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Dedicated Energy Crops and Competition for Agricultural Land

By Ronald D. Sands, Scott A. Malcolm,
Shellye A. Suttles, and Elizabeth Marshall

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Abstract

Dedicated energy crops, such as switchgrass in the United States, have received much attention as potential renewable feedstocks for liquid fuels or bioelectricity; however, markets do not presently exist for large-scale use of this resource. This study examines three policy scenarios that could create a market for bioelectricity using dedicated energy crops: a subsidy for bioelectricity generation, a national Renewable Portfolio Standard (RPS), and a national cap-and-trade policy to limit carbon dioxide (CO_2) emissions. Model results suggest that energy crops as a share of total cropland by region would be greatest in the Northern Plains, Southeast, and Appalachia. Even though the impact of energy crop production on land use across scenarios is similar by design, the impacts on other model outputs are quite different, including the mix of electricity-generating technologies, the price of electricity, CO_2 emissions, and the cost relative to a no-policy reference scenario. For example, the price of electricity increases with cap-and-trade but declines with a bioelectricity subsidy. In all scenarios, U.S. CO_2 emissions decrease relative to the reference scenario. Emissions reductions are greatest in the cap-and-trade scenario, but significant reductions are also obtained with an RPS.

Keywords: bioenergy, land use, energy crops, scenarios, renewable portfolio standard, climate policy

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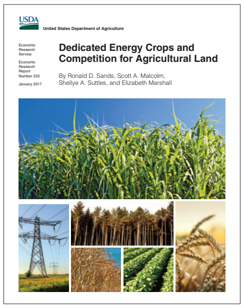

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What Is the Issue?

Dedicated energy crops, such as switchgrass in the United States, are viewed as potential renewable feedstocks for liquid fuels or bioelectricity. However, markets do not presently exist for large-scale use of this resource. This study examines three policy scenarios that could create a market for bioelectricity using dedicated energy crops: a subsidy for bioelectricity generation, a national Renewable Portfolio Standard (RPS), and a national cap-and-trade policy to limit carbon dioxide (CO_2) emissions. Many States already have an RPS that requires a percentage of electricity production to be generated from renewable energy sources. A policy with a cap on CO_2 emissions would have the potential to create demand for combustible biomass to generate electricity, including crops grown solely for their energy content.

What Did the Study Find?

The introduction of dedicated energy crops on a large scale could affect other agricultural land uses, prices of other crops, and trade in agricultural products. Each scenario provides 250 terawatt-hours (TWh) of electricity generation from switchgrass and approximately 50 TWh from forest residue.

- A policy that provides incentives for bioelectricity generation of 250 TWh per year from switchgrass would require 25 to 29 million acres (10.1 to 11.8 million hectares) of land in 2030, an area about one-half that used now for U.S. wheat production. However, this estimate depends directly on the average yield for energy crops and the rate of yield growth over time for both energy crops and other crops. For a sense of scale, the United States produced 267 TWh of electricity from hydropower in 2013, providing 6.6 percent of total U.S. electricity generation of 4,070 TWh.
- Generation of 250 TWh of bioelectricity from switchgrass plus 50 TWh from forest residue would require 234 million short tons of dry biomass in 2030. A feasibility study of biomass supply by the U.S. Department of Energy provides a similar estimate.
- Energy crops would be grown in regions where they have a comparative yield advantage relative to other crops. Model results suggest that switchgrass as a share of total cropland in 2030 would be highest in Appalachia, the Southeast, and the Northern Plains.

ERS is a primary source of economic research and analysis from the U.S. Department of Agriculture, providing timely information on economic and policy issues related to agriculture, food, the environment, and rural America.

Regions with the greatest number of acres in switchgrass would be the Northern Plains (11.1 million acres), Appalachia (8.6 million acres), the Corn Belt (4.2 million acres), and the Southeast (3.0 million acres). Due to the large area of cropland in the Corn Belt, switchgrass would account for a small share of total cropland, less than 5 percent.

- Extensive planting of switchgrass coupled with reduction of acreage of nonenergy crops reduces soil erosion by 5 percent nationally, with greater reductions in regions with high energy crop plantings—17 percent in Appalachia, 12 percent in the Southeast, and 9 percent in the Northern Plains. The amount of nitrogen lost to water declines compared with the reference scenario by about 4 percent. Nitrogen fertilizer application intensity increases, but increased planting of switchgrass leads to more nutrient retention.

- By scenario design, the amount of land used for switchgrass is similar across policy scenarios. Production declines for major field crops as land shifts to switchgrass from cropland, pasture, and forest. Changes in harvested area, production, and price by 2030 are similar between the subsidy and RPS scenarios for wheat, coarse grains, and oilseeds. For these nonenergy crops, harvested area declines 3.6 to 7.2 percent, production declines 0.6 to 4.0 percent, and prices increase 1.9 to 3.5 percent. Crop exports decline to compensate for most of the decline in production, with small changes in consumption and imports. Percentage increases in crop prices are greater in the CO_2 cap-and-trade scenario.

- Some impacts of energy crop production differ widely across policy scenarios. By 2030, the price of electricity increases 55 percent with cap-and-trade but declines 0.5 percent with a bioelectricity subsidy. In all scenarios, U.S. CO_2 emissions decrease relative to the no-policy reference scenario. Emissions reductions are greatest in the cap-and-trade scenario (40 percent) but are also significant with an RPS (10 percent). The emissions reduction in the bioelectricity subsidy scenario is small (1.2 percent).

How Was the Study Conducted?

This study uses two ERS models: the Future Agricultural Resources Model (FARM) provides a global computable-general-equilibrium platform with the ability to simulate alternative energy and climate policies, and the Regional Environment and Agriculture Programming (REAP) model provides finer detail on crops and land use in the United States. In both models, switchgrass competes in land markets with other crops, pasture, and managed forests. The primary biofuel pathway is solid biomass—either forest residue or switchgrass—to bioelectricity. The pathway of corn to ethanol is not a focus of this study but is part of the reference scenario.

The global model provides results on the mix of electricity-generating technologies, the price of electricity, CO_2 emissions, and the cost relative to a no-policy reference scenario. The national model allocates production of energy crops among regions with differing yields. Analysis is coordinated between the models with targets of 50 TWh from forest residue and 250 TWh from switchgrass in 2030, for a total of 300 TWh from solid biomass in each scenario. The analysis provides variations on these scenarios with alternative switchgrass yields and alternative bioelectricity targets.

Dedicated Energy Crops and Competition for Agricultural Land

Introduction

Approximately 33 million acres of cropland in the United States are used to grow corn that is later converted to ethanol as a transportation fuel. Another example of a pathway from bioenergy feedstock to energy is the co-firing of forest residue with coal to generate electricity. With the potential for policies that address energy and climate issues, interest is rising in expanding the use of renewable energy such as solar, wind, and bioenergy derived from dedicated (nonfood) energy feedstocks, often referred to as second-generation feedstocks (table 1). For bioenergy, the motivation is to replace a portion of U.S. fossil energy consumption using feedstocks other than food crops.

The U.S. Department of Energy (DOE) has published three studies on the feasibility of supplying 1 billion short tons of second-generation biomass feedstock, including the *U.S. Billion-Ton Update* (U.S. DOE, 2011). Supply of biomass is estimated at various prices: $40, $50, and $60 per dry short ton for agricultural biomass and $20, $40, and $80 per dry short ton for forest biomass. However, the DOE study states that "bioenergy markets currently do not exist for the resource potential identified." The DOE study covers the supply side of bioenergy but does not provide analysis of potential drivers for bioenergy demand, nor does it consider the effects of increases in biomass harvest on other parts of agricultural production.

The DOE study therefore provides background on the supply of biomass feedstocks at various offer prices. This ERS study goes further by providing analysis on the *competitive potential* of biomass. First, scenarios are constructed that provide a demand for dedicated energy crops. Second, ERS's modeling framework contains a land market, where energy crops compete for land with food crops and forest. Third, the ERS study includes an electricity market, where electricity generated with biomass competes with other sources of renewable electricity, especially wind and solar power.

Several policies have the potential to create markets for second-generation feedstocks: (1) the national Renewable Fuel Standard (RFS) with incentives for ethanol derived from cellulosic biomass; (2) a Renewable Portfolio Standard (RPS) for electricity generation, as in some States;

Table 1
Biomass feedstocks

	Primary agricultural resources	Primary forestland resources
First-generation feedstocks	Corn, oil crops, sugar crops, sorghum	
Second-generation feedstocks	Crop residues, switchgrass, miscanthus, dedicated biomass sorghum	Forest residues, hybrid poplar plantations, southern pine plantations, eucalyptus plantations, shrub willow

Source: USDA, Economic Research Service.

(3) a climate policy with a cap on emissions of carbon dioxide (CO_2); and (4) a subsidy on bioelectricity. Volumes of cellulosic biofuel production today are small relative to corn ethanol production in the RFS, and it is not known if the cost of producing cellulosic biofuel will fall enough to enable it to compete against other liquid fuels.[1] The U.S. Energy Information Administration (EIA) projects that the quantity of cellulosic-based liquid fuels will remain small through 2040 (U.S. EIA, 2015). Even without greater volumes of cellulosic biofuel production, the demand for dedicated energy crops could increase significantly as a feedstock for electricity generation. This study analyzes three alternative policy scenarios that could create a market for bioelectricity in the United States.

Many States already have a Renewable Portfolio Standard that requires a percentage of electricity to be generated from renewable energy sources. Major renewable technologies that can contribute to RPS include hydropower, wind power, solar photovoltaic, and bioelectricity. The selection of technology will vary by geographic location, with consideration of solar and wind resources, water availability, soil characteristics, and options for electricity storage. Bioelectricity is generated by combusting biomass to raise steam to power a turbine generator. One advantage of bioelectricity over solar or wind power is that greater control over the timing of power generation is achieved through storage of biomass fuel.

