TRANSITION TO A BIO ECONOMY

Environmental and Rural Development Impacts

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Weaning Off Corn: Crop Residues and the Transition to Cellulosic Ethanol

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Abstract: Recent legislation has set ambitious targets for cellulosic ethanol to be realized in the not-too-distant future. While corn-based ethanol will continue to be the most important supply, its share—but not the quantity—will diminish over time. How agriculture responds to market and environmental challenges will be in large part governed by the evolution and adoption of cellulosic ethanol production technology. One possible scenario is that development of cellulosic production technology occurs more rapidly than expected, before the establishment of alternative cellulosic feedstocks, enabling crop residues to be used in lieu of corn during the transition to dedicated energy crops. This article examines the market and environmental consequences of shifting biofuel production from corn to cellulosic production technology fed by crop residues. Results show that reducing corn required for ethanol by increasing production of crop residue-based cellulosic ethanol shifts crop production and changes tillage and rotation choice. These changes demonstrate mixed effects on key environmental indicators, with benefits and adverse consequences varying regionally.

Recent and recurring episodes in energy markets, environmental concerns, and growing concerns about dependency on oil imports have fueled great interest in biofuels. Demand for biofuels has expanded the market for agricultural products, putting pressure on the land base and squeezing competitive demands for corn. Emerging biofuel production technologies will in fact create new agricultural products, which will compete for land and resources with traditional crops. These new products, while promising for the long-term, are not yet planted in commercial quantities, and are unlikely to be major components of the first wave of cellulosic ethanol production. Concurrently, high prices for food and feed have led to calls for reduced reliance on traditional crops for the production of biofuels.

Recent legislation has set ambitious targets for cellulosic ethanol to be realized in the not-too-distant future. Throughout the duration of the legislation, corn-based ethanol will continue to be the most important supply, but its share—not its quantity—will diminish over time. How agriculture responds to market and environmental challenges will be in large part governed by the evolution of cellulosic ethanol. One possible scenario is that development of cellulosic production technology occurs more rapidly than expected, before the establishment of alternative cellulosic feedstocks, enabling crop residues to be used in lieu of corn during the transition to dedicated energy crops. This article examines the market and environmental consequences of shifting biofuel production from corn to nascent cellulosic production technology fed by crop

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residues. Results show that taking pressure off corn by encouraging crop residue-based cellulosic ethanol provides some environmental gains.

Over the history of domestic biofuel production the predominant feedstock has been corn. During most of that time, ethanol has been a small market for corn growers. Recently, however, the share of total domestic corn production supplying the ethanol market has grown, rising from 7.5% (705 million bushels) in 2001 to 22.6% (2950 million bushels) in 2007 (USDA-ERS, 2008). This share is expected to climb even further, to around 35%, when corn ethanol production reaches 15 billion gallons. This diversion of a significant portion of the corn crop for energy uses has sparked a wide debate on its effects on food and feed prices, both domestically and internationally. Also, because of the relatively intensive nature of corn production, the effects on the environment of greater corn production at the expense of other, less intensive crops are of concern.

Technological advances in production of ethanol from cellulosic feedstocks promise to be commercially realized in the near future. Recent policy initiatives, such as the Energy Independence and Security Act of 2007 (EISA), are founded on the premise that such technology will come online soon and grow at a rate that will make cellulosic-based ethanol a majority of production by 2022. While there is a provision in the legislation for waivers of mandated levels for cellulosic-based biofuels, predictions about when and how much cellulosic capacity will actually be available range from very pessimistic to very optimistic.

As new technologies emerge, corn will remain the predominant feedstock for ethanol production, but different cellulosic feedstocks will compete to supply the new refineries. Crop residues, such as corn stover and wheat straw, are already widely available, although significant markets for residues do not currently exist. Crop residues do, however, play an important role in nutrient, erosion, and carbon levels in the soil, and the amount of residue that can be harvested while maintaining soil productivity is affected by tillage regime and other factors (USDA-NRCS, 2006). Switchgrass and other perennial grasses present high-yielding alternatives to crop residues. While they show promise in field trials, these grasses are not yet grown on a commercial scale, and issues of farmer adoption, logistics, and market institutions will need to be resolved before large-scale production of these crops takes place. Since the management practices that will prevail are unknown, the consequences to the environment of large-scale production of perennial grasses are difficult to assess. Short-rotation woody crops, such as willow and poplar, are another feedstock option. These are fast growing trees that produce sufficient biomass for harvest in a few years, rather than the decades common in traditional forestry. These crops are also not currently grown on a wide scale. While it is impossible to forecast the supply of each feedstock with certainty, it is reasonable to assume that crop residues will factor prominently in the early phases of cellulosic production.

