U.S. biomass supply for electricity generation: Climate policy implications and carbon neutrality

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Abstract

This paper investigates three important energy and climate policy issues: (1) the availability of biomass for electricity generation (i.e., supply), (2) climate policy effects on this supply, and (3) the net greenhouse gas reduction when biomass is used for electricity generation. Using a detailed model of U.S. agriculture and forestry markets and land-use, that includes a broad and diverse set of biomass feedstocks, we evaluate competing potential sub-national and feedstock specific supplies of biomass for U.S. electricity generation. Our preliminary results suggest significant supply, with residues dominating at lower delivered energy prices, and dedicated crops significant at higher prices. Sub-national variation is dramatic and will affect generation siting and sustainability. We find displacement of food crops, but net forest land <u>and</u> cropland expansion. We also find that GHG policies could substantially increase the delivered cost of biomass; however, the implications for individual regions and feedstocks is non-uniform, with some supplies falling to zero and others increasing. Finally, we find that bioelectricity is not carbon neutral, but can be emissions reducing relative to coal generation, yield greater direct GHG benefits than biofuels, and even result in domestic indirect emissions reductions with incentives for forest based feedstocks.

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Introduction

There is increased attention on the potential of biomass energy as an alternative to fossil fuels for both energy independence and climate benefits. Enthusiasm for biomass is high, but tempered by concerns about farmers, food supplies, unintended land conversion and international leakage. Much of the attention in recent years has been on biofuels (ethanol and biodiesel) due to European and U.S. mandates for their use (e.g., Hertel *et al.*, 2010, Searchinger et al., 2008). However, biomass feedstocks can also be used for electricity. Policy-makers and utilities are in the process of evaluating bioelectricity opportunities in the context of renewable portfolio and climate policy compliance. At the same time, land owners are interested in considering new revenue streams, while environmental groups and others are cautious about land-use implications. Recent literature has spent a great deal of time looking at biofuel potential and implications, but very little on biomass for electricity. In addition, given the complexities of modeling land-use and land-based product markets, and significant differences in biomass feedstocks, there is a need for detailed analysis that considers the broad and diverse set of biomass feedstocks.

This study explores biomass for U.S. electricity production with a three phase analysis. First, we model the potential supply of biomass for power generation and evaluate supply differences across U.S. sub-regions. The analysis considers a vast set of alternative agriculture and forestry biomass feedstocks, where the feedstocks compete with each other on a variety of fronts—end-use (electricity versus liquid), within an end-use (such as electricity generation), and for production inputs (in particularly land). In addition, it is essential to evaluate potential complementarities between bioenergy, food, feed, and forest production.

We then consider policy implications on supplies. How might greenhouse gas and/or renewable fuels policies affect supply? For instance, climate policies will increase the cost of fossil fuel combustion, provide incentives for biofuels expansion, and could reward agriculture and forestry greenhouse gas abatement. Each of these will affect the cost of delivering biomass for electricity production and are therefore important considerations for utilities and policy-makers in evaluating renewable generation options.

Finally, we investigate the GHG offset implications, or "carbon neutrality," of biomass by modeling greenhouse gas emissions throughout the growing to delivery process and across the landscape, including those associated with land management, land use, and input production. Because sustained biomass production sequesters the carbon emitted when combusted, biomass is frequently regarded as neutral in that it fully offsets its own carbon emissions. However, a broader accounting of greenhouse gases released in production, transport, etc., as well as land conversion, implies non-neutrality. In this paper, we explore the degree of non-neutrality, but in a broader context than analyzed by others (e.g., Hertel et al., 2010; Searchinger et al., 2008; Qin et al., 2006; McCarl et al., 2000) where multiple agriculture and forest biomass feedstock alternatives and end-uses are available and more detailed market and regional characteristics considered.

Modeling Framework

For this study, we use a U.S. forest and agriculture economic model that was recently updated and modified with, among other things, expanded bioenergy and forestry management options (Adams et al., 2009). We simultaneously and dynamically model US sub-national alternative land-use and GHG strategies, with near-term and long-run land allocation determined by relative economic returns and suitability. We consider forestry log, pulp, and wood chip markets and agricultural primary and processed commodity markets, crops and animal products.

We model agriculture and forestry production in eleven U.S. subregions (Table 1). An extensive set of agriculture and forestry residue and dedicated biomass feedstocks are available regionally for either liquid or solid end-uses, with co-products affecting their profitability. Table 2 summarizes the biomass feedstocks possible and the energy end-uses. Table 2 illustrates both competition between end-uses for feedstocks and competition between feedstocks in any particular end-use. For instance, residues (agriculture and forest) can be used for cellulosic ethanol production as well as electricity generation. Meanwhile, residues compete with dedicated energy crops such as switchgrass and hybrid poplar in supporting generation.

The relative value of each biomass feedstock is a function of numerous factors, including energy and moisture content, direct costs (processing, harvesting, transportation, and storage costs), opportunity costs (net returns to existing and alternative land-uses and management), energy prices, and joint production and co-products opportunities (e.g., crop commodities, feed substitutes, and oils), and, if valued, changes in emissions and sequestration as well as alternative GHG abatement strategies. Table 3 illustrates the differences in energy and moisture content across feedstocks. Higher heating values (HHVs) reflect the energy output per short ton of biomass, and the differences in HHVs reflect intrinsic differences in the energy and moisture stored in different plant matter. The HHVs in Table 3 are "as-fired" HHVs which represent the heat potential of biomass as delivered, i.e., not bone-dry, which would correspond to the heat content after a drying process. In our modeling, transportation costs vary by feedstock, and transportation costs increase with average distance, which is a function of supply quantity, land density for each feedstock, yield, and load size.

GHG implications are tracked with detailed accounting for nitrous oxide (N_2O), methane (CH_4), and carbon dioxide (CO_2)—emissions and sequestration, such that biomass delivery affects GHG emissions and sequestration in production, hauling, fertilizer manufacture, processing, as well as byproduct credit emissions, and land-use change.

The model baseline is calibrated to U.S. Department of Agriculture commodity price projections, and U.S. Department of Energy energy price projections from the Annual Energy Outlook for 2009. The U.S. Energy Independence and Security Act's renewable fuels mandate is imposed on the model. Therefore, the model must provide the required volumes of domestic agriculture and forestry based conventional and cellulosic ethanol and biodiesel. In addition, a minimum of 30 million acres is retained in USDA Conservation Reserve Program lands in accordance with current federal policy.