There is also the possibility that a future climate policy may place controls on the level of CO_2 emissions. Dedicated energy crops contain carbon recently removed from the atmosphere through photosynthesis, and net emissions of CO_2 from biomass combustion can be much less than those from combustion of fossil fuels. Further, if capturing and sequestering CO_2 underground is available, bioelectricity combined with CO_2 capture and storage (BECCS) can become a negative-emissions technology. A strict emissions target, especially one designed to keep global average temperatures from increasing more than 2 degrees Celsius above pre-industrial temperatures, may require a negative-emissions technology for CO_2: the most-cited example is BECCS. Therefore, the focus of this study is the demand for dedicated energy crops to generate electricity. Dedicated nonfood energy crops include switchgrass, miscanthus, and short-rotation trees.

Switchgrass is a perennial grass native to most of North America and grows well on rain-fed marginal land. However, the application of nitrogen fertilizer is needed to optimize switchgrass yield. Giant miscanthus, another potential energy crop, is a perennial grass hybrid that has lower fertilizer requirements than row crops or switchgrass. Perennial grasses can restore carbon to soil that previously lost carbon to cultivation. Short-rotation wood crops, such as hybrid poplar trees, are already grown commercially for pulpwood production in Washington and Oregon. Shrub willow trees are another option for an energy feedstock, with harvest 3 to 4 years after planting (U.S. DOE, 2011).

This study is organized around scenarios that provide a minimum 300 terawatt-hours (TWh) per year of electricity generated from solid biomass by 2030, including 50 TWh from forest residue and 250 TWh from a dedicated energy crop.[2] Two ERS models are employed in the

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[1] The 2005 Energy Policy Act created the original RFS program, which established the first renewable fuel volume mandate in the United States. The original RFS program (RFS1) required 7.5 billion gallons of renewable fuel to be blended into gasoline by 2012. The updated RFS program (RFS2) was expanded under the 2007 Energy Independence and Security Act. RFS2 includes biodiesel, increases the volume from 9 billion in 2008 to 36 billion gallons of ethanol equivalent by 2022, establishes new categories of renewable fuels, and requires renewable fuels to emit fewer greenhouse gases than the petroleum fuel it replaces.

[2] One TWh is the same as 1 billion kilowatt-hours. Total U.S. electricity generation in 2013 was 4,070 TWh (U.S. EIA, 2015).

analysis. One simulates global markets, and a second simulates U.S. (national) cropland response at a regional level. Several “what-if” policy scenarios that could spur a U.S. market for an energy crop were created: a subsidy for bioelectricity, a national RPS, and a national cap-and-trade system that provides financial incentives to limit U.S. CO_2 emissions. Policy scenarios are coordinated between the global and national models to meet the annual 250 TWh target for electricity from energy crops by 2030. Electricity generation is endogenous in the global model, and policy parameters are adjusted to meet the target. For example, the global model searches for a bioelectricity subsidy until the 250 TWh energy-crop target is met.[3] In contrast, the electricity-generation targets are exogenous to the national model for forest residue and an energy crop. Both models simulate the growth of switchgrass in the United States as a dedicated energy crop, with the national model providing finer geographic detail on crops and land use in the United States. Switchgrass was chosen as the energy crop, rather than giant miscanthus, as switchgrass has been grown more extensively in experimental plots in the United States, providing greater availability of data on production costs and yield. Switchgrass is native to the United States, but giant miscanthus is not.

The following questions are of particular interest to this study:

- To what extent might an energy policy influence the amount of land used for dedicated energy crops?
- How much biomass is required?
- Where are dedicated energy crops likely to be grown in the United States?
- What impacts are similar across policy scenarios?
- What impacts differ across policy scenarios?

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[3] 250 TWh was selected as the target because it is large enough to be comparable to other electricity-generating technologies (e.g., hydropower) yet technically is feasible.

Economic Analysis Framework

A global economic model consisting of 13 world regions is used to simulate U.S. economic policies, the interaction between agricultural and electricity markets, and the impacts on international trade. An economic model of U.S. agriculture is then used to simulate land use by USDA farm production region (USDA region), along with impacts on production and prices of field crops. ERS developed and maintains both the global model—Future Agricultural Resources Model (FARM)—and the national model—Regional Environment and Agriculture Programming (REAP).[4]

The global model maximizes consumer welfare (essentially real consumption) in each world region, while the national model maximizes net returns to producers and consumers of U.S. agricultural products. In both models, switchgrass competes in land markets with all other crops and managed forests. The primary biofuel pathway is solid biomass to bioelectricity, using either forest residue or switchgrass. The pathway of corn to ethanol remains important because of the land required for corn ethanol. It is assumed that the current RFS policy remains in place with no more than 15 billion gallons of corn ethanol per year.

We use two models to exploit the relative strengths between them. The global model has broad coverage of energy and agricultural activities in 13 world regions, including the United States, and provides an estimate of the change in economic welfare (e.g., the change in real Gross Domestic Product, or GDP) under a policy scenario relative to a reference scenario. Further, the model's international trade structure allows for an assessment of the effect of a U.S. policy on the rest of the world. The national model has a more detailed set of crops than the global model and simulates the allocation of crops across USDA farm production regions. Of particular interest is how switchgrass production might be distributed across the United States and how competition for land might impact the rest of the U.S. agriculture sector.

A coordinated reference scenario for the global and national models is the starting point for the analysis. A global reference scenario runs from 2007 through 2052 in 5-year steps; model output is then interpolated to report results from 2010 to 2050. The reference scenario includes corn ethanol production up to 15 billion gallons per year but does not include cellulosic liquid fuel production. The national model operates for a single year, in this case 2030.

Results from the global model include (1) changes in land area over time for crops, pasture, and forest in the United States and in the rest of the world; (2) changes in the mix of electricity-generation technologies; and (3) changes in energy prices. Two U.S. markets are important for bioelectricity: the market for land and the market for electricity. Bioelectricity must compete against crops, pasture, and forest for land, and must also compete for a share of electricity generation. Land competition is based on the land rent for each competing use: land use is adjusted within agro-ecological zones (AEZs) until rents at the margin are equal. Market share for electricity technologies is based on cost per megawatt hour (MWh): market share increases when the unit cost declines relative to other generating technologies.

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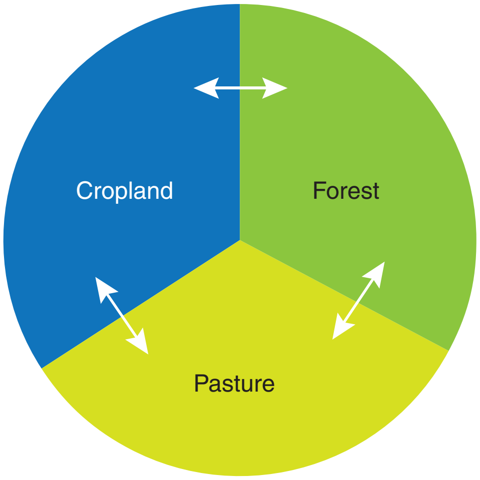
[4] Appendixes C and D provide further background on the ERS global (FARM) and national (REAP) models.

Results from the national model include (1) changes in land area for crops, pasture, and forest by USDA region; (2) changes in production quantities for crops by USDA region; and (3) changes in nutrient and soil loss. Land is divided into three categories: cropland, pasture/rangeland, and forest (see fig. 1). Each of these land types has a set of production activities. In each USDA region, the sum of land areas used for the three activities is fixed in total. Land for other purposes (e.g., industrial, residential, and recreational) does not compete with agricultural land. While the total land available for agriculture and forestry remains constant in each USDA region, the equilibrium levels of each land use category can change in response to a shock. Cropland includes land in USDA's Conservation Reserve Program (CRP).[5] Crop yields for 2030 are derived by extending USDA agricultural projections (U.S. Department of Agriculture, 2015).

A number of additional scenarios for sensitivity analysis are constructed for the global and national models. The global model has three alternative yield levels for switchgrass that span the range of switchgrass yields across USDA regions. In addition to the 300 TWh bioelectricity target, results from the national model include alternative scenarios of 200 TWh and 400 TWh, with electricity generation from forest residue held constant at 50 TWh in each scenario.

Figure 1

Representation of agricultural land (CRP is wholly contained in cropland)



Source: USDA, Economic Research Service.

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[5] CRP land remains constant in REAP model scenarios.

Policy Context

The U.S. Energy Information Administration publishes projections of U.S. production and consumption of energy through 2040 (U.S. EIA, 2015). EIA projects that production of biofuels from cellulosic biomass for transportation will remain very small through 2040. It projects electricity generation at 59 TWh using wood and other biomass, 47 TWh using solar photovoltaic, and 317 TWh using wind by 2040. For comparison, in 2013, electricity generation from hydropower was 267 TWh, generation from wind was 168 TWh, and generation from all sources was 4,070 TWh.

ERS's scenario of 250 TWh of electricity from dedicated energy crops in 2030 has a land requirement of 25 to 29 million acres (10.1 to 11.8 million hectares) needed to produce 234 million short tons of biomass. The technical potential to produce this quantity of biomass exists: the land requirement is less than that presently used for corn ethanol, and U.S. DOE (2011) estimates that 400 million dry short tons of biomass from energy crops would be available in 2030 at $60 per dry short ton, if energy crop yield increases at 1 percent per year. Even with a renewable energy or climate policy in place, biomass will compete with wind and solar power. The competitive potential of biomass electricity depends in part on its advantage to store biomass fuel across days of the week and across seasons, whereas wind and solar require backup generating capacity or electricity storage.

The United States does not have a national renewable electricity mandate. Currently, 29 States, the District of Columbia, and 2 U.S. territories have renewable portfolio standards that require the production of energy from renewable sources, which can include biomass (DSIRE, 2015), while 9 States and 2 additional territories have nonmandatory renewable electricity goals (see box "Renewable Portfolio Standards"). In 2013, 40 TWh of electricity generation came from wood and other biomass sources in the United States (U.S. EIA, 2012).

A greenhouse gas cap-and-trade policy, or a carbon tax, could provide economic incentives for bioenergy produced from dedicated energy crops. As with a renewable portfolio standard, bioelectricity would compete with wind and solar power. Under a cap-and-trade policy, fossil fuel consumption would incur a carbon fee based on the amount of CO_2 released during combustion.