EISA is the latest step on a policy pathway to stimulate greater production and use of biofuels. The legislation sets separate targets for two major categories: “conventional” ethanol, principally from corn; and “advanced” biofuels, which includes ethanol from cellulosic sources. Since the end product—ethanol—is the same for both processes and the production costs are likely to be different, there is no reason to believe that the pre-ordained quantity levels specified by legislation will be the most economically efficient. Production of ethanol from corn is a mature technology but there are likely to be many competing cellulosic conversion systems, some of which may not prove to be commercially sustainable in the long-run. Predicting capacity levels for cellulosic ethanol production is difficult, though it is possible to analyze the consequences of various production levels of crop residue-based systems.

Using a regional partial-equilibrium model of agricultural supply and demand in the United States, we assess the implications of cellulosic ethanol being allowed to substitute on a gallon-for-gallon basis for corn-based ethanol, thus reducing the amount of corn necessary for ethanol production. The results show that there are both market and environmental benefits to accelerating the development of crop residue-based cellulosic biofuel production, primarily due to the reduced need for corn and taking advantage of existing residue supply. The increasing economic value of residue drives movement into no-till systems, reducing soil erosion and improving nutrient deposition. This indicates a need to spur research into crop residue management and cellulosic ethanol technologies to use them.

2. Modeling Framework and Data

The Regional Environment and Agriculture Programming Model (REAP) is a mathematical optimization model that quantifies agricultural production and its associated environmental outcomes for 50 regions in the United States (Johansson, et al., 2007). The regions are defined by the intersection of the USDA’s Farm Production Regions (10 groups of states with similar agro-economic characteristics) and the Natural Resource Conservation Service’s Land Resource Regions (defined by predominant soil type and geography). Production levels are also determined for livestock and processed products, which are integrated with the crop production system. Regional differences in crop rotations, tillage practices, and input use such as fertilizer and pesticides are explicitly accounted for. Input use and national product prices are determined endogenously. Data on crop yields, input requirements, costs and returns, and environmental indicators are derived from the USDA Agricultural Resource and Management Survey (ARMS) and the Environmental Productivity and Integrated Climate (EPIC) model. The model is calibrated to prices and quantities established by the 2008 USDA Baseline (USDA, 2008). REAP has been widely applied to address agro-environmental issues such as water quality and environmental policy design (Johansson and Kaplan, 2004), environmental credit trading (Ribaudo et al., 2005), climate change mitigation policy (Faeth and Greenhalgh, 2002), and regional effects of trade agreements (Cooper et al., 2005)

REAP is implemented as a non-linear mathematical program using the General Algebraic Modeling System (GAMS) programming environment. The goal of the model is to find the competitive equilibrium (welfare-maximizing) outcome of production levels subject to land constraints and processing and production balance requirements. The model is calibrated to production levels for 2016 given by the 2008 USDA baseline. It should be noted that REAP holds constant many factors that influence planting decisions and the markets for agricultural commodities. Weather and pest conditions are assumed to be average for the growing season.

Total ethanol production for 2016 is taken to be 19.25 billion gallons (15 billion from corn, 4.25 billion from cellulosic in the base scenario) as specified in EISA. Both corn-based and cellulosic ethanol demand are modeled as perfectly inelastic; there are no explicit factors in the model to generate the market-based allocation of the two quantities. To measure the effects of a different proportion of corn to cellulosic ethanol, crop residue-based ethanol production is ranged from 2.0 billion gallons to 8.5 billion gallons with corn-based ethanol making up the difference. So that corn-based ethanol production is capped at 15 billion gallons, crop residue ethanol production less than 4.25 billion gallons is complemented by switchgrass production. For the purpose of this analysis, switchgrass is modeled as a continuous hay rotation with similar production, cost, and environmental parameters.