Results

Biomass supply for electricity generation

For this study, we are interested in the supply of delivered biomass for electricity generation, not the supply of electricity. In other words, we focus on estimating the amount of biomass that could be available at the power plant gate at a feedstock price.

This provides us with pure estimates of feedstock supply that would compete directly with the supplies of other feedstocks in the generation portfolio for servicing electricity loads (e.g., competing directly with coal and less directly with other fuels such as nuclear, wind, and natural gas). Since we are focused on delivered biomass supplies, considerations beyond the power plant gate are not included here, e.g., preparation yard costs, plant size, heat rate, co-firing levels, fossil feedstock options, and overall electricity system considerations (e.g., transmission, reliability, base and peak load requirements). To estimate the supply of delivered biomass we vary the price projections for delivered coal off of the AEO 2009 reference projection. Specifically, we increase the level by 50%, 150%, and 300% ceteris paribus.

Our preliminary results suggest that there is significant biomass supply available nationally. For instance, in 2030, we estimate that 1.8 trillion Btu could be available at $2/MMBtu and 12 trillion Btu at $5.14/MMBtu (Figure 1). Regionally, the largest supplies are available in the Corn Belt, Northern and Southern Plains, and South Central, i.e., the down the productive agricultural center of the country.

Residue feedstocks, particularly from agriculture, dominate at lower delivered feedstock prices, with dedicated crops also significant at higher prices (Figure 2). At lower feedstock prices, there is enough of an incentive to modify current land management activities in order to exploit the additional revenue associated with collecting and delivering agriculture and forestry waste streams for electricity generation. At higher feedstock prices, the incentive is strong enough to displace some current land-use activities with switchgrass, and to a smaller extent willow and hybrid poplar, in addition to increasing residue extraction from continued food crops and timber production.

Sub-national variation in feedstock supplies is dramatic—in total and in feedstock mix—and will affect regional power plant siting and conversion, transmission, and sustainability. For instance, while corn residues dominate crop residue supplies in the Corn Belt, sweet sorghum and wheat dominate in the Northern Plains, with contributions from barley and oats (Table 4). At higher feedstock prices, switchgrass overwhelms the Corn Belt supply, yet in the Northern Plains, switchgrass is significant but sweet sorghum residues are the dominant contributor. Alternatively, in the Northeast, where total supply is comparatively modest, willow is the primary supply, while in the Pacific Northwest East, where total supply is even smaller, the primary supply is from hybrid poplar.

Nationally, with higher delivered feedstock prices, we find displacement of food crops and overall cropland expansion with increases in energy crop feedstocks. However, we also find net forest land expansion, with the cropland and forest land expansion coming at the expense of pasture (Figure 3). While not immediately intuitive, forest land expansion results from the additional revenue from forest residues. The additional revenue stimulates afforestation and changes in forest management with extended rotation lengths and increased use of thinning and partial cuts.

Climate and energy policy implications

As mentioned upfront, a climate policy could affect the domestic supply of biomass for electricity generation by changing direct costs and opportunity costs. We model three key mechanisms by which that might occur: (1) the additional cost of fossil fuel use when GHG emissions are valued, (2) the additional incentive that might be available for biomass transportation fuels in the decarbonization of the transportation sector, and (3) potential incentives for non-energy related agriculture and forestry GHG abatement, such as changes in livestock and fertilizer management, tillage practices, afforestation, and forest management. Current U.S. legislative proposals permit agriculture and forestry GHG abatement in the form of *offsets*, i.e., GHG abatement that occurs outside the economic sectors subjected to a GHG cap that could be purchased by entities in capped sectors to offset an equivalent quantity of capped sector emissions. Offsets are a key cost containment feature in recent U.S. legislative proposals, and agriculture and forestry are estimated to be the primary domestic offset sources (USEPA, 2009; 2010).

By putting a GHG price on GHG emissions and carbon sequestration, we can evaluate the effects on the delivered cost of biomass for electricity. In considering a climate policy, we represent different degrees of GHG abatement stringency using three carbon dioxide equivalent price paths that start at $15, $30, and $50/tCO2eq in 2010 with each rising at 5% per year. The price paths are chosen to cover a broad range of potential GHG allowance prices. The low GHG price path is consistent with estimated price paths for the core scenarios from recent analysis of proposed U.S. climate legislation (USEPA, 2009; 2010), while the upper end represents GHG price paths associated with less optimistic assumptions on abatement technology availability and costs and/or more stringent GHG reduction targets.

We find that GHG policies could substantially increase the delivered cost of biomass (Figure 4). For instance, in 2030, at $2/MMBtu the supply falls from 1.8 trillion Btu to near zero or zero, with reductions of 83 percent under a GHG price path of

$15+5%/yr, and 100 percent under the highest GHG price scenario. However, the shift is not parallel, with the upper end of the biomass supply less sensitive to the GHG price. Biomass supply is still positive at higher feedstock prices, but the reductions in supply are still significant at 18 to 68 percent at $5/MMBtu across GHG price scenarios and 3 to 29 percent at $8/MMBtu.

The GHG price implications for biomass supplies for individual regions and feedstocks is complex and far from uniform as biomass supplies from some regions fall to zero while others may even increase depending on the GHG and feedstock price combination and relative effects on other sub-regions (Table 5). Relative regional differences in, among other things, transportation costs, land productivity, market conditions, GHG abatement opportunities, and initial biomass supplies over time, imply very different GHG price burdens.

Supply from some prominent regions like the Corn Belt could fall to zero under the rising $15/tCO2e GHG price scenario and low feedstock price, while Northern Plains supply falls 70% and those of the Pacific Northwest fall 40-60%. However, this relationship reverses at higher feedstock prices, with, for instance, the Corn Belt increasing biomass supply for electricity, while supplies from the Pacific Northwest decline. At lower GHG and feedstock prices, some feedstocks are still supplied such as barley, oat, and sorghum residues, and lignin. However, at higher GHG prices, without corresponding higher feedstock prices, the increased costs become prohibitive. Of course, feedstock prices are expected to rise under a GHG policy. Therefore, it is less likely that there will be a complete loss of most feedstock supplies under a GHG policy due both to higher feedstock prices and the value of offset fossil fuel emissions in electricity generation. Nonetheless, the price of delivered biomass would be expected to rise.