Winchester and Reilly (2015) assess the role of biomass in the context of a global climate policy, with a time horizon to 2050. Their analysis shows that cellulosic biofuels for transportation could become the major form of bioenergy with a sufficient decline in the cost of production. If production costs do not fall as needed for cellulosic biofuel expansion, then bioelectricity and bioheat would become the dominant bioenergy pathways that would use cellulosic feedstocks (see box "Bioelectricity and Negative CO_2 Emissions").

Renewable Portfolio Standards

Currently, 29 States and the District of Columbia have renewable portfolio standards (RPS), while 8 States have renewable portfolio goals that are not legally binding (DSIRE, 2015). These RPSs require utilities to use renewable energy (or procure renewable energy credits) in a certain amount of their total electricity generation or retail sales. Additionally, certain RPS provisions require that utilities use a specific renewable resource, such as wind or solar, to account for a certain amount of electricity generation or sales.

Box table 1

States with renewable portfolio standards or goals in 2015

Renewable portfolio standards	AZ, CA, CO, CT, DC, DE, HI, IA, IL, MA, MD, ME, MI, MN, MO, MT, NC, NH, NJ, NM, NV, NY, OH, OR, PA, RI, TX, VT, WA, WI
Renewable portfolio goals	IN, KS, ND, OK, SC, SD, UT, VA

Source: USDA, Economic Research Service using Database of State Incentives for Renewables & Efficiency (2015).

Individual States implement various mandates and incentives to achieve renewable energy and energy efficiency goals. Colorado, for example, mandates 30 percent renewables by 2020 for investor-owned utilities and 10 percent renewables by 2020 for electric cooperatives and large municipal utilities. Certain States have set-asides for fuel-specific provisions, such as New Jersey's mandate for 4.1 percent solar energy by 2028 in addition to the 20.4-percent renewables mandate. States that have capacity mandates, instead of fractional mandates, include Texas, which has a goal of 5,880 megawatts (MW) in 2015 (already exceeded).

Regulations and policies that promote the use of renewables include net metering, renewable electricity interconnection to distribution grids, solar equipment certification, access laws to ensure proper sunlight for solar energy systems, construction and design of energy codes for new buildings, and a mandatory green power option for retail consumers. Financial incentives to promote renewable energy include personal, corporate, sales, and property tax credits; rebates; grants; loans; industry support; bonds; and performance-based incentives.

In 2006, California passed the Global Warming Solutions Act (California's RPS), which required the State to reduce its greenhouse gas emissions to 1990 levels by 2020, meaning approximately 15 percent below a "business as usual" scenario (California Global Warming Solutions Act, 2006). California's strategy for reducing emissions from electricity includes encouraging energy efficiency in buildings and appliances, renewable energy to displace fossil electricity, grid management, and solar heating (CARB, 2014).

In EIA's 2014 Annual Energy Outlook, States are projected to meet their ultimate RPS mandates in the reference case through 2040, where each State-level mandate is modeled as a share of a National Energy Modeling System electricity region (Bredehoeft and Bowman, 2014; U.S. EIA, 2014). Nationally, the mandates account for slightly less than 10 percent of U.S. electricity sales in 2025. The modeled RPS mandates are based on State renewable energy requirements that were enacted by October 2013 but do not include voluntary goals or targets that can be satisfied by nonrenewable resources.

Bioelectricity and Negative CO_2 Emissions

If carbon dioxide (CO_2) capture and storage (CCS) technology becomes widely available, then bioelectricity has a unique advantage over all other electricity-generating technologies: bioelectricity combined with CCS (BECCS) can provide negative emissions of CO_2. In this case, CO_2 is removed from the atmosphere by an energy crop, the crop is combusted to generate steam to drive electric turbines, the CO_2 released from biomass combustion is captured, and then the CO_2 is pressurized and stored underground.

Given the potential importance of CCS, the Intergovernmental Panel on Climate Change (IPCC) produced a comprehensive Special Report (IPCC, 2005). Also reflecting the importance of CCS, the journal *Climatic Change* published a special issue on negative emissions technologies (Tavoni and Socolow, 2013). The economics of bioelectricity with CCS differ from those of all other electricity-generation technologies, with joint products of electricity and carbon sequestration, and with economic rents accruing to land owners (Sands et al., 2014a).

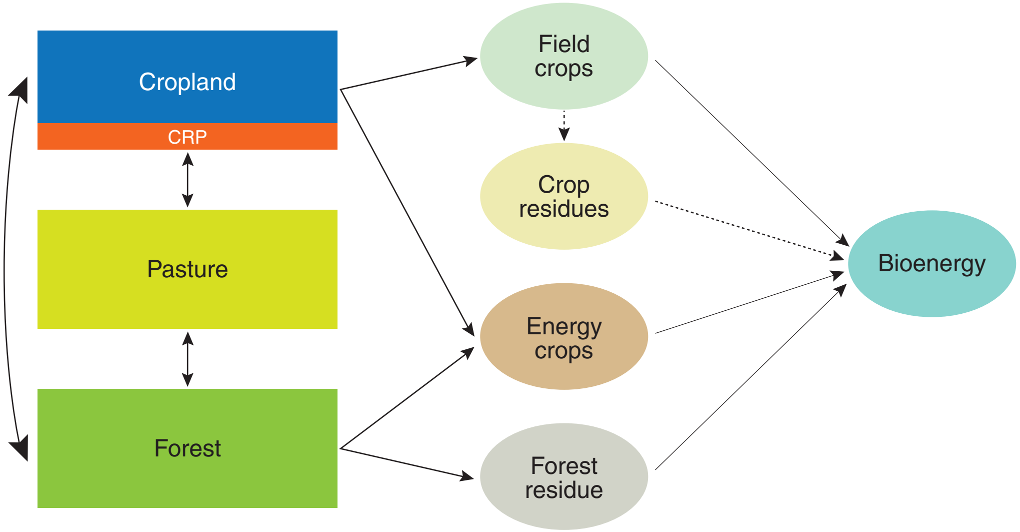
Many studies with scenarios that limit the long-term, steady-state global mean surface temperature increase to less than 2 degrees Celsius use large-scale bioenergy combined with CCS (e.g., Edmonds et al., 2013). BECCS is part of the technology mix for nearly all global integrated assessment models running scenarios with net CO_2 emissions approaching zero toward the end of this century. Economical operation of CCS requires a CO_2 price high enough to cover the cost of CCS installation and operation. It is not known when BECCS might operate at large scale, but BECCS has large potential as a negative-emissions technology.

Bioenergy Pathways

Solid biomass for bioenergy production can be derived from forest residue, crop residue, or dedicated energy crops (fig. 2). Several biofuel pathways are relevant to this study: corn ethanol, cellulosic biofuels, and switchgrass electricity. Corn ethanol is part of the reference scenario to the extent allowed by the RFS. Cellulosic biofuels have not reached large-scale production and therefore are not included in the reference scenario. Crop residues are a potential feedstock but are not considered in this study. (For a discussion of the tradeoffs with nutrients and greenhouse gases when removing residue from cropland, see box "Crop Residues"). Electricity generated from municipal solid waste (MSW) is part of the reference scenario but does not count toward this study's target of 300 TWh. Bioelectricity using switchgrass and forest residue are the primary pathways examined in this study.

Figure 2

Modeled bioenergy pathways



CRP = Conservation Reserve Program.
Source: USDA, Economic Research Service.

Crop Residues

Crop residues, primarily corn stover, are a potentially useful feedstock for production of bioelectricity. Removing all residue remaining on a field after harvest is not feasible because residues are important to maintain soil nutrients, moisture, and erosion control. The amount of residue that can be sustainably removed from a field is farm-specific and depends on soil organic carbon, wind and water erosion, plant nutrient balance, soil water and temperature dynamics, soil compaction, and off-site environmental impacts (Wilhelm et al., 2010). Removal of residues affects nutrients embodied in the soil. This may require additional application of fertilizer to replace nutrients, adding to the cost of supplying residues for energy production, although revenue from residues may offset additional costs.

Table 4.6 of the *U.S. Billion-Ton Update* (see U.S. DOE, 2011) provides a summary of agricultural residue supply from corn stover and wheat straw, assuming limits to residue harvest imposed by tillage practice. Residue removal is allowed under no-till and reduced-till cultivation but not under conventional tillage. Assuming that corn and wheat yields will increase between now and 2030, the study estimates 77 dry tons of residue at $40 per dry ton, 160 dry tons at $50 per dry ton, and 176 dry tons at $60 per dry ton. These quantities of residues could provide a significant share of fuel required for 250 terrawatt hours of bioelectricity generation. Table 5.1-1 of *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis* (U.S. EPA, 2010) provides specific residue removal rates for corn: 50 percent for no-till, 35 percent for reduced-till, and no removal for conventional till.

Table 2 provides energy balances and net conversion efficiencies for switchgrass to electricity. Besides switchgrass yield, the most important parameter is electricity-generating efficiency for bioelectricity. Given the wide range of switchgrass yields across studies, table 2 has three scenarios that vary by yield. Estimates of energy requirements for switchgrass ethanol help inform the energy requirements for switchgrass electricity (National Research Council, 2011).

Table 2

Energy balance for switchgrass electricity

	Units	Low yield	Medium yield	High yield
U.S. switchgrass yield	t/ha (short tons/acre)	8 (3.6)	12 (5.4)	16 (7.1)
Switchgrass energy density	GJ/t	18	18	18
Gross energy yield	GJ/ha	144	216	288
Generation efficiency	Percent	30	30	30
Energy yield (as electricity)	GJ/ha	43	65	86
Fossil input	GJ/ha	12	12	12
Input (electricity equivalent)[a]	GJ/ha	4.2	4.2	4.2
Net energy yield (as electricity)	GJ/ha	39	61	82
Net electricity generated	MWh/ha	10.8	16.8	22.8
Net conversion efficiency	Percent	27	28	29
Land requirement	kha/TWh	92	59	44

Note: t/ha = tons/hectare. GJ/t = gigajoules/ton. GJ/ha = gigajoules/hectare. MWh/ha = megawatt hour/hectare. kha/TWh = thousand hectares/terrawatt hour.