Crops that provide residue for cellulosic ethanol production are corn, wheat, soybeans, barley, and oats. The quantity of residue produced per bushel of crop is taken from Graham et al. (2007) (Table 1). The amount of residue that can be recovered from a field is determined by harvest technology, soil nutrients, water availability, and erosion potential, among other factors. While there has been much research examining the relationship (Wilhelm et al., 2004), much is yet unknown about the effects of removing residue on soil productivity. In this analysis, we assume that 50% can be harvested from fields using no-till systems, 30% from fields using reduced tillage systems, and 10% from systems using conventional systems. These figures are meant as a starting point, and are meant to represent one possible residue collection scenario. Future research will refine these values. Residue harvest costs vary by crop, amount collected, the value of nutrients, and soil and future yield lost. Nutrient loss depends on the crop and amount harvested. Typical nutrient contents are about 17 pounds of nitrogen and 4 pounds of phosphate per ton of corn residue, and 11 pounds of nitrogen and 3 pounds of phosphate per ton of wheat residue. Wortmann et al. (2008) places the value of nutrients lost per ton of corn residue at $17.93. Graham et al. (2007) provide a set of curves that estimate the cost of collection as a function of stover collected per acre and collection method, including the cost of nutrient replacement (given as $6.50 per ton). For this analysis we simplify by imposing a constant $40/ton cost across regions and crop residue. This value represents the midpoint of the curves in Graham et al. adjusted by the higher replacement cost of the Wortmann et al. analysis. There is much ongoing research into how much residue can be harvested to maintain soil productivity, and the removal rates used in this analysis may be higher than optimal given soil organic carbon requirements (Wilhelm et al., 2007). Because of erosion considerations, no residue is allowed to be harvested from land classified as highly erodible.

Table 1. Residue to grain ratio (pounds of residue per pound of grain, dry mass)

	Residue-to-grain ratio
Corn	1.0
Soybeans	1.5
Wheat	1.3
Oats	1.4
Barley	1.5
Sorghum	1.0

To eliminate harvest of residues where transportation costs are likely to be too high and where there is insufficient economically retrievable material to support a commercially-sized biofuel plant, collection of crop residues is further limited to regions where at least 769,000 tons can be harvested—sufficient to produce 50 million gallons at 65 gallons per ton of residue. This is implemented as an endogenous constraint, so conceivably some regions could produce more crops than they otherwise would if the value of residue made it feasible to do so.

3. Results

Of the 42 REAP regions that grow the residue-producing crops, 13 produce quantities sufficient to meet the 50 million gallon minimum. The total production of cellulosic ethanol from crop residues in each region estimated to be produced under alternative scenarios for cellulosic ethanol demand is shown in Table 2. (Note that the results are reported by Farm Production Region, which are aggregates of REAP model regions). Below 4.5 billion gallons of cellulosic ethanol production, supply of crop residue exceeds the demand by ethanol producers in most regions. There are some regions where all available crop residues are used, after accounting for rate of removal by tillage, thereby inducing a marginal value for the residue. Above 4.5 billion gallons of cellulosic demand, all available residue is consumed in each region where the 50 million gallon requirement is met, effectively creating a national market value for residue. The shadow price for residue reaches $38.83 per ton at a demand of 8.5 billion gallons.

Table 2. Cellulosic ethanol production from crop residues, by region

	Cellulosic production (million gallons)				
Farm Production Region	2082	4250	5525	7012.5	8500
Northeast	100.0	100.0	106.7	133.0	157.6
Lake States	352.4	502.6	635.4	802.5	966.1
Corn Belt	503.3	2471.8	3156.8	3915.0	4749.6
Northern Plains	965.1	1010.1	1403.9	1864.7	2254.6
Appalachian	161.6	165.5	222.2	297.3	372.1

Crop prices relative to the 4.25 billion gallon cellulosic demand are shown in Figure 1. Prices for all major crops vary considerably over the range of cellulosic production. Corn shows the largest decline in price, dropping 6.5% as cellulosic production increases from 4.25 to 8.5 billion gallons. The price decline for corn is steady over the whole range. Less corn for ethanol and lower prices lead to more corn for food and feed. Wheat prices decline slightly over the whole range. Over the range of analysis, the fraction of the corn crop used for ethanol declines from 36.3% to 27.3% while the amount of corn available for food, feed, and exports increases from 9.4 billion bushels to 10.2 billion bushels.