The increase in some feedstock supplies is interesting as it illustrates production complementarities—between, for example, forest residues and carbon sequestration, and manure based energy and livestock GHG emissions management. It is important to remember that in addition to potential bioenergy GHG abatement, an agriculture and forestry GHG offset program will offer an additional GHG abatement supply. Results from our scenarios suggest that the supply quantity could be noteworthy and fairly insensitive to the supply of biomass for electricity. For instance, we find that approximately 715 to 750 MtCO2eq/yr of abatement from agriculture and forestry offsets available in 2030 across feedstock prices under the $50+5% GHG price scenario. The actual offset potential will be contingent on the GHG price, as well as offsets policy design and implementation that will determine the eligibility of activities, quantity credited and credit timing.

We also analyze land-use implications in detail. Without a GHG price, we find that higher feedstock prices can lead to a displacement of food crops with increased switchgrass production. Figure 5 provides an illustration for the Corn Belt. At lower feedstock prices, corn acreage is unaffected in the Corn Belt as food and feed crop activities continue and residue feedstocks are profitable. However, at higher feedstock prices farmers are inclined to dedicate some land to switchgrass in lieu of corn and other crops (only corn shown in Figure 5). A GHG policy has two effects on this outcome. Figure 5 illustrates both effects using the $50+5%/yr GHG price scenario ($133/tCO2e in 2030), which relative to the other GHG price scenarios provides the most extreme illustration of the effects. First, we find a reduction in total cropland as just over ten million acres of Corn Belt cropland is converted to forest (with about half of the reduction from lost corn acreage). Second, the threshold price at which switchgrass displaces cropland rises as the cost of cropland displacement increases due to rising cropland rents that are a consequence of the reduction in total cropland acreage. In Figure 5, the threshold energy price for switchgrass rises from approximately $3/MMBtu to $5/MMBtu.

Subsequent work will explore the effects of changes in renewable generation and liquid fuel requirements on biomass supplies for electricity.

Carbon neutrality

In this section, we discuss our estimates of the direct emissions reductions associated with delivering biomass feedstocks, as well as the indirect emissions from domestic land-use change.

Overall, we find that bioelectricity is not carbon neutral. While the carbon emitted from combusting biomass is offset by the carbon sequestered during biomass growth, the direct emissions associated with production and delivery imply less than 100% displacement of the emissions associated with the displaced coal on an equivalent energy output basis. Within the model, we are able to compute the direct fossil fuel emissions displacements associated with different feedstock and end-use combinations (Table 6). Table 6 reveals a number of insights. First, we find that while not carbon neutral, biomass used for electricity could be nearly carbon neutral with direct fossil fuel emissions offset rates of 87 to 98 percent depending on the feedstock and level of cofiring with coal. Second, we find categorically, that biomass used for generation has a far higher GHG benefit than biofuels. For instance, switchgrass used for electricity could displace 90-94% of coal emissions, compared to a 72% benefit as cellulosic ethanol, where both far surpass crop ethanol at 30-40%. Finally, with all the feedstock-end-use combinations, we find a positive direct emissions GHG benefit (i.e., greater than zero percent).

However, potential indirect emissions from land-use change are the emissions most troubling policy-makers and the private sector. These are the emissions associated with changes in land-use that may result from the changing net returns to alternative land-uses and market conditions. In this analysis, we focus solely on estimating domestic indirect emissions, and initially on the no climate policy case. Surprisingly, we find a net *reduction* in indirect US ag/forest emissions with increasing biomass supply to generation. This finding runs counter to claims that biomass production leads to increased land displacement emissions. In comparing the AEO2009 and 300% delivered feedstock price scenarios with no GHG price, we observe increased forest management & afforestation carbon uptake over time (Figure 6). This result is consistent with our forest area expansion finding discussed earlier and the corresponding lengthening of rotations and increase in thinning and partial cuts. Initially, in 2010, we observe carbon releases from agricultural soils and current forests as cropland expands into pasture and timber supplies adjust. However, over time we see an increase in forest carbon uptake that leads to cumulative carbon gains. In addition, in later years, we observe cellulosic ethanol being replaced with grain ethanol as cellulosic feedstocks are redirected to generation as feedstock prices rise over time. This effect occurs after the renewable fuels mandate for specific fuel volumes is relaxed in the model (in 2035) and only a total ethanol requirement is modeled in subsequent years. This result illustrates the greater direct GHG benefit of directing some biomass feedstocks to electricity versus liquid fuels, even without a GHG price.

Estimating international indirect emissions is also important as shown by others (e.g., Searchinger et al., Hertel et al., 2010). While our results are domestic, they illustrate that there are fundamental uncertainties and complexities that need to be evaluated that may lead to refinements of these current assessments.

Conclusion

Using a detailed U.S. model of agriculture and forestry markets and land-use, that included a broad and diverse set of biomass feedstocks, we evaluated the potential supply of biomass for U.S. electricity generation. Our preliminary results suggest significant supply, with residues dominating at lower delivered feedstock prices, and dedicated crops significant at higher prices. However, sub-national variation is dramatic and will affect regional generation siting, transmission, and sustainability. We find displacement of food crops, but net forest land and cropland expansion at the expense of pasture. GHG policies could substantially increase the delivered cost of biomass by driving up direct and opportunity costs. The GHG price implications for biomass supplies for individual regions and feedstocks is complex and far from uniform as biomass supplies from some regions fall to zero while others may even increase. Finally, we find that bioelectricity is not carbon neutral, but can be emissions reducing relative to coal generation, yield greater direct GHG benefits than biofuels, and surprisingly could yield domestic indirect emissions reductions with incentives for forest based biomass feedstocks.

This study focused on delivered biomass supplies for electricity generation. Bioelectricity penetration in the generation portfolio will ultimately be a function of both biomass supply and demand, and may vary substantially from supply estimates and across sub-regions and individual power plants. The relative supply and processing costs of alternative generation fuels, GHG reduction incentives and renewable mandates, and available technology assumptions will affect the net appeal of biomass, and thereby its penetration. This study provides a detailed and comprehensive assessment of regional biomass supplies and the potential net domestic resource and environmental implications for whatever specific supply quantities might result.

References

Adams, D.M., Alig, R.J., McCarl, B.A., Murray, B.C., Blair, L., Depro, B., Latta, G., Lee, H.-C., Schneider, U.A., Callaway, J.M., Chen, C.C., Gillig, D., and Nayda, W.I. (2009). FASOMGHG conceptual structure and specification, http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf.