[a] Assumes 35 percent generation efficiency using refined petroleum.

Sources: USDA, Economic Research Service using the Future Agricultural Resources Model and National Research Council (2011).

Campbell et al. (2009) compare land-use efficiency for renewable transportation fuels and conclude that bioelectricity is more efficient than cellulosic biofuels in terms of land requirements and greenhouse gas emissions. Historically, switchgrass was selected as a high-potential energy crop: out of 34 species used in field trials across research institutions in 7 States starting in the late 1980s, 6 of 7 institutions identified switchgrass as being a high priority for further development (Wright, 2007). Switchgrass was particularly successful in projects in Virginia and Alabama, where it had high yields, deep rooting, and potential value for carbon sequestration.

Thomson et al. (2009) provide a comprehensive assessment of U.S. switchgrass yield potential using eight-digit watersheds as the primary modeling unit with EPIC as the crop model. The highest average yields, by two-digit watersheds, were in the Lower Mississippi, Upper Mississippi, Ohio, and Tennessee watersheds. For these watersheds, average switchgrass yield is approximately 7 tons per hectare (t/ha), but the maximum within each watershed is above 14 tons per hectare. Switchgrass grows very well in the U.S. Corn Belt, but it also grows well in other regions.

Searle and Malins (2014a) reviewed potential yields of five energy crops, including switchgrass. The authors sought to understand whether commercial energy crop production can meet the expectations of previous literature and renewable energy policies. In comparing plot size, the authors found several energy crops to have lower yields at a larger scale than small experimental plots. Energy crops are more expensive to produce at lower yields, as more time, energy, and resources are needed per unit of output, which means that commercial ventures and government policies might fail to meet their goals if they are based on optimistic yield projections.

The DOE's *U.S. Billion-Ton Update* (see U.S. DOE, 2011) included estimates of the economic potential of several categories of biomass, including residue and waste from forestry and agriculture, and energy crops grown specifically for bioenergy (see box "Perennial Grasses and Woody Crops" for further discussion of biomass feedstocks). A wide range of energy crop yields was considered, with the middle of the range at 7 to 8 dry short tons per acre in 2012. The baseline scenario assumes a 1-percent annual growth in yield for energy crops and corn. The middle range in the *U.S. Billion-Ton Update* is close to this study's high yield scenario (see table 2). Our analysis also assumes 1 percent annual yield growth for switchgrass.

Wullschleger et al. (2010) note that switchgrass has two distinct varieties across its geographic range: a lowland type in wetter habitat of southern latitudes and an upland type in drier habitat of northern latitudes. The researchers found that switchgrass variety, temperature, precipitation, and land quality were the most important variables affecting yield. The study finds that mean yields for upland and lowland varieties were 3.9 and 5.8 dry short tons per acre (8.7 and 12.9 dry metric tons per hectare), respectively. Wullschleger et al. sought, but did not find, bias toward higher yields of switchgrass in small plots or on higher quality land. The study examined data on location, stand age, plot size, cultivar, crop management, yield, temperature, precipitation, and land quality. Unlike Searle and Malins, Wullschleger et al. conclude that field trials can be used to extrapolate biomass yield to larger spatial scales, but there should be a full understanding of the uncertainty of such extrapolation.

Perennial Grasses and Woody Crops

The *U.S. Billion-Ton Update* (see U.S. DOE, 2011) provides estimates of solid biomass supply in the United States at various prices per ton of dry biomass. Estimates are sensitive to the rate of yield growth over time for energy crops, and supply estimates are presented for selected years through 2030. Yield of energy crops increases by 1 percent per year in the baseline scenario. At $60 per short ton of dry biomass, supply in 2030 is provided for three types of energy crops: perennial grasses (255 short tons); woody crops (126 short tons); and annual energy crops (19 short tons).

In this ERS study, we make the simplifying assumption that perennial grasses, specifically switchgrass, along with forest residue provide all the biomass for bioelectricity, at 300 TWh in 2030. Using data in table 2 and the medium-yield assumption, we calculate that generating 300 TWh of electricity requires 234 million short tons of biomass, which is within the potential energy crop supply in 2030 from the *U.S. Billion-Ton Update*.

300 TWh x 59 kha/TWh x 12 t/ha x 1,000 ha/kha = 212 million metric tons of dry biomass
= 234 million short tons of dry biomass

Given the findings in the *U.S. Billion-Ton Update*, it is possible that this quantity of dry biomass could be supplied by a combination of perennial grasses and woody crops. Potential woody crops in the U.S. include plantations of southern pines, shrub willow, hybrid poplar, and eucalyptus. Each woody crop, and each perennial grass, has its own distribution of yield across U.S. regions.

TWh = terrawatt hours. kha = thousand hectares. t/ha = tons per hectare.

Searle and Malins (2014b) have critiqued energy crop modeling studies and found that the models were inconsistent with the best available evidence: upon revising the studies' original assumptions, the authors lower the upper-end estimates for potential biomass availability. The authors argue that yield growth of energy crops will not mirror historical yield growth of cereals because growth in cereals comes from increasing the ratio of grain to stalk, not from increasing the total biomass of the plant.

Table 3 provides a yield comparison for corn ethanol. The range of corn yields, between 128 and 191 bushels per acre, covers current and projected yields in the United States. Based on USDA survey results, ethanol yields have shown steady improvement. Ethanol yield across survey respondents has a mean of 2.76 gallons per bushel of corn, with a standard deviation of 0.07 gallons per bushel (Shapouri et al., 2010).

Table 3

Energy yield for corn ethanol

	Units	Low yield	Medium yield	High yield
U.S. corn yield[a]	tons/hectare	8	10	12
	(short tons/acre)	(3.6)	(4.5)	(5.4)
	(bushels/acre)	(128)	(159)	(191)
Ethanol yield[b]	liters/kilogram	0.411	0.411	0.411
	(gal/short ton)	(99)	(99)	(99)
Ethanol production[c]	liters/hectare	3,290	4,113	4,935
	(gal/acre)	(352)	(440)	(528)
Energy yield (as ethanol)	gigajoule/hectare	70	87	105

[a] One bushel of corn weighs 56 pounds. [b] One bushel yields 2.76 gallons of ethanol. [c] One liter equals 0.2642 gallons.

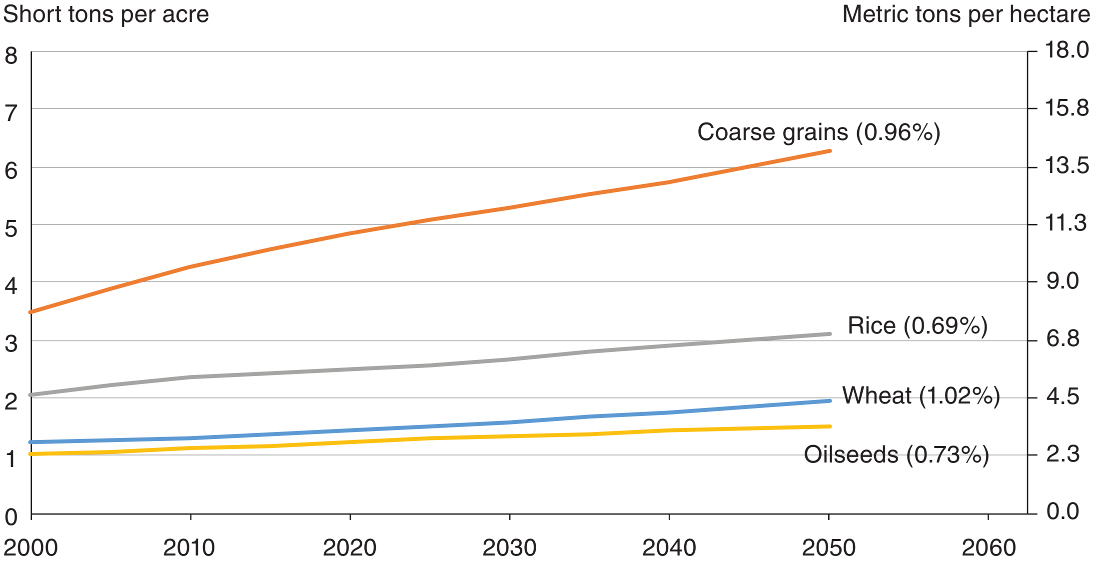
Source: USDA, Economic Research Service using Shapouri et al. (2010).

U.S. Reference Scenario

The United States is one of 13 world regions in the global model used in this study, and a global reference scenario of land use through 2050 can be found in Sands et al. (2014b). Here, the analysis focuses primarily on the United States and begins with a reference scenario that provides sufficient cropland for the RFS but excludes other energy or climate policies. The U.S. reference scenario provides a point of comparison, but first we describe how agricultural yield changes over time in this scenario. The starting point is an exogenous yield index for each crop type (fig. 3). This index is considered to be land augmenting: less land is needed per unit of product, but requirements for other inputs per unit of product are not affected. Projected yield growth rates from 2010 through 2050 are approximately 1 percent per year for coarse grains (mostly corn) and wheat, with a lower growth rate for oilseeds. These growth rates were provided by the International Food Policy Research Institute (IFPRI) to global economic modeling teams participating in the Agricultural Model Intercomparison and Improvement Project (AgMIP). Estimates of future agricultural yield growth are based on a combination of expert opinion on the biological potential for yield gains in individual countries, historical yield improvements, and expectations about future private and public research (Nelson et al., 2014).