Figure 1. Prices for crops, relative to 4.25 billion gallon cellulosic demand

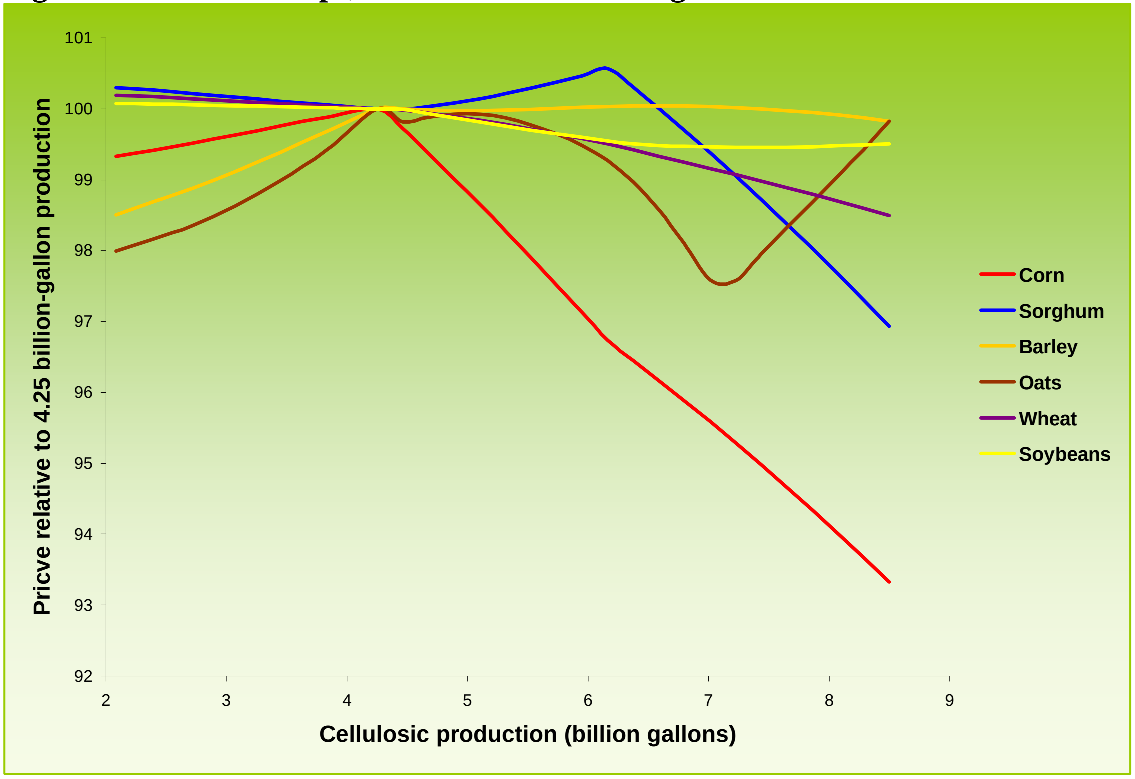
