land allocated to various crops in each CRD, commodity prices, production, consumption, and trade in crop and livestock commodities for each year (2007–2030).

Data

The simulation model incorporates data on costs of producing crop and livestock commodities for each of the 295 CRDs at 2007 prices for fifteen major row crops in the United States, alfalfa, and two bioenergy crops, switchgrass and miscanthus. These two grasses have been identified as among the best choices for low-input and high dry matter yield per hectare (Jain et al. 2010). A review of literature shows that annual yield of the lowland variety of switchgrass ranges between 11 and 16 metric tons of dry matter per hectare (MT/ha) and is about 50% higher than that of the upland varieties, which are suitable for major portions of the upper Midwest (Lemus and Parrish 2009). In the absence of long-term observed yields for switchgrass and miscanthus for each CRD, we use a crop productivity model, MISCANMOD, to simulate the yields of miscanthus and upland
varieties of switchgrass, using Geographic Information Systems data on climate, soil moisture, solar radiation, and growing degree days. Switchgrass yields from MISCANMOD were increased by 50% for all regions other than the upper Midwest to allow for higher yields of lowland varieties. Production of these crops is limited to the rainfall regions (see U.S. Farm Production Regions at http://www.usda.gov/news/pubs/factbook/002a.pdf), which include the Northern and Southern Plains, Midwest (Corn Belt and Lake States), South (Delta States and Southeast), and Atlantic (Appalachia and Northeast), while conventional crops can be grown in the Western region (Pacific and Mountain) as well. Switchgrass and miscanthus are long-lived grasses with annual yields that differ over their lifetime (Jain et al. 2010). Simulated yields also differ spatially due to differences in climatic factors. The average delivered yield of miscanthus is highest in the Atlantic states at 31.6 MT/ha, followed by the South at 30.2 MT/ha, the Midwest at 23.8 MT/ha, and the Plains at 19.8 MT/ha. Corresponding estimates for average switchgrass yield are 16.4, 15.2, 10.7, and 11 MT/ha, respectively. Note that delivered yields account for losses during harvesting, storing, and transporting, and switchgrass yield in most regions is about 50% of that for miscanthus. For row crops, we use the historical five-year (2003–2007) average yield per hectare for each CRD as its representative yield (National Agricultural Statistics Service [NASS09]). The yields of corn, soybeans, and wheat are assumed to grow over time and are price elastic (Chen et al. 2010). Corn stover yields are estimated based on a 1 : 1 grain-to-residue ratio, while wheat straw yields are estimated assuming a 1 : 1.5 grain-to-residue ratio. The sustainable removal rate for corn stover is assumed to be 30% with conventional till and 50% with no till, while for wheat straw it is 50%. In contrast to miscanthus, the average delivered yield for corn stover is highest in Midwestern and Plain states at 4.0 MT/ha, followed by southern and western states at 3.3 and 3.2 MT/ha, respectively. Atlantic states have the lowest corn stover yield at 2.8 MT/ha, while wheat straw delivered yield is highest in the West at 3.1 MT/ha, followed by the Midwest at 2.3 MT/ha and less than 2 MT/ha in other regions.

Costs of producing row crops and alfalfa vary by rotation, tillage, and irrigation practices across CRDs based on the crop yields per hectare for each crop and practice. Costs of producing corn stover and wheat straw include the additional cost of replacement nutrients. Agronomic assumptions about fertilizer, seed, and pesticide application rates for switchgrass and miscanthus and the costs of harvesting, storing, baling, and transporting biomass from farmgate to the biorefinery located 50 kilometers away are described in Jain et al. (2010) under two alternative scenarios, high cost and low cost. The two scenarios differ in their assumptions about nutrient requirements, ease of establishment of the grasses, and harvest-related loss in yields and costs. In each case, these costs differ over the life of the crop and across space due to differences in yields, costs of field operations, input prices, and implicit opportunity costs of land. Costs could be higher than those estimated here with longer transportation distances, satellite processing facilities, and indoor storage of biomass to preserve quality.