Figure 3

U.S. crop yield projections



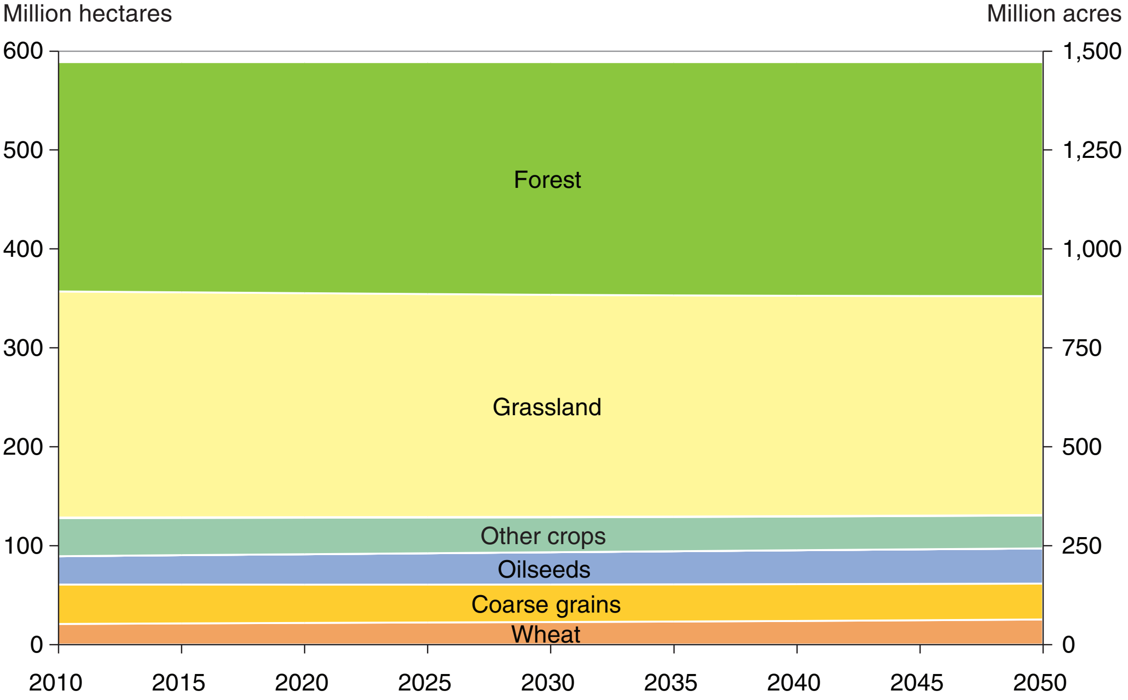
Note: Percentages following crop labels are annual growth rates from 2010 to 2050.
Source: USDA, Economic Research Service using data from International Food Policy Research Institute.

Other important drivers of future agricultural activity are population and income. We use population and income projections from Shared Socioeconomic Pathway (SSP) 2, the "middle of the road" pathway among five SSPs (O'Neill et al., 2014, 2015).[6] Quantified population and Gross Domestic Product (GDP) projections for all SSPs are available in a database maintained by the International Institute for Applied Systems Analysis (IIASA, 2013). We align GDP growth with SSP 2 projections. Between 2010 and 2050, the U.S. population is projected to grow at an average rate of 0.65 percent per year; per capita GDP is projected to grow at 1.20 percent per year; and real GDP is projected to grow at 1.85 percent per year.

Projected agricultural yield growth is high enough to keep pace with food demand from an increasing population in the United States. Furthermore, land used for crops in the United States increases slightly over time, enabling U.S. exports of crops to increase for wheat, coarse grains, and oilseeds (fig. 4).

Figure 4

U.S. land use in the reference scenario



Source: USDA, Economic Research Service using Future Agricultural Resources Model.

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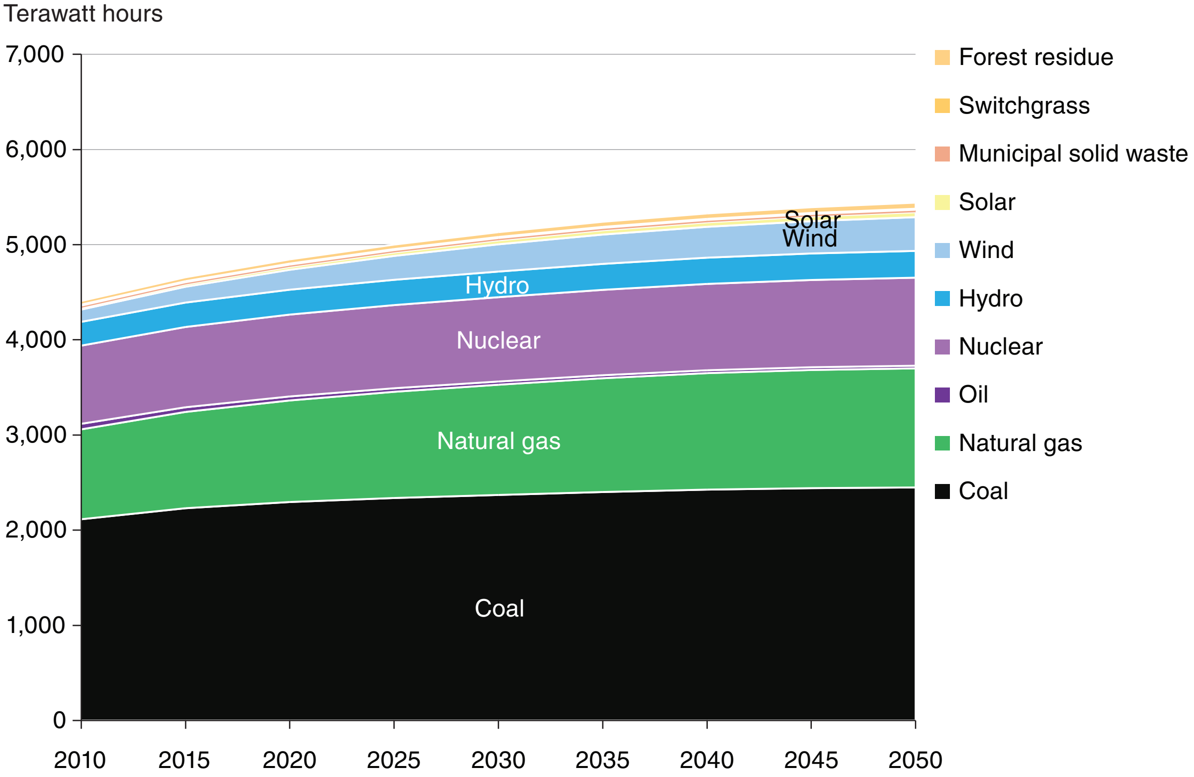
[6] Five Shared Socioeconomic Pathways were developed by the climate change research community to describe alternative futures of societal development. Some aspects are described by narrative only, but others, including population and per capita income, are quantified through 2100 worldwide. In SSP 2, the "middle of the road" scenario, economic and technological trends are similar to historical patterns.

The path of land use over time appears stable but is actually the result of offsetting drivers. Increases in population and per-capita income increase the demand for agricultural and forest products over time, but offsetting increases in crop yield decrease the demand for land. Sands et al. (2014b) provide a description of these drivers at a global scale, but the process for each world region is similar.

Figure 5 presents a reference scenario of electricity generation, where various electricity-generating technologies compete for market share. Renewable electricity technologies include hydropower, solar power, wind power, municipal solid waste, and bioelectricity from either switchgrass or forest residue. The share of renewables other than hydro and wind is small in the reference scenario. A small amount of bioelectricity appears in the reference scenario: about 1 percent of U.S. electricity generation uses solid biomass as fuel, mostly from forest residue. Total electricity generated in this scenario approximates the projection from the EIA (EIA, 2015), which is 5,060 TWh of generation in 2040.

Figure 5

U.S. electricity generation in the reference scenario[1]



[1] Our reference scenario for electricity generation is higher than projections in the Annual Energy Outlook (AEO 2016), mainly because our model base year is 2007 and our projections do not reflect the decrease in electricity generation during the Great Recession. The AEO 2016 reference scenario has 4,090 terawatt hours (TWh) of generation in 2015 and 5,060 TWh in 2040.

Source: USDA, Economic Research Service using Future Agricultural Resources Model.

Policy Scenarios

The previous section described a U.S. reference scenario that aligns GDP growth and income growth with the "middle of the road" SSP 2. Electricity generation in the scenario was adjusted to approximate projections in the Annual Energy Outlook (see U.S. EIA, 2015). With the reference scenario as a starting point, three policy scenarios were constructed to provide a demand for bioelectricity: a subsidy for bioelectricity, a renewable portfolio standard, and CO_2 cap-and-trade (see table 4). If the goal is only to increase the amount of electricity generated from biomass, then a bioelectricity subsidy is a simple way to do so. We also simulate a stylized nationwide renewable portfolio standard that requires total renewables to be 20 percent of total electricity generation by 2020, 30 percent by 2030, and 40 percent by 2040.[7] This section provides selected results on electricity generation, land use, international trade, CO_2 emissions, and cost for these policy options.

Table 4

Definitions of policy scenarios

Scenario	Characteristics
Reference (REF)	Population and income growth aligned with SSP 2, the "middle of the road" Shared Socio-economic Pathway, through 2050 for 13 world regions. U.S. electricity generation approximates projections from the Annual Energy Outlook (U.S EIA, 2015).
Bioelectricity subsidy (SUBSIDY)	Subsidy adjusted to meet target generation using switchgrass of 250 TWh in 2030 and 350 TWh in 2040.
Renewable Portfolio Standard (RPS)	Stylized national (U.S. only) policy that requires renewable electricity to be 20 percent of total electricity generation by 2020, 30 percent by 2030, and 40 percent by 2040. This scenario has two constraints: the target for total renewables, and a target of 250 terawatts (TWh) for switchgrass electricity. The supply curves for wind and solar were adjusted to allow 250 TWh from switchgrass electricity.[1]
CO_2 cap-and-trade (CAP)[2]	Carbon dioxide (CO_2) emissions are reduced to 37 percent below 2005 historical emissions by 2030 and held constant thereafter. This scenario uses the same wind and solar supply curves as the RPS scenario. The CO_2 emissions target was adjusted to allow 250 TWh from switchgrass electricity.

[1] Supply curves for wind and solar derived in the RPS scenario were then used for all other scenarios.

[2] Carbon capture and storage (CCS), and therefore bioenergy with carbon capture and storage, is not available in this cap-and-trade scenario. We have run a cap-and-trade scenario with CCS, which reduces the cost of meeting a CO_2 emissions target.

Source: USDA, Economic Research Service.