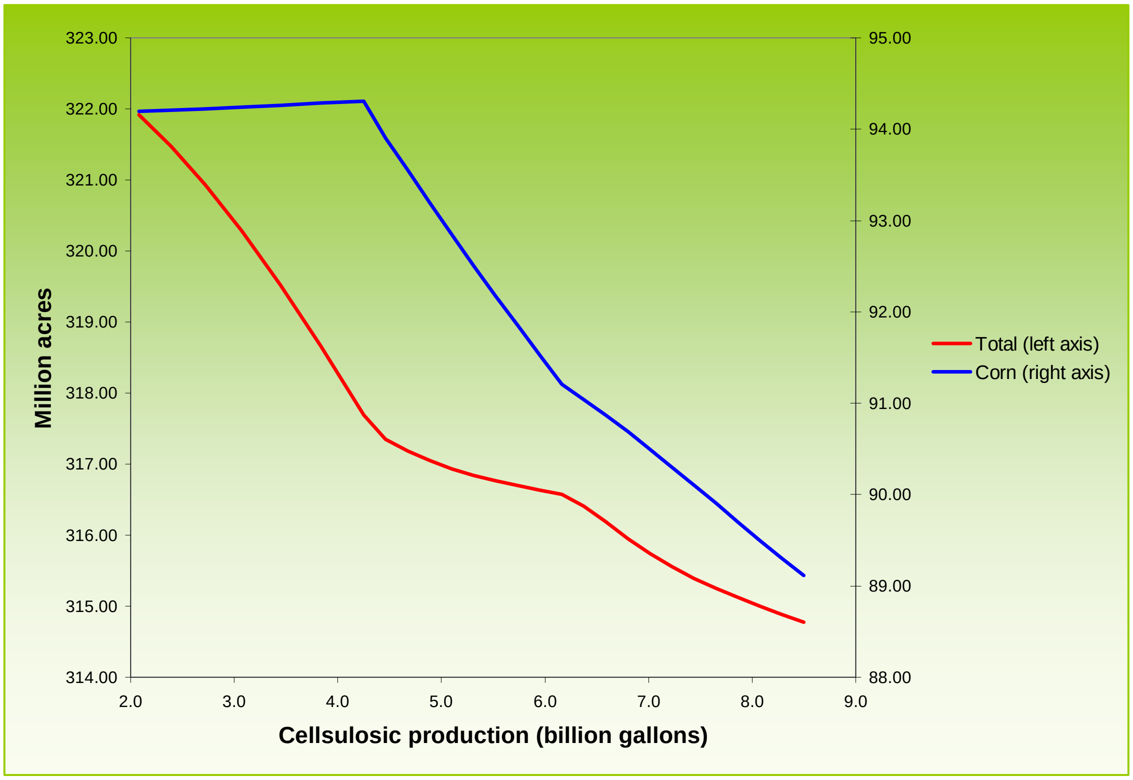
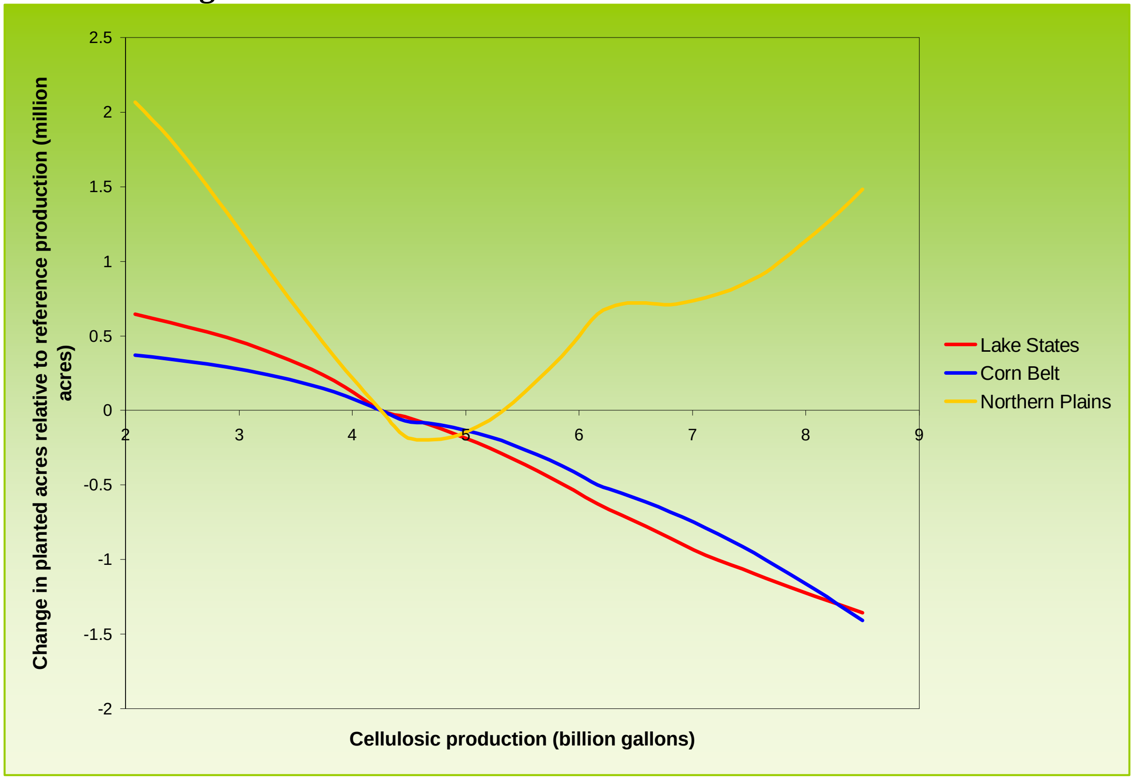