Hertel, T.W., W.E. Tyner and D.K. Birur, 2010. "Global Impacts of Biofuels", *The Energy Journal*, 31(1):75-100.

McCarl, Bruce A., Darius M. Adams, Ralph J. Alig and John T. Chmelik, 2000. "Competitiveness of biomass-fueled electrical power plants." *Annals of Operations Research* 94: 37–55.

Searchinger, T., R. Heimlich, R. A. Houghton, F. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D., Hayes and T.-H. Yu, 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change." *Science* 319(5867): 1238-1240.

Qin, Xiaoyun, Tanya Mohan, Mahmoud El-Halwagi, Gerald Cornforth, Bruce A. McCarl, 2006. "Switchgrass as an alternate feedstock for power generation: an integrated environmental, energy and economic life-cycle assessment." *Clean Techn Environ Policy* 8:233–249.

USEPA, 2009. *Analysis of the American Clean Energy and Security Act of 2009, H.R. 2454 in the 111th Congress*, U.S. Environmental Protection Agency, Office of Atmospheric Programs, June 23, 2009, http://www.epa.gov/climatechange/economics/economicanalyses.html.

USEPA, 2010. *EPA Analysis of the American Power Act in the 111th Congress*, U.S. Environmental Protection Agency, Office of Atmospheric Programs, June 14, 2010, http://www.epa.gov/climatechange/economics/economicanalyses.html.

Table 1: U.S. subregions modeled

Region		State	Region		State
1	Pacific Northwest West	W. Oregon W. Washington	9	South Central	Alabama Arkansas Kentucky Louisiana Mississippi E. Oklahoma Tennessee E. Texas
2	Pacific Northwest East	E. Oregon E. Washington			
3	Pacific Southwest	California			
4	Rocky Mountains	Arizona Colorado Idaho Montana Nevada New Mexico Utah Wyoming	10	Northeast	Connecticut Delaware Maine Maryland Massachusetts New Hampshire New Jersey New York Pennsylvania Rhode Island Vermont West Virginia
5	Northern Plains	Kansas Nebraska North Dakota South Dakota			
6	Southern Plains	W. Oklahoma W. Texas			
7	Lake States	Michigan Minnesota Wisconsin	11	Southeast	Florida Georgia North Carolina South Carolina Virginia
8	Corn Belt	Illinois Indiana Iowa Missouri Ohio			

Table 2: Agricultural and forestry biomass feedstocks

Feedstock	Electricity	Ethanol	Biodiesel
Biomass:			
Softwood Logging Residues	x	x	
Hardwood Logging Residues	x	x	
Softwood Milling Residues	x	x	
Hardwood Milling Residues	x	x	
Bagasse	x	x	
Switchgrass	x	x	
Poplar	x	x	
Willow	x	x	
Corn Residue	x	x	
Sorghum Residue	x	x	
Wheat Residue	x	x	
Barley Residue	x	x	
Oat Residue	x	x	
Rice Residue	x	x	
Lignin	x		
Hardwood Lignin	x		
Softwood Lignin	x		
Manure	x		
Grains and Sugar:			
Corn		x	x*
Sorghum		x	
Wheat		x	
Barley		x	
Oats		x	
Rice		x	
Sugar		x	
Soybeans			x*
Other:			
Editable tallow			x
Non-editable tallow			x
Lard			x

* includes oils and yellow grease

Table 3: Higher heating values (as-fired) and moisture content

	HHV (btu/short ton)	Moisture percent
Bagasse	10,276,632	31%
Barley residue	14,883,920	10%
Corn residue	9,226,139	14%
Hardwood mill residue	10,666,667	33%
Hardwood logging residue	10,666,667	33%
Hybrid poplar	11,492,271	31%
Lignin	18,222,001	33%
Hardwood lignin	21,239,991	33%
Softwood lignin	22,679,998	33%
Manure	8,114,032	26%
Oats residue	14,883,920	10%
Rice residue	11,109,200	15%
Softwood mill residue	12,000,007	33%
Softwood logging residue	12,000,007	33%
Sorghum residue	11,917,456	10%
Switchgrass	13,749,781	12%
Wheat residue	15,055,891	9%
Willow	14,153,995	8%

Table 4: Regional biomass supplies for electricity generation by feedstock in 2030 (Million MMBtu)