Electricity Generation

Figures 6a, 6b, and 6c present electricity generation over time for the three policy scenarios. In each scenario, various electricity-generating technologies compete for market share. All policy scenarios are designed to generate approximately 250 TWh of switchgrass electricity in 2030, but the pattern of electricity generation by other technologies varies across scenarios. In all scenarios, hydro and nuclear power are constrained to increase slowly over time.

In the subsidy scenario, switchgrass electricity generation increases to the target of 250 TWh in 2030, while generation from all other technologies remains close to levels in the reference scenario

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[7] In 2013, electricity generated from renewables accounted for 13 percent of total U.S. electricity generated (U.S. EIA, 2015).

(fig. 6a). The amount of switchgrass electricity generated with a subsidy is manipulated by varying the subsidy rate. This leads to lower electricity prices and higher electricity consumption, relative to the reference scenario.

The RPS scenario, with renewables at 30 percent of total electricity generation in 2030, allows switchgrass electricity generation to become approximately equal to hydropower, and wind power grows to be about the same as nuclear power generation (fig. 6b). A renewable portfolio standard is implemented through a subsidy on hydro, wind, solar, and bioelectricity. This is offset by a tax at the same rate on electricity generation using fossil fuels so that RPS is revenue neutral. The model solves for the price of renewable certificates, in units of dollars per MWh, so that renewables are 20 percent of electricity generation in 2020, 30 percent in 2030, and 40 percent in 2040. By 2020, most of the renewable portfolio is supplied by wind and hydro. However, the share of other renewables increases by 2030 as renewable electricity technologies beyond wind and hydro power contribute to the RPS target.

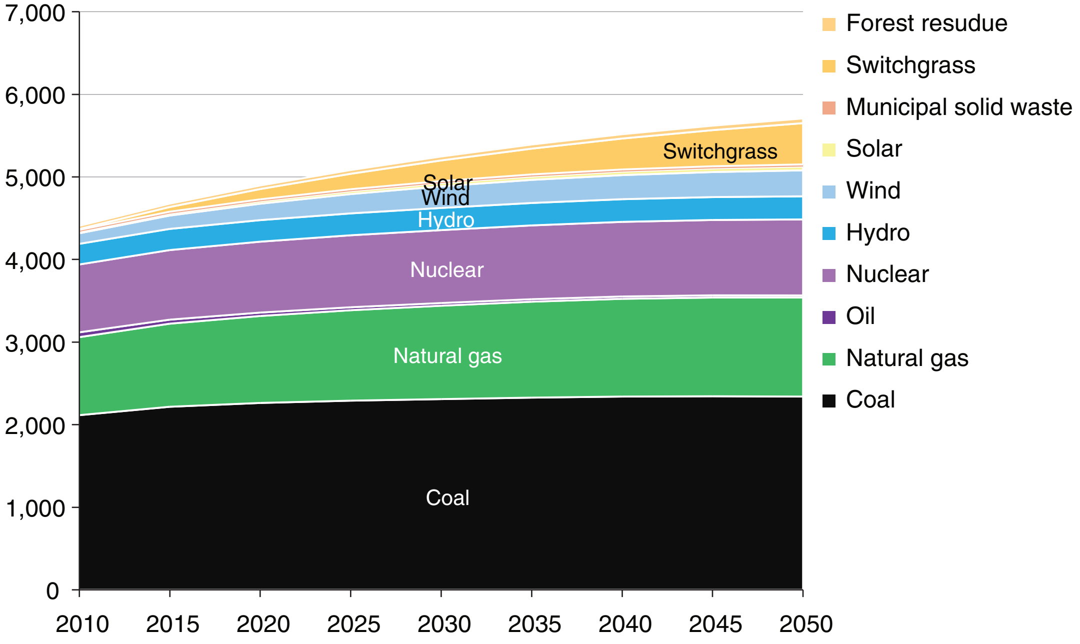
A CO_2 cap-and-trade scenario (CAP) was constructed to reduce U.S. CO_2 emissions to 37 percent below 2005 levels by 2030 and held constant after 2030.[8] This emissions cap was selected so that switchgrass electricity generates 250 TWh for comparison with other scenarios. During each simulation year, a price on CO_2 emissions is adjusted until emissions are reduced to the cap. This can be viewed as either a carbon tax or an auction of CO_2 permits, where all revenues are returned to consumers as a lump sum. Electricity generated from natural gas is less carbon intensive than electricity generated from coal, and natural gas becomes the dominant fossil fuel (fig. 6c). All sectors of the U.S. economy are under the cap and are affected by the CO_2 price: electricity generation, industry, transportation, and buildings.

Figure 6

U.S. electricity generation scenarios through 2050

a. U.S. electricity generation: subsidy for switchgrass electricity

Terawatt hours



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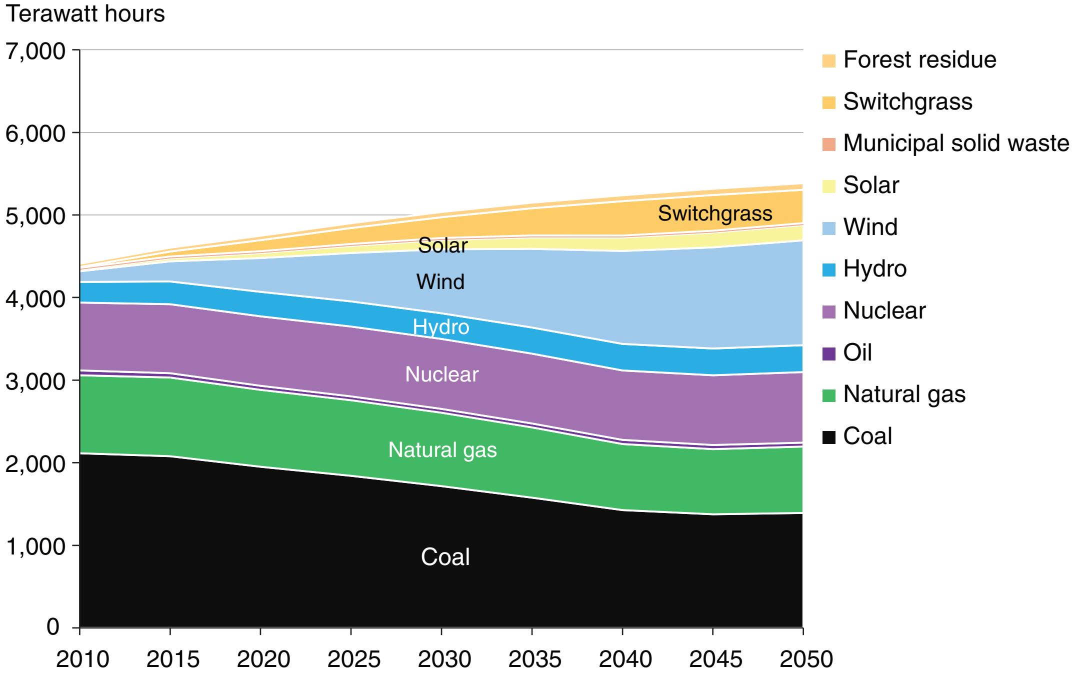
[8] For comparison, the March 31, 2016, U.S. submission of its intended nationally determined contribution (INDC) to the U.N. Framework Convention on Climate Change states that "The United States intends to achieve an economy-wide target of reducing its greenhouse gas emissions by 26%-28% below its 2005 level in 2025 and to make best efforts to reduce its emissions by 28%." http://www4.unfccc.int/submissions/INDC

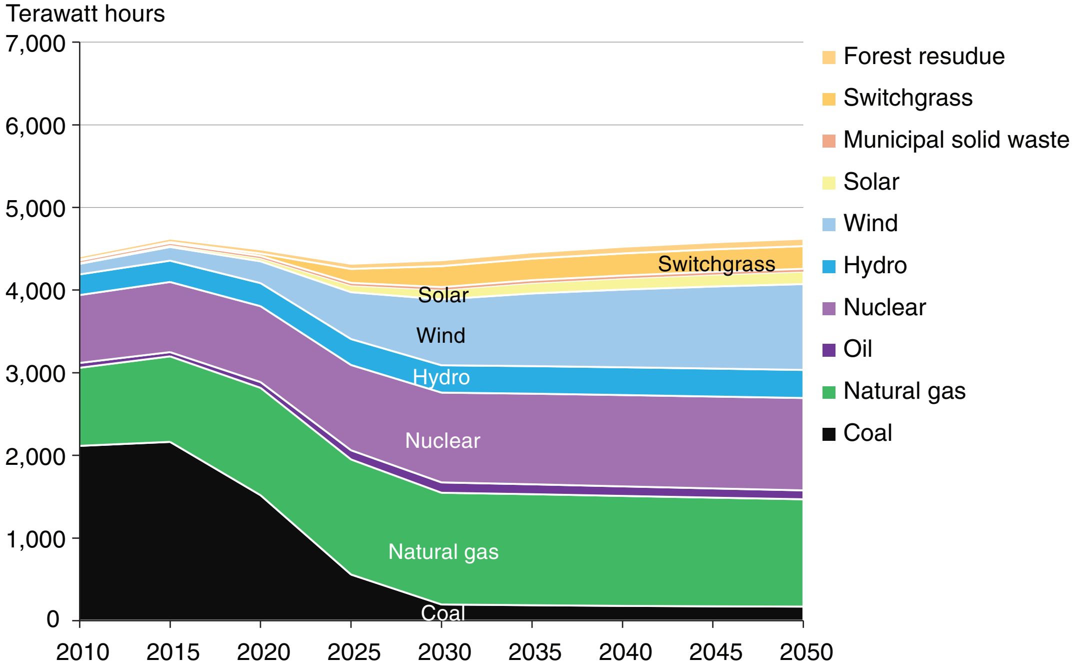
Figure 6

U.S. electricity generation scenarios through 2050—continued

b. U.S. electricity generation: Renewable Portfolio Standard



c. U.S. electricity generation: CO_2 cap-and-trade



CO_2 = Carbon dioxide.
Source: USDA, Economic Research Service using Future Agricultural Resources Model.