Figure 2. Change in total planted acreage and acres planted to corn



At the target level of 15 billion gallons of ethanol from corn and 4.25 billion gallons of cellulosic ethanol, total land planted to major crops is 317.7 million acres. As cellulosic demand increases, less total land is planted to traditional crops. The rate of decline in acreage as cellulosic demand increases is about 700,000 acres per billion gallon demand increase (Figure 2). The Corn Belt and Lake States show declines in total acreage as cellulosic demand is increased but the Northern Plains shows an increase, as illustrated in Figure 3. As crop residues gain economic value, the Northern Plains adds wheat acres, contributing to an increase in acreage in the region. Land for corn in the major corn producing regions of the Corn Belt, Lake States, and Northern Plains are the principal components of the decline in acreage. Over the 4.25 to 8.5 billion gallon range, corn acres decline from 94.3 to 89.1 million acres (Figure 2).

Figure 3. Change in total planted acreage for major crop producing regions, relative to 4.25 billion gallon cellulosic ethanol demand



Even though total acreage is reduced at higher levels of cellulosic ethanol demand, aggregate environmental effects are not reduced. In general, this is due to the fertilizer that needs to be applied to replace the nutrients removed with the harvested residue. We examine the levels of four critical environmental measures – nitrogen deposited to groundwater, nitrogen deposited to estuaries, nitrogen deposited to surface water, and soil erosion. Figure 4 shows how these measures change across the range of cellulosic ethanol demand relative to the baseline target. To remove the direct effect of the contribution of fewer acres, the values have been adjusted by dividing by the change in total acres for the given demand level. Net levels of the environmental measures generally increase despite the reduction in total land. Nitrogen deposited to groundwater holds fairly steady up to about 6 billion gallons of cellulosic demand, and increases as demand increases. However, not all regions exhibit an increase in this measure, as shown in figure 5 (also adjusted for changes in total acreage). The increase in the national level of nitrogen lost by surface runoff at lower cellulosic demands is mainly caused by high levels of runoff in the corn producing regions. The Delta and Southeast regions show a decrease in nitrogen deposition to groundwater, demonstrating that environmental consequences do not appear uniformly among regions. Shifting ethanol demand from corn to residue based systems increases nitrogen fertilizer requirements, although the effect of potentially applying less fertilizer and settling for lower yields has not been examined. Changes in management practices contribute to lower levels of soil erosion. The major management changes that happen over this range are a reduction in acres planted to continuous corn, particularly in the Corn Belt, and a national movement into no till systems (figure 6). No till systems grow from 11% to 21% and conventional systems decline from 72% to 53%. This is driven by the economic value for crop residues, more of which can be harvested from no till systems.

Figure 4. Change in selected national environmental measures, relative to 4.25 billion gallon cellulosic ethanol demand

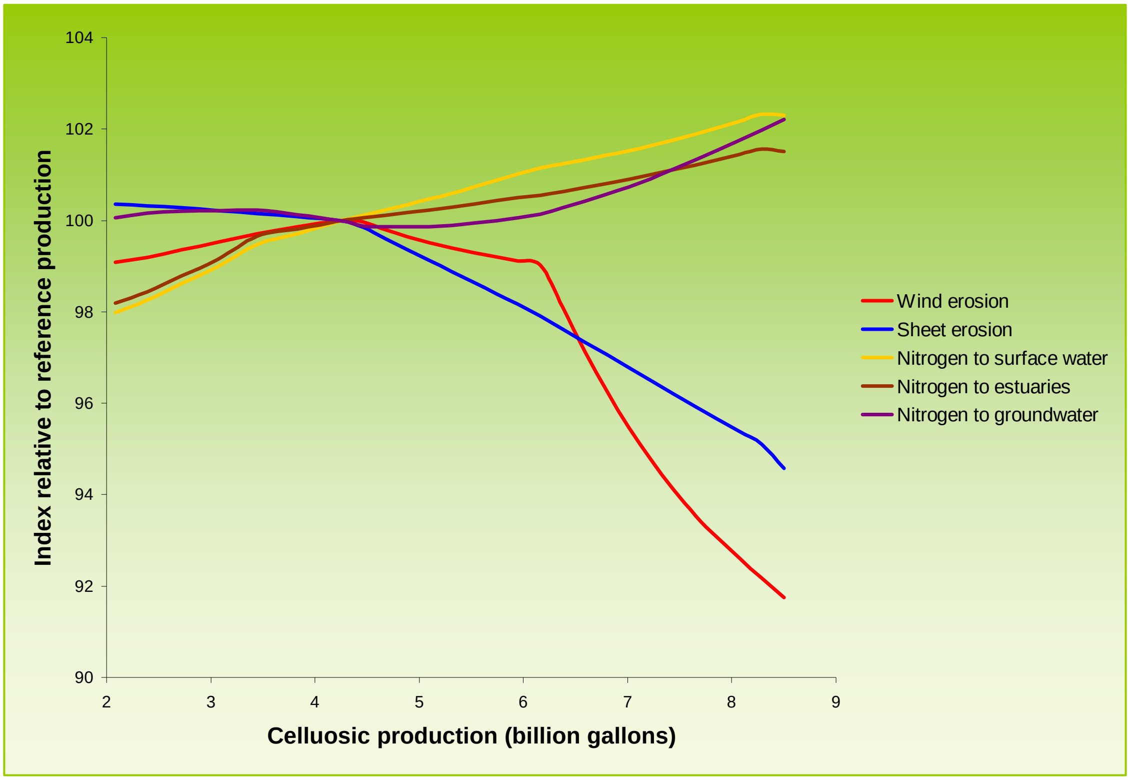


Figure 5. **Index of nitrogen deposition to groundwater, by region, relative to 4.25 billion gallon cellulosic ethanol demand**