County-specific data on land availability in different classes are obtained from NASS (2009). Land availability is limited to the 319 million hectares (M ha) of land that is considered cropland (C) and pastureland in 2007, with cropland accounting for 39% (125 M ha) of the total. Pastureland includes 15 M ha that are classified as idle cropland (CI), which is mostly Conservation Reserve Program (CRP) acres, 13 M ha of cropland pasture (CP) (which moves in and out of active crop production depending on economic viability), 155 M ha of permanent pastureland, and 10 M ha of woodland pasture. We keep the level of permanent pastureland and woodland pasture fixed at 2007 levels but allow CI and CP to move into and back into an idle state. It can also be used for perennial bioenergy crop production. The land cost of using CI (including CRP) and CP to produce bioenergy crops is assumed to be the same and equal to the returns from the least profitable crop produced in that CRD. We impose a limit of 25% on the amount of land (C + CI + CP) in a CRD that can be converted to perennial grasses due to concerns about the impact of monocultures of perennial grasses on biodiversity or subsurface water flows. Crop acreage price elasticities, the opportunity cost of land, and implications of expanding crop production to CI and CP for average yields of conventional crops in each CRD as well as other data used are described by Chen et al. (2010). Yields of perennial grasses are assumed to be unaffected by soil quality.
We examine the impact of several biomass prices ranging from $20/MT to $140/MT in $10 intervals under six different scenarios. Figure 1 shows the amount of biomass produced in 2030 at each price, assuming that price is maintained for the 2007–2030 period. Scenario 1 considers low costs for the production of all cellulosic feedstocks with an upper limit of 25% of C + CI + CP for the available land in a CRD to produce perennial grasses. In other scenarios, we change one assumption at a time. Scenario 2 is similar to Scenario 1 but considers 50% higher yields per hectare for switchgrass. Scenario 3 considers a higher residue collection rate for corn stover of 50% under conventional till and 70% under no-tillage practices that could be technically feasible and environmentally sustainable with future residue collection technology (Perlack et al. 2005). In Scenario 4 CRP acreage is preserved at 32 M ha (as authorized by the Food, Conservation, and Energy Act) from 2008 onward and not used for conventional crop or bioenergy crop production due to environmental concerns. Scenario 5 considers high costs for the production of all cellulosic feedstocks, while Scenario 6 considers low costs of production of switchgrass, corn stover, and wheat straw and high costs of production of miscanthus.

Biomass production is found to be viable at about $40/MT, except in Scenarios 2 and 3, where it becomes viable at $30/MT from switchgrass and corn stover, respectively. In Scenario 5, with high costs of production, large-scale production becomes viable only at a price of $50/MT. The amount of production varies considerably across scenarios—at $40/MT, it ranges from 406 million metric tons (MMT) under Scenario 3 to 0.3 MMT under Scenario 5. At a price of $140/MT, maximum production of biomass is 923 MMT under Scenario 3 and 617 MMT under Scenario 6. Compared with Scenario 1, the imposition of the constraint that CRP land cannot be used for biomass production reduces total biomass availability by 27% at the price of $40/MT; this difference diminishes as the biomass price increases and perennial grass production becomes viable on cropland. High costs of production of miscanthus in Scenarios 5 and 6 pose a larger constraint on the economically viable level of biomass production at various prices than the availability of land in Scenario 4. Perlack et al. (2005) estimated that 623 MMT is available from perennials and crop residues under an optimistic scenario of productivity growth and availability of perennial grasses. Our analysis shows that this quantity could be available at a price of $60–70/MT but could require a price of $140/MT under less optimistic cost conditions, particularly for a high-yielding grass like miscanthus.

We find that the supply curves for biomass from switchgrass and wheat straw are fairly steep, and together these feedstocks provide less than 10%, even at a high biomass price, with the exception of Scenarios 2, 5, and 6. In these three scenarios, switchgrass production is much higher, even at relatively low biomass prices; however, the supply curve for switchgrass is backward bending, because switchgrass competes with miscanthus for land and is much more competitive with miscanthus at low biomass prices than at high biomass prices. As biomass price increases, the relatively higher yields of miscanthus compared with that of switchgrass result in much higher returns per hectare on land under miscanthus, and therefore land allocated to miscanthus increases while that under switchgrass decreases. With 50% higher yields in Scenario 2, biomass production from switchgrass is five times higher than in Scenario 1, at the price of $40/MT, and switchgrass provides more than 60% of total biomass production. High yield of switchgrass results in an expansion of land under switchgrass and less land under miscanthus compared with Scenario 1. But if biomass prices are expected to be above $40/MT, land under switchgrass decreases, while that under miscanthus would increase. The share of switchgrass falls to 7% at the price of $140/MT. Similarly, switchgrass production exceeds that of miscanthus in Scenario 6 and provides more than 50% of total biomass below $70/MT, but its share declines relative to miscanthus declines at higher prices.