	$/MMBtu	Bagasse	Barley residue	Beef manure	Corn residue	Dairy manure	Hardwood residue	Hybrid poplar	Lignin hardwood	Lignin softwood	Lignin	Manure	Oats residue	Rice residue	Softwood residue	Sorghum residue	Sweet sorghum residue	Switch-grass	Wheat residue	Willow	Total
Corn Belt	$ 2.06	0.00	0.00	0.00	0.00	7.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.39
	$ 3.08	0.01	0.53	0.00	0.00	66.39	0.00	0.00	1.03	0.00	151.92	0.00	1.57	1.48	0.11	4.24	0.00	31.80	0.00	0.00	259.07
	$ 5.14	0.01	0.48	13.11	441.93	75.41	0.00	0.00	0.69	0.00	136.20	0.00	1.66	1.28	0.09	5.60	0.00	2369.93	0.00	0.00	3046.40
	$ 8.22	0.01	0.47	8.01	360.54	44.14	7.05	0.00	0.00	0.00	145.48	80.78	1.96	1.28	0.08	5.36	0.00	2372.45	0.00	0.00	3027.60
Northern Plains	$ 2.06	0.00	26.95	2.07	0.00	0.00	0.00	0.00	0.00	0.00	69.14	0.00	9.38	0.00	0.00	65.21	0.00	0.00	445.90	0.00	618.65
	$ 3.08	0.01	29.67	23.99	0.00	0.00	0.00	0.00	0.00	0.00	66.67	0.00	11.83	0.00	0.00	67.07	0.00	0.00	460.92	0.00	660.17
	$ 5.14	0.01	58.55	31.99	0.00	0.00	0.00	0.00	0.00	0.00	76.78	0.00	21.62	0.00	0.00	0.00	1565.43	547.48	469.35	0.00	2771.22
	$ 8.22	0.01	71.35	115.25	0.00	30.29	0.00	0.00	0.00	0.00	68.31	14.42	34.47	0.00	0.00	0.00	1943.73	405.57	532.41	0.00	3215.82
Lake States	$ 2.06	0.00	0.00	0.00	0.00	4.37	0.00	0.00	0.00	0.09	0.00	0.00	17.60	0.00	0.00	0.00	0.00	0.00	50.73	0.00	72.79
	$ 3.08	0.01	9.02	0.00	381.48	35.79	0.00	0.00	0.88	0.00	20.35	0.00	14.60	0.00	1.07	0.00	0.00	0.00	49.27	0.00	512.46
	$ 5.14	0.01	2.90	0.00	326.56	37.29	0.00	0.00	1.19	0.00	24.82	10.43	8.06	0.00	0.84	0.00	0.00	814.78	28.48	0.00	1255.35
	$ 8.22	0.01	2.20	0.79	339.93	25.73	12.87	0.00	0.00	0.00	24.02	53.29	4.71	0.00	0.83	0.00	0.00	805.82	28.42	0.00	1298.62
Northeast	$ 2.06	0.00	6.57	0.00	0.00	0.00	0.00	0.00	1.90	0.00	0.00	6.61	6.04	0.00	4.84	0.19	0.00	0.00	0.00	0.00	26.16
	$ 3.08	0.01	6.48	0.00	41.26	63.28	25.07	0.00	0.04	0.00	0.00	0.00	7.46	0.00	4.70	0.19	0.00	0.00	0.00	211.21	359.69
	$ 5.14	0.01	4.43	1.32	103.34	83.06	26.24	0.00	0.04	0.00	0.00	0.00	7.88	0.00	4.63	0.34	0.00	0.00	0.00	252.65	483.92
	$ 8.22	0.01	4.43	0.80	103.38	103.14	27.35	0.00	0.00	0.00	0.00	6.61	7.88	0.00	4.29	0.34	0.00	0.00	0.00	254.56	512.79
Pacific Northwest East	$ 2.06	0.00	13.40	0.00	0.00	0.00	0.00	0.00	86.07	7.19	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	66.62	0.00	173.38
	$ 3.08	0.01	12.65	0.00	0.00	3.19	0.00	0.00	88.11	7.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	70.41	0.00	181.61
	$ 5.14	0.01	13.57	0.00	3.58	4.25	0.00	106.72	81.85	5.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	65.55	0.00	281.31
	$ 8.22	0.01	15.04	1.84	5.35	7.57	0.03	106.72	70.52	2.04	0.00	4.18	0.00	0.00	1.94	0.00	0.00	0.00	65.81	0.00	281.04
Pacific Northwest West	$ 2.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.16
	$ 3.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.43	0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.17
	$ 5.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.71	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.11
	$ 8.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.04
Pacific Southwest	$ 2.06	0.00	6.34	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.00	0.83	0.00	7.51	6.46	1.46	0.00	0.00	16.78	0.00	39.42
	$ 3.08	0.01	5.86	0.00	5.70	13.09	0.00	0.00	0.03	0.01	0.00	0.00	0.00	7.39	6.45	1.42	0.00	0.00	20.51	0.00	60.47
	$ 5.14	0.01	6.18	5.11	8.48	1.23	0.00	0.00	0.03	0.00	0.00	11.11	0.00	7.47	6.57	1.43	0.00	0.00	19.29	0.00	66.90
	$ 8.22	0.01	6.87	2.72	8.08	75.52	0.27	0.00	0.00	0.00	0.00	7.82	0.50	7.75	5.48	0.00	21.30	0.00	19.03	0.00	155.35
Rocky Mountain	$ 2.06	0.00	47.63	0.00	0.00	0.00	0.00	0.00	0.03	0.02	0.00	5.21	0.00	0.00	7.46	0.00	0.00	0.00	150.14	0.00	210.48
	$ 3.08	0.01	47.40	22.48	26.70	0.00	0.00	0.00	0.03	0.02	0.00	17.67	1.24	0.00	7.46	7.89	0.00	0.00	187.17	0.00	318.07
	$ 5.14	0.01	65.90	20.85	39.56	30.18	0.00	0.00	0.03	0.00	0.00	2.52	1.31	0.00	7.58	8.27	0.00	0.00	198.67	0.00	374.87
	$ 8.22	0.01	51.33	15.12	41.12	38.40	0.17	0.00	0.00	0.00	0.00	30.79	2.93	0.00	4.91	7.27	0.00	234.04	176.80	0.00	602.89
South Central	$ 2.06	0.00	0.00	0.00	101.73	0.00	0.00	0.00	2.40	0.00	0.00	6.40	0.00	51.98	36.83	9.84	0.00	0.00	0.00	0.00	209.19
	$ 3.08	0.00	0.50	0.00	104.90	58.25	89.55	0.00	2.40	0.00	0.00	2.45	0.00	48.81	38.15	8.80	0.00	1096.03	0.00	0.00	1449.84
	$ 5.14	89.14	0.24	2.26	237.27	55.19	96.75	0.00	8.26	0.00	0.00	23.49	0.00	41.03	39.02	21.86	0.00	1091.86	0.00	0.00	1706.35
	$ 8.22	89.14	0.24	1.35	241.59	33.40	88.82	0.00	3.77	0.00	0.00	86.81	0.53	41.77	39.57	21.86	0.00	1091.86	0.00	0.00	1740.71
Southeast	$ 2.06	0.00	3.15	9.00	112.98	0.00	0.00	0.00	2.78	0.00	0.00	1.55	0.00	0.00	24.13	0.00	0.00	0.00	0.00	0.00	153.59
	$ 3.08	0.00	4.23	0.00	125.19	66.43	37.42	0.00	2.63	0.00	0.00	0.00	0.00	0.00	24.53	2.75	0.00	419.42	0.00	0.00	682.60
	$ 5.14	78.53	4.19	2.39	205.86	86.18	49.58	0.00	4.49	0.00	0.00	0.00	0.00	0.00	25.69	3.41	0.00	423.88	0.00	0.00	884.20
	$ 8.22	75.67	4.17	7.71	224.97	73.56	58.92	0.00	2.99	24.42	0.00	82.84	0.00	0.00	25.98	3.15	0.00	425.36	0.00	0.00	1009.75
Southern Plains	$ 2.06	0.00	0.00	6.44	0.00	0.00	0.00	0.00	0.00	0.00	21.51	0.00	0.00	0.00	0.00	70.11	0.00	0.00	167.86	0.00	265.93
	$ 3.08	0.00	0.00	0.00	44.07	46.82	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.69	0.00	77.17	0.00	807.95	217.46	0.00	1202.16
	$ 5.14	7.39	1.14	62.43	59.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.82	0.00	101.19	0.00	807.95	222.86	0.00	1270.79
	$ 8.22	8.16	1.66	81.28	50.89	49.60	0.00	0.00	0.00	0.00	0.00	16.39	3.53	8.39	0.00	93.82	209.21	964.31	226.70	0.00	1713.95
U.S.	$ 2.06	0.00	104.03	17.52	214.71	11.76	0.00	0.00	93.62	8.05	90.65	20.72	33.02	59.50	79.72	146.82	0.00	0.00	898.02	0.00	1778.14
	$ 3.08	0.05	116.36	46.48	729.30	353.24	152.04	0.00	95.57	8.02	238.94	20.12	36.70	66.37	82.46	169.52	0.00	2355.19	1005.74	211.21	5687.31
	$ 5.14	175.10	157.57	139.44	1425.60	372.80	172.58	106.72	96.98	6.50	237.81	47.53	40.52	58.60	84.41	142.09	1565.43	6055.87	1004.20	252.65	12142.42
	$ 8.22	173.02	157.75	234.88	1375.85	481.35	195.48	106.72	77.63	27.17	237.81	383.94	56.51	59.20	83.09	131.79	2174.24	6299.41	1049.16	254.56	13559.57