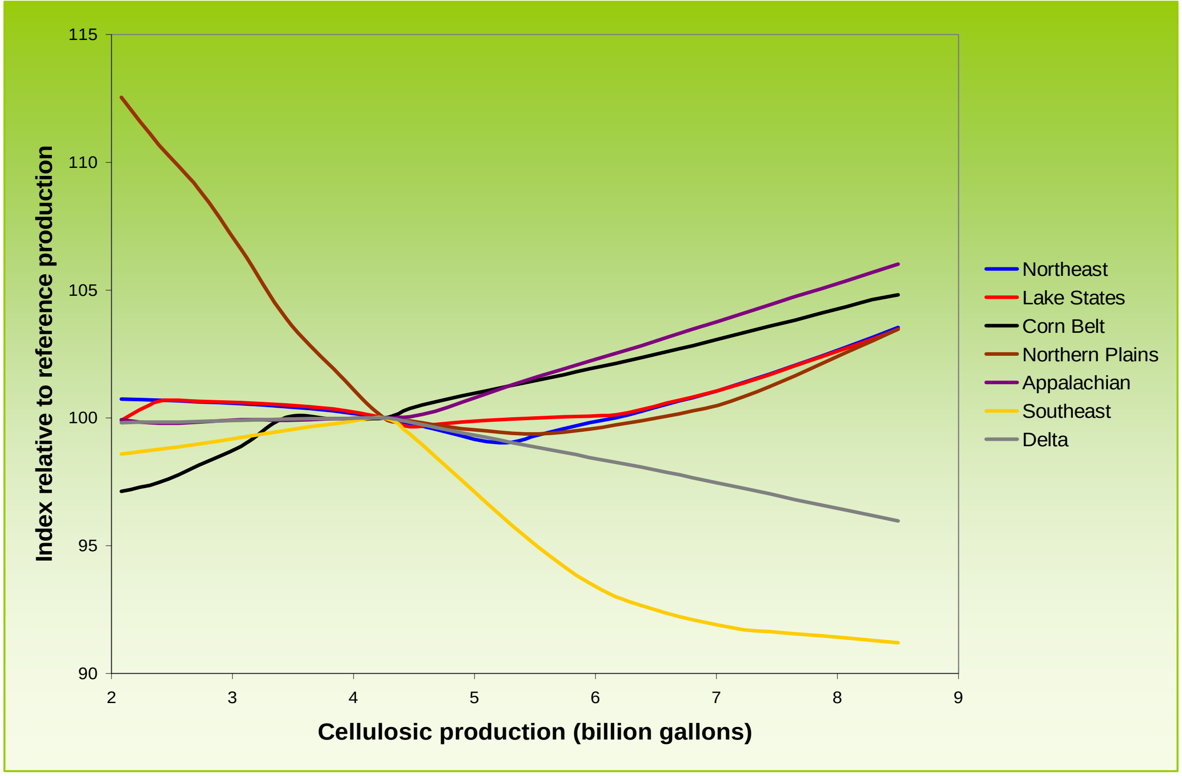
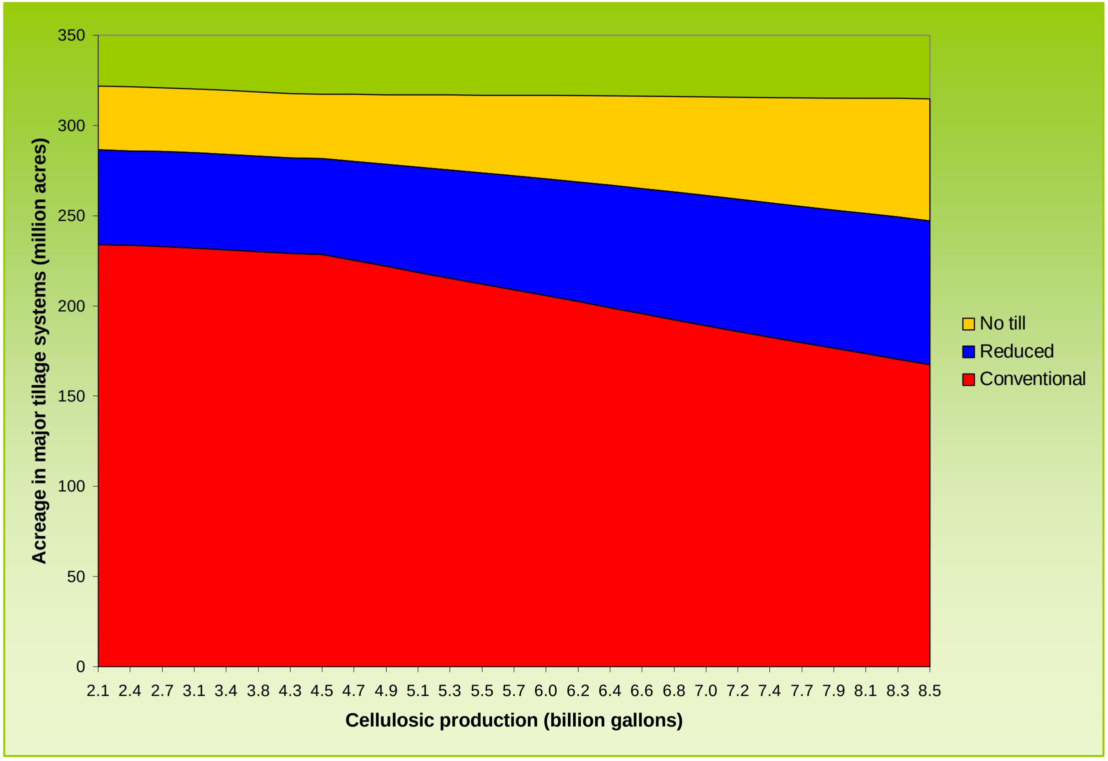