In Scenario 1, corn stover production increases from 17 MMT to 161 MMT as biomass price increases from $40 to $80/MT but tends to level off after that. In Scenario 3, production of corn stover could increase to 227 MMT in 2030 (which is close to the optimistic amount projected by Perlack et al. [2005]) but at a price of $140/MT. The share of crop residues in total biomass increases to about 40% at low biomass prices in Scenario 3 with high collection rates of crop residues. Miscanthus provides a significant share of the total biomass produced, and its production is fairly price elastic; its production increases from about 200 MMT at a price of $40/MT
to about 640 MMT at a price of $140/MT in Scenario 1. With high costs of producing it in Scenarios 5 and 6, miscanthus production is viable at $60/MT and $70/MT, respectively, and its share in the total biomass is much smaller than in Scenario 1 at corresponding prices. Restricting the use of CRP land reduces production of switchgrass by about 40% and of miscanthus by about one-third at low prices relative to Scenario 1. The effect on miscanthus is less than 15% at prices above $100/MT because at those prices miscanthus production becomes viable on regular cropland.

In the table, we show the land requirements for feedstock production at biomass prices of $50/MT and $100/MT. At a price of $50/MT, perennial grasses would not be planted in Scenario 5. In other scenarios, land under miscanthus and switchgrass ranges between a low of 9.4 M ha at $50/MT in Scenario 4 and 23 M ha at $100/MT under Scenarios 2 and 3. Due to the lower opportunity cost of CI and...
Table 1. Land Used for Cellulosic Feedstock Production Under Various Production Conditions

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Biomass Price ($/metric ton)</th>
<th>Low Cost of Production</th>
<th>50% Higher Switchgrass Yield</th>
<th>High Rates of Residue Collection</th>
<th>Exclusion of CRP Land</th>
<th>High Cost of Miscanthus and Low Costs of Other Feedstocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional crops (M Ha)</td>
<td>50</td>
<td>117.55</td>
<td>117.52</td>
<td>117.54</td>
<td>117.66</td>
<td>122.04</td>
</tr>
<tr>
<td>Conventional crops (M Ha)</td>
<td>100</td>
<td>113.23</td>
<td>113.11</td>
<td>112.85</td>
<td>111.37</td>
<td>117.09</td>
</tr>
<tr>
<td>Bioenergy crops (M Ha)</td>
<td>50</td>
<td>16.03</td>
<td>16.92</td>
<td>16.05</td>
<td>9.40</td>
<td>0</td>
</tr>
<tr>
<td>Bioenergy crops (M Ha)</td>
<td>100</td>
<td>22.76</td>
<td>22.94</td>
<td>23.15</td>
<td>17.81</td>
<td>17.17</td>
</tr>
<tr>
<td>Idle cropland/cropland pasture</td>
<td>50</td>
<td>15.76</td>
<td>16.56</td>
<td>15.76</td>
<td>8.98</td>
<td>0</td>
</tr>
<tr>
<td>Idle cropland/cropland pasture</td>
<td>100</td>
<td>17.58</td>
<td>17.59</td>
<td>17.59</td>
<td>9.78</td>
<td>16.26</td>
</tr>
<tr>
<td>Total biomass (MMT)</td>
<td>50</td>
<td>504.46</td>
<td>512.29</td>
<td>619.77</td>
<td>358.12</td>
<td>39.18</td>
</tr>
<tr>
<td>Wheat straw (M Ha)</td>
<td>100</td>
<td>758.64</td>
<td>775.50</td>
<td>836.12</td>
<td>660.11</td>
<td>525.00</td>
</tr>
<tr>
<td>Crop price index</td>
<td>50</td>
<td>1.05</td>
<td>1.04</td>
<td>1.03</td>
<td>1.03</td>
<td>1.01</td>
</tr>
<tr>
<td>Crop price index</td>
<td>100</td>
<td>1.06</td>
<td>1.06</td>
<td>1.04</td>
<td>1.07</td>
<td>1.01</td>
</tr>
</tbody>
</table>