The results for renewables in table 5 show that generation from switchgrass electricity in 2030 is close to 250 TWh for the policy scenarios. Generation from forest residue is near 50 TWh for the reference and subsidy scenarios but is greater in the RPS and cap-and-trade scenarios due to economic incentives on electricity generated from forest residue that are not present in the reference and subsidy scenarios. In the subsidy scenario, only switchgrass electricity receives the subsidy. In the RPS scenario, all renewables except municipal solid waste receive an incentive payment funded by taxes on nonrenewables.[9] In the cap-and-trade scenario, renewables do not receive a subsidy, but they become less expensive relative to fossil fuels.

Table 5

Simulated electricity generation from renewables in 2030 (TWh)

	Reference	**Subsidy**	**RPS**	**Cap-and-trade**
Bioelectricity (switchgrass)	11	250	252	254
Bioelectricity (forest residue)	50	47	62	71
Municipal solid waste	25	25	23	32
Solar power	42	38	113	116
Wind power	286	262	775	798
Hydro power	269	268	310	330
Total renewables	683	891	1,536	1,602

TWh=terawatt hours. RPS = Renewable Portfolio Standard.

Source: USDA, Economic Research Service using Future Agricultural Resources Model.

Land Use

With all policy simulations, switchgrass competes with crops, pasture, and forests for land. The amount of land used for switchgrass depends on base-year yield (see table 2) and the growth rate of yield over time (1 percent per year). With the introduction of a bioelectricity subsidy, the total area of land used for crops other than switchgrass declines from 318 million acres (129 Mha) in the reference scenario to 302 million acres (122 Mha) in year 2030. Switchgrass requires 25.0 million acres (10.1 Mha) of land: 16.0 million acres from cropland, 4.9 million acres from pasture, and 4.1 million acres from forest land.

Figure 7 shows estimated U.S. land use over time with the subsidy scenario and for three levels of switchgrass yield. In this scenario, with a fixed target for electricity from switchgrass, land use for switchgrass varies inversely with yield. This is not the case for the RPS scenario: switchgrass yield affects the share of switchgrass in renewables, exceeding the 250 TWh target in the high-yield scenario and falling below the target in the low-yield scenario (not shown).

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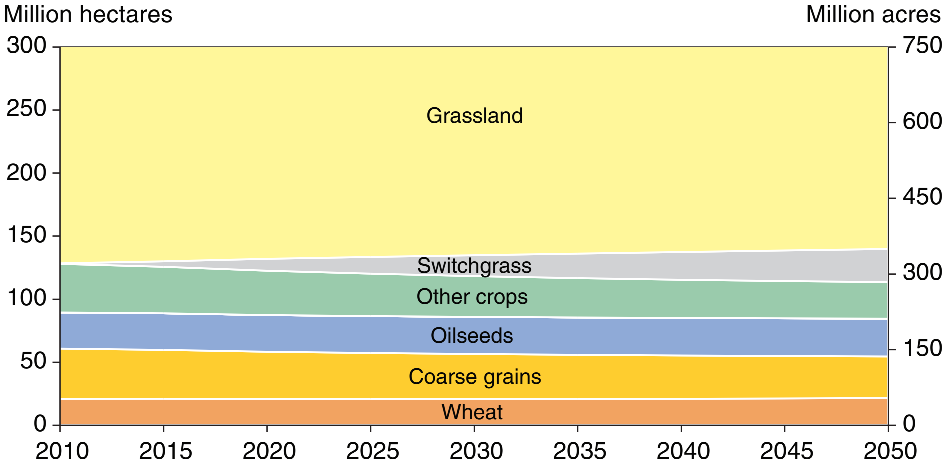
[9] The incentive payment per megawatt-hour increases with the stringency of the RPS and is just large enough to meet the RPS target.

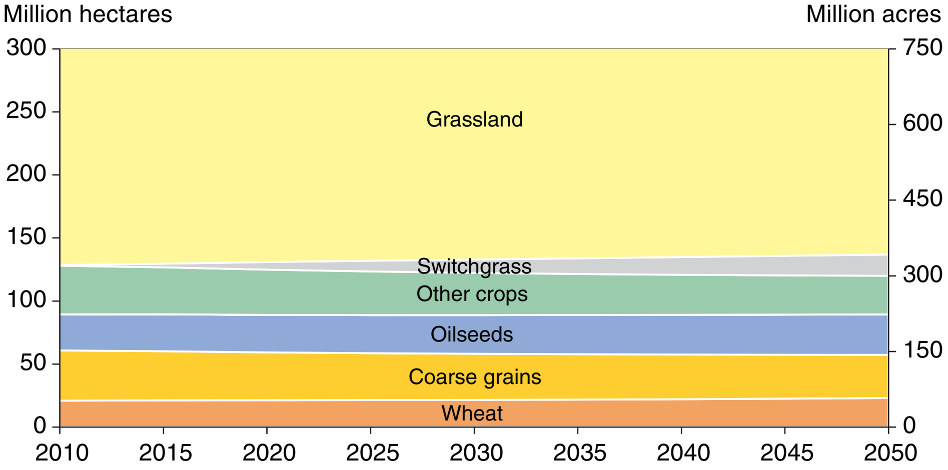
Figure 7

U.S. land use with SUBSIDY scenario across varying switchgrass yield

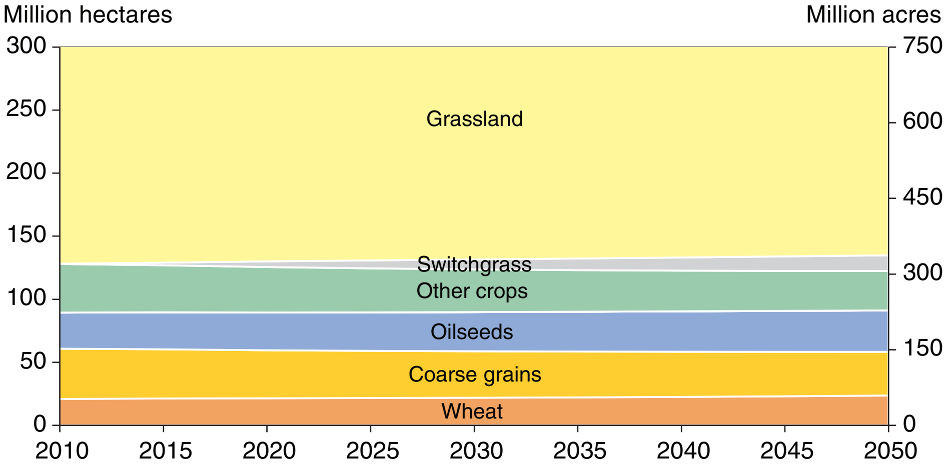
Low switchgrass yield



Medium switchgrass yield



High switchgrass yield



3.6 short tons/acre = 8 metric tons/hectare (top); 5.4 short tons/acre = 12 metric tons/hectare (middle); 7.1 short tons/acre = 16 metric tons/hectare (bottom)

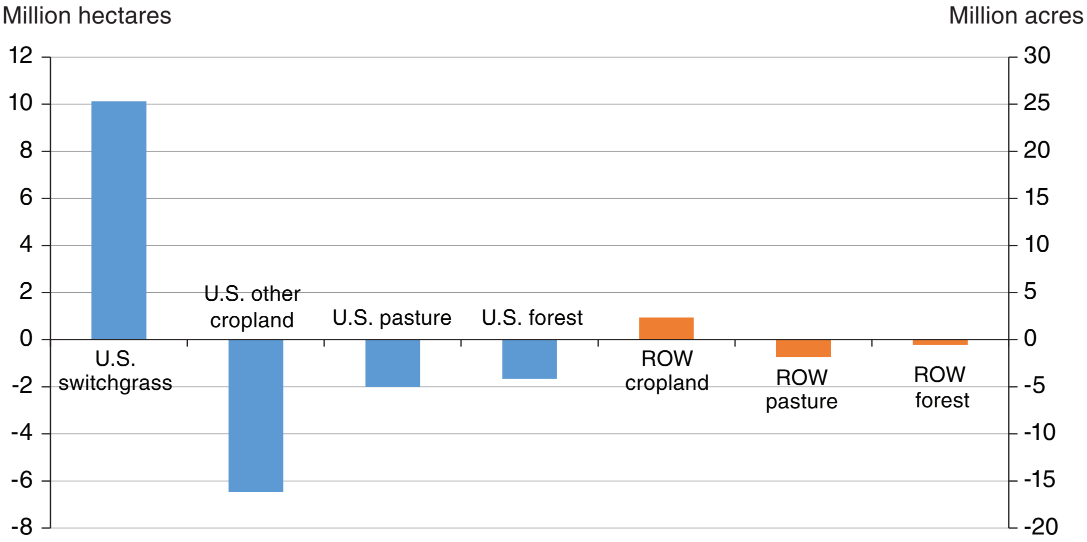
Source: USDA, Economic Research Service using Future Agricultural Resources Model.

An increase in land area for switchgrass leads to changes in land use within the United States and internationally due to market clearing of traded agricultural products. In all scenarios, total agricultural land is constant in each world region, but the allocation to crops, pasture, and forest may change. An increase in land for an energy crop is offset by a net decrease in other land uses. This pattern of adjustment is shown in figure 8 for land use in 2030. Land can be converted to switchgrass from cropland, pasture, or forest, with the largest share from cropland. Induced land-use change in the rest of the world is small relative to changes in the United States.

Land-use change differs somewhat in the RPS and cap-and-trade scenarios because of the economic incentive to increase electricity generation from forest residue. Some forest land is converted to switchgrass in the subsidy and RPS scenarios (4.1 and 1.0 million acres, respectively), but forest land expands by 2.5 million acres in the cap-and-trade scenario because the CO_2 price increases the value of forest residues used to generate electricity.