Figure 6. **National planted acreage by tillage system (million acres)**



5. Discussion

Unless and until alternative cellulosic crops like switchgrass and short-rotation woody crops are planted on a large scale, it is likely that the first wave of cellulosic production capacity will be attracted to those regions already planting residue-producing crops—namely the Corn Belt, Lake States, and Northern Plains. A sufficient supply of economically recoverable crop-residues will be available in 2016 to meet feedstock requirements at the EISA target of 4.25 billion gallons. If corn ethanol production is able to shift to crop residue-based cellulosic production, it will mean a greater need for crop residues, but the crop production system would not be significantly stressed by that need. Greater demand for crop residue would further concentrate cellulosic capacity in the major crop producing regions, rather than increase residue producing plantings in other regions.

Shifting away from corn and using more crop residues in place of corn provides mixed results on the environment. On the one hand, the reduced need for corn coupled with an ample supply of residues means less land is needed to meet agricultural market needs. Much of the reduction in corn acres is manifest in a move away from intensive continuous corn rotations. More use of nitrogen fertilizer leads to greater nutrient loadings. Change on a broad scale away from conventional tillage and into conservation tillage improves soil erosion. Since crops, practices, and growing conditions are widely distributed, the environmental outcomes vary by region.

One consequence of pricing crop residues is that with accelerated and localized use, producers in regions where the source of residue is too far from ethanol plants to be commercially viable will suffer lower returns relative to their colleagues nearer to ethanol plants. This is due to the lower price for the crop and the inability to sell the residue. This especially holds true for corn, which shows the largest drop in price as cellulosic demand is ramped up and demand for corn ethanol is reduced. Overall, returns to crop production increase as cellulosic demand increases beyond 4.25 billion gallons since returns from crop residues make up for the losses in crop production that result from lower crop prices. Regionally, returns to residues are not proportional to returns to crops; the major crop producing regions garner a relatively greater fraction.

Critical to the economic development of crop residues for biofuels is a thorough understanding of the implications of removal of residues on the land that produces them. Removal of residue affects soil nutrient content, erosion, and water retention. The REAP model accounts for these factors through tillage and rotation choice in each region. However, the possibility exists that in an environment where residues have real economic value there will be an incentive to remove residues in excess of the amount optimal to maintain soil productivity. Sensitivity analysis around the removal rates (which are likely to be different for each crop) and the implications for excess removal are topics for further research.

One of the challenging aspects of analyzing the costs and benefits of biofuels is to assess their life cycle carbon footprint. While beyond the scope of this study, this framework can be extended to account for sector-wide changes in carbon sequestration and greenhouse gas emissions. Changes in management practice that lead to changes in carbon sequestration and

GHG factors can be quantified under a set of policies, such as carbon prices, emissions trading programs, and incentives (green payments, cost sharing).

This analysis has focused on the near-term use of crop residues as the transitional feedstock. Alternative cellulosic crops will make an appearance once demand for such products is in place and issues have been resolved surrounding best management practices, market institutions, and protection from risk. Any analysis that looks further into the future must consider these alternative crops even though there is much uncertainty regarding how and where they will, or most economically, be grown and marketed.

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