Note: CRP = Conservation Reserve Program; M Ha = million hectares; MMT = million metric tons.
most of the miscanthus production occurs on this land, particularly at biomass prices below $60/MT in all scenarios and even at high biomass prices in Scenarios 5 and 6. Switchgrass production is primarily competitive on noncropland at all biomass prices in all scenarios. In case costs of producing switchgrass are low and costs of miscanthus are high, acreage under switchgrass could expand significantly to as much as 17 M ha at $70/MT and be larger than that under miscanthus. However, even in this case, at biomass prices above $80/MT, switchgrass acreage declines as noncropland is used for miscanthus.

Acreage on which crop residues are harvested, in particular wheat straw, also increases several fold as the biomass price increases. Corn stover is harvested on 10% of corn acreage at a price of $40/MT and about 97% of acreage at a price of $140/MT across all the scenarios. Similarly, wheat straw is harvested on only 25% of the wheat acreage at a price of $40/MT and 95% of acreage at a price of $140/MT. A high price for biomass does not induce a substantial increase in corn and wheat acreage; thus biomass from crop residue is limited by acreage under corn, and wheat and does not change much as biomass prices rise in all scenarios. Total land on which residues are harvested at a low biomass price is considerably higher in Scenario 3 than in other scenarios, indicating the importance of crop yields and residue collection rates in making crop residues a viable source of biomass.

Land under conventional crops declines by 1–5% as biomass price increases from $50 per MT to $100 per MT and some cropland is converted to miscanthus; this decline is lower in Scenarios 5 and 6, where miscanthus production costs are high. Exclusion of CRP land for producing perennial grasses reduces the marginal land in CI and CP available for these grasses. It also reduces the potential for expansion of cropland on land formerly under CI and CP and thus results in less land under crop production. The last two rows in the table show the effect of diversion of cropland for bioenergy crops on a composite crop price index in 2030 relative to business as usual with no biomass production. Crop price index is found to increase by at most 7% even at high biomass prices and with restriction on CRP land use.

Figure 2 (a)–(c) shows the spatial distribution of production of the four cellulosic feedstocks at a price of $50 per MT in Scenario 1. We find that of the total corn stover produced (96 MMT), 65% is produced in the Midwest and 28% in the Plains, while wheat straw production is more evenly distributed in the Northern Plains and the West. In contrast, of the total miscanthus produced (352 MMT), 38% is in the Plains, 27% in the Midwest, 20% in the Atlantic, and 14% in the Southern states. Switchgrass production occurs mainly in the Southern Plains and in some northern states. The spatial pattern of biomass production changes across scenarios. For instance, in Scenario 6 with low costs for switchgrass and high costs for miscanthus, there is no production of miscanthus at a price of $50/MT, while a substantial amount of switchgrass, 187 MMT,
is produced primarily in the Plains (48%) and the Atlantic states (20%).

Conclusions

Our analysis shows that 617–923 MMT of biomass can be produced in 2030 at a price of $140/MT depending on residue collection technology, costs of producing bioenergy crops, and their yields and land availability. At that price, it would lead to the use of about 18 M ha of idle cropland or cropland pasture for perennial grasses. Restricting the use of CRP land makes it economically feasible to produce only 80–90% of biomass compared with what would be otherwise viable. Even greater reduction in production is likely to occur if costs of producing biomass crops are high. Corn stover production is sensitive to the residue collection rate, while the role of switchgrass and miscanthus as cellulosic feedstocks depends not only on their own yields and costs of production but on their costs relative to each other, since they both compete for the same noncropland. Miscanthus has the potential to provide 50% to 70% of the total biomass across the various scenarios and prices considered. Switchgrass can make a substantial contribution to total biomass if its yields are high and costs of production are low while those of miscanthus are high, particularly at low biomass prices.

Our analysis used Scenario 1 as the benchmark and considered deviations from it one at a time. It is possible that various combinations of these changes might occur simultaneously, leading to higher or lower levels of biomass than projected at a given price. Nevertheless, it provides a quantitative assessment of the economic and regional potential for biomass production under various conditions. It also shows that although it is possible to produce a billion tons of biomass while meeting demand for food/feed, very high biomass prices would be needed to make it viable under current assumptions about yields and costs of production.

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References