Table 5: 2030 percentage changes in biomass supplies under GHG price scenarios

GHG price scenario		**$15+5%**				**$30+5%**				**$50+5%**			
$/tCO2e in year		**$40**				**$80**				**$133**			
$/MMBtu		**$ 2.06**	**$ 3.08**	**$ 5.14**	**$ 8.22**	**$ 2.06**	**$ 3.08**	**$ 5.14**	**$ 8.22**	**$ 2.06**	**$ 3.08**	**$ 5.14**	**$ 8.22**
Region	**Feedstock**												
Corn Belt	Total	(100)	(81)	(20)	6	(100)	(100)	(25)	(24)	(100)	(100)	(91)	(24)
Northern Plains	Total	(67)	(3)	(18)	(4)	(100)	(30)	(77)	(8)	(100)	(79)	(76)	(11)
Lake States	Total	(100)	(78)	(42)	(27)	(100)	(95)	(89)	(44)	(100)	(100)	(90)	(48)
Northeast	Total	(94)	(82)	(55)	(17)	(100)	(99)	(79)	(32)	(100)	(100)	(79)	(58)
Pacific Northwest East	Total	(58)	(26)	(49)	(18)	(100)	(30)	(52)	(35)	(100)	(66)	(57)	(61)
Pacific Northwest West	Total	(39)	(19)	(14)	(22)	(100)	(10)	(6)	(15)	(100)	(100)	(15)	(17)
Pacific Southwest	Total	(100)	(11)	1	1	(100)	(64)	(10)	(52)	(100)	(100)	(14)	(59)
Rocky Mountain	Total	(100)	(21)	(14)	(7)	(100)	(47)	(19)	(45)	(100)	(100)	(22)	(45)
South Central	Total	(100)	(83)	(3)	3	(100)	(94)	(30)	(22)	(100)	(100)	(51)	(35)
Southeast	Total	(100)	(66)	(3)	4	(100)	(95)	(10)	(6)	(100)	(100)	(76)	(34)
Southern Plains	Total	(91)	(70)	(1)	(3)	(100)	(85)	(2)	(23)	(100)	(97)	(5)	(27)
US	Total	(83)	(62)	(18)	(3)	(100)	(80)	(43)	(22)	(100)	(96)	(68)	(29)
US	Bagasse	n/a	(100)	(8)	0	n/a	(100)	(18)	(13)	n/a	(100)	(100)	(23)
US	Barley residue	(68)	(23)	(31)	(16)	(100)	(29)	(39)	(15)	(100)	(71)	(44)	(17)
US	Beef manure	(100)	31	11	(3)	(100)	(100)	(10)	(49)	(100)	(100)	19	(27)
US	Corn residue	(100)	(57)	(68)	(6)	(100)	(91)	(74)	(57)	(100)	(100)	(87)	(88)
US	Dairy manure	(100)	(57)	(44)	(14)	(100)	(100)	(59)	(63)	(100)	(100)	(36)	(59)
US	Hardwood residue	n/a	(92)	(26)	13	n/a	(100)	(49)	3	n/a	(100)	(94)	(37)
US	Hybrid poplar	n/a	n/a	(100)	0	n/a	n/a	(100)	(27)	n/a	n/a	(100)	(100)
US	Lignin hardwood	(31)	2	4	(43)	(100)	(2)	0	(35)	(100)	(40)	(13)	(41)
US	Lignin softwood	(69)	(21)	(68)	133	(100)	(1)	(4)	107	(100)	(99)	214	124
US	Lignin	40	(2)	27	(0)	(100)	(18)	20	17	(100)	(41)	30	32
US	Manure	(100)	(35)	314	13	(100)	(100)	488	(32)	(100)	(100)	223	(50)
US	Oats residue	(95)	(11)	(36)	(26)	(100)	(42)	(35)	(29)	(100)	(100)	(28)	(42)
US	Rice residue	(100)	(23)	(11)	(1)	(100)	(47)	(39)	(23)	(100)	(100)	(52)	(38)
US	Softwood residue	(100)	(65)	3	8	(100)	(96)	6	11	(100)	(100)	(48)	15
US	Sorghum residue	(51)	(12)	(9)	(5)	(100)	(24)	(18)	(15)	(100)	(100)	(6)	(17)
US	Sweet sorghum residue	n/a	n/a	(19)	(8)	n/a	n/a	(100)	(9)	n/a	n/a	(100)	(21)
US	Switchgrass	n/a	(100)	(10)	(1)	n/a	(100)	(33)	(20)	n/a	(100)	(76)	(21)
US	Wheat residue	(100)	(11)	(1)	(4)	(100)	(52)	(5)	(4)	(100)	(100)	(6)	(7)
US	Willow	n/a	(100)	(53)	(20)	n/a	(100)	(100)	(32)	n/a	(100)	(100)	(59)

Table 6: Percentage of fossil fuel GHG emissions offset by feedstock and energy end-use

Commodity	Crop Ethanol	Cell Ethanol	Biodiesel	5% cofire	10% cofire	15% cofire	20% cofire	100% fire
Corn	30.5							
HardRedWinterWheat	31.5							
Sorghum	39.6							
softwoodres		79.7		97.1	97.1	97.1	97.1	96
hardwoodres		79.6		95.8	95.9	95.8	95.8	95.3
cornres		74.6		92.1	92.2	92.1	92	86.5
wheatres		70.2		93.8	93.9	93.8	93.7	89.5
softmillres		82.3						
hardmillres		81.7						
biomanure				98	97.8	97.7	97.6	95
SwitchGrass		71.8		93.9	94	93.9	93.8	90.1
HybrdPoplar		61.4		92.5	92.6	92.5	92.4	87.6
Willow		67.3		95.1	95.1	95.1	95	92.2
EnergySorghum		75.6		95.8	95.8	95.7	95.6	93.1
SoybeanOil			70.2					
RefSugar	64							
CornOil			53.6					
Bagasse		87.7		97.6	97.7	97.6	97.6	97
Lignin				97.3	97.4	97.3	97.3	96.5
LigninHardwood				97.5	97.5	97.5	97.5	96.8
LigninSoftwood				98.1	98.1	98.1	98.1	97.8

Figure 1: Regional biomass supplies for electricity generation in 2030

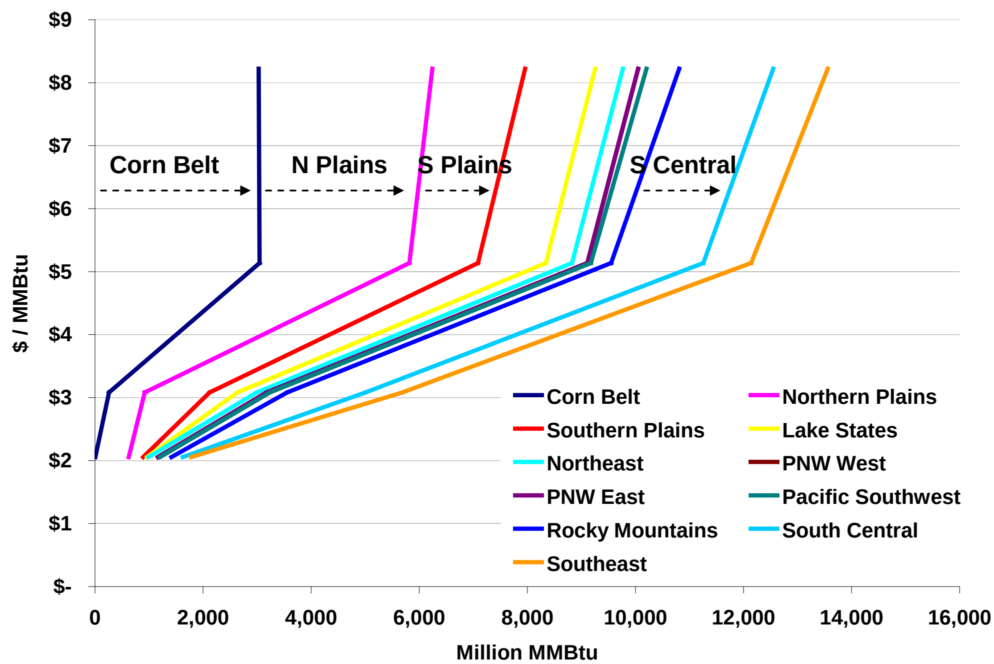

Figure 2: U.S. biomass feedstock supplies in 2030

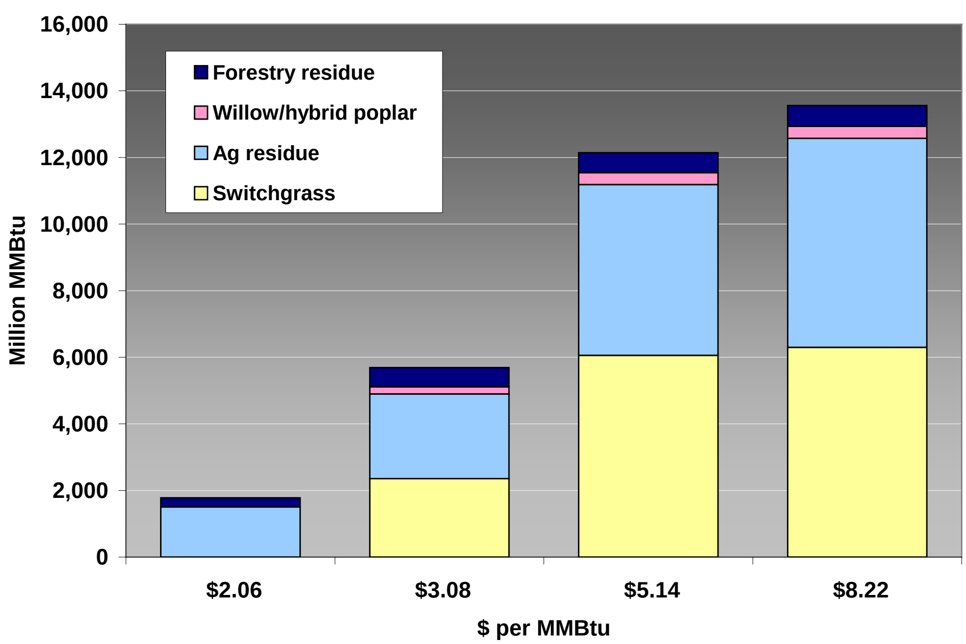

Figure 3: U.S. agricultural and forest land-use conversion in 2030 with higher feedstock prices (relative to conversion with $2/MMBtu)

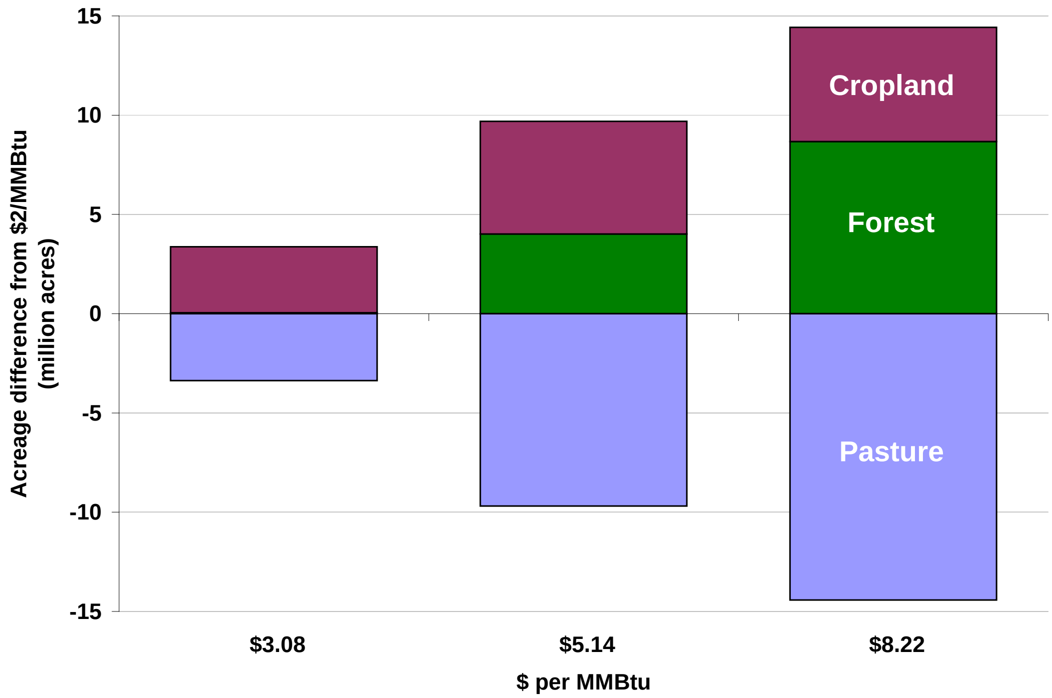

Figure 4: U.S. biomass supply for electricity generation under different GHG price scenarios

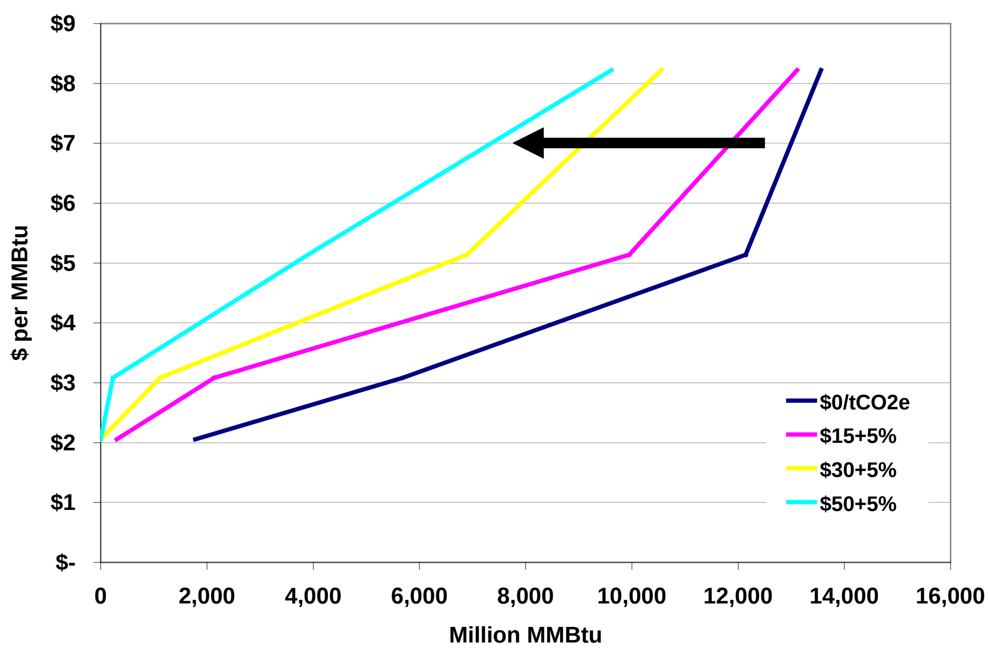

Figure 5: Corn Belt cropland acreage without a GHG price and under a $50/tCO2e + 5%/yr scenario

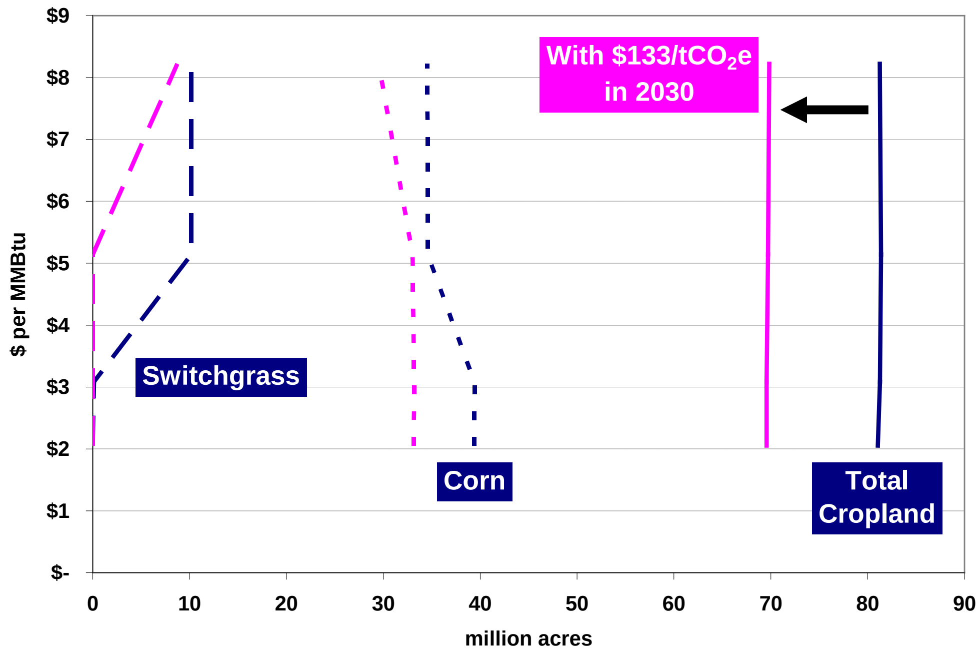

Figure 6: Biomass supply (million MMBtu) and corresponding differences in domestic indirect GHG emissions with 300% higher $/MMBtu and no GHG price (MtCO2e/yr)