Figure 8

Land-use change in the United States and the rest of the world (ROW) in 2030 under SUBSIDY scenario relative to reference scenario



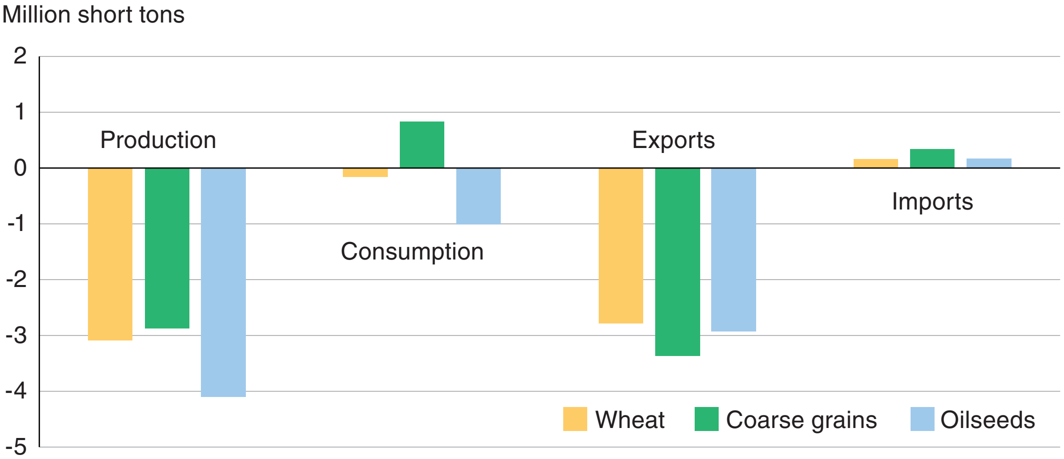
Source: USDA, Economic Research Service using Future Agricultural Resources Model.

Production and International Trade

Land competition from conversion to switchgrass results in declines in production of major field crops and ruminant meat. U.S. production of major field crops (wheat, coarse grains, and oilseeds) declines in 2030 (fig. 9), relative to the reference scenario. The general pattern is for exports to compensate for most of the decline in production, with small changes in consumption and imports. For all crops, production plus imports equals consumption plus exports. Prices for major crops increase relative to the reference scenario: wheat (up 2.5 percent), coarse grains (up 1.9 percent), and oilseeds (up 2.8 percent) in the subsidy scenario.

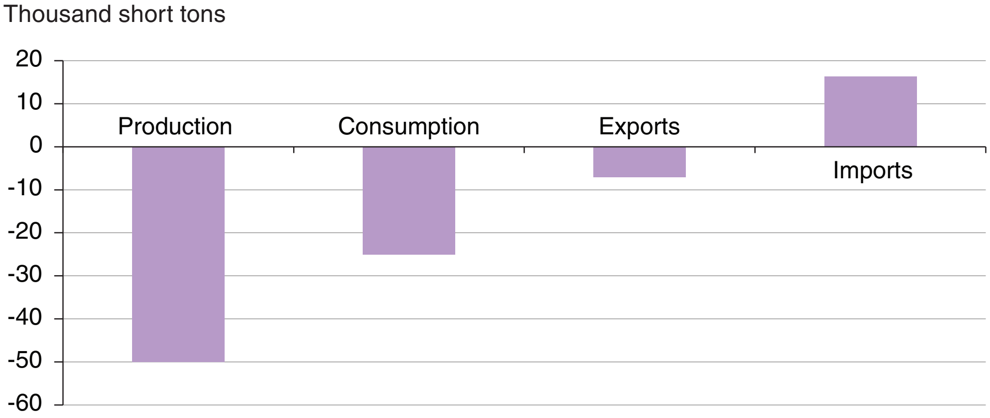
The reduction in U.S. pasture area is reflected in greater consumption of coarse grains (for feed, fig. 9) and less production of beef (fig. 10). The change in production of ruminant meat in the United States is small, decreasing by 0.3 percent in 2030 compared to the reference scenario.

Figure 9
U.S. production, consumption, and international trade under the SUBSIDY scenario relative to reference scenario



Source: USDA, Economic Research Service using Future Agricultural Resources Model.

Figure 10
U.S. ruminant meat in 2030 under the SUBSIDY scenario relative to reference scenario



Source: USDA, Economic Research Service using Future Agricultural Resources Model.

Price Impacts

Even though energy generated from bioelectricity is coordinated across policy scenarios, prices for electricity vary widely across scenarios (table 6). Prices of electricity decline by a small amount in the subsidy scenario and increase by a large amount in the cap-and-trade scenario. Price increases for wheat, coarse grains, and oilseeds are similar in the subsidy and RPS scenarios but are greater in the cap-and-trade scenario. For all fossil fuels, energy prices increase economy-wide in the cap-and-trade scenario but not in other scenarios.

In 2030, the subsidy for switchgrass electricity is 2.1 cents per kWh (same as \$21 per MWh). The RPS certificate price is 2.8 cents per kWh (\$28 per MWh), and the carbon price is \$107 per metric ton of CO_2.[10]

Table 6

Electricity generation and price changes in 2030 relative to reference scenario (United States)

Policy scenario	Bioelectricity *(TWh)*		Price increase *(percent)*			
	Forest residues	Switchgrass	Electricity	Wheat	Coarse grains	Oilseeds
Subsidy	47	250	- 0.5	2.5	1.9	2.8
RPS	62	252	5.5	2.9	2.3	3.5
Cap-and-trade	71	254	55.0	7.9	5.8	5.7

TWh=terawatt hours. RPS=Renewable Portfolio Standard.
Source: USDA, Economic Research Service using Future Agricultural Resources Model.

CO_2 Emissions

Emissions in the cap-and-trade scenario in 2030 are 37 percent less than historical emissions in 2005 (fig. 11). The cap-and-trade scenario is designed to reduce CO_2 emissions at least cost, but there are also emissions reductions in the subsidy and RPS scenarios. A carbon price of \$107 per metric ton of CO_2 is needed to reduce emissions to the 2030 target in the cap-and-trade scenario.[11]

CO_2 emissions are calculated directly from energy consumption by applying emissions coefficients to coal, refined petroleum, and natural gas at the point of combustion. The model is calibrated to base-year (2007) energy consumption for 38 production sectors and 13 world regions.

There is some carbon leakage to the rest of the world in the U.S. cap-and-trade scenario. CO_2 emissions outside the United States increase by an amount equal to 19.7 percent of the reduction in U.S. emissions.

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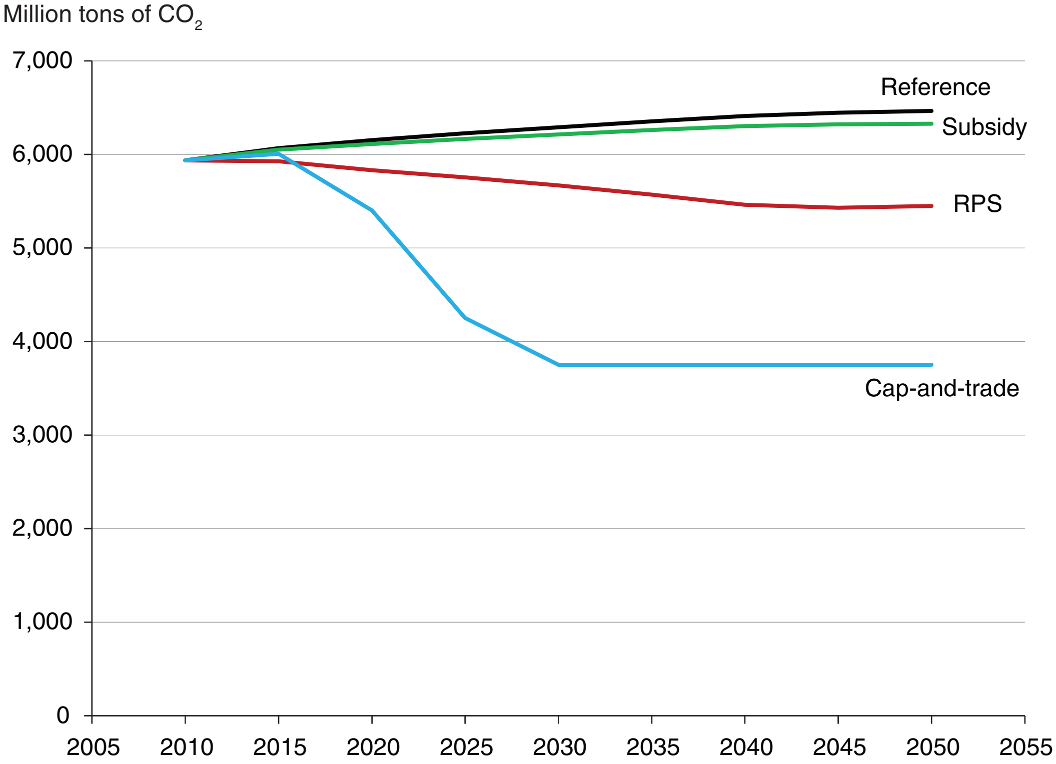
[10] A range of CO_2 prices across similar cap-and-trade scenarios and models is documented in Clarke et al. (2014). For scenarios without CCS, prices in the ERS global model (FARM) are above the average of other models. For scenarios with CCS, prices in FARM are near the average of other models.

[11] We have also run the cap-and-trade scenario with CCS available to bioelectricity and fossil-generating technologies. The carbon price falls to \$60 per metric ton of CO_2 with CCS as an option.

Figure 11

Annual U.S. CO_2 emissions



RPS = Renewable Portfolio Standard. CO_2 = carbon dioxide.
Source: USDA, Economic Research Service using Future Agricultural Resources Model.

Cost Distribution Between United States and Rest of World

An energy or climate policy has both a cost and a benefit. It is often difficult to place a value on the benefit, even in an economic modeling framework, but we can construct quantitative indicators such as a reduction in carbon dioxide emissions. We construct economic models to compare the cost of achieving alternative environmental targets, with a goal of achieving any given target at least cost. The policy scenarios rely on either a tax or subsidy to change the mix of electricity-generating technologies. In the SUBSIDY scenario, taxpayers pay the cost of a subsidy to bioelectricity generation. The RPS scenario is revenue neutral from the perspective of taxpayers. In the cap-and-trade scenario, all revenues from the sale of emissions permits are returned to consumers as a lump sum. There is a cost of meeting the target in each of the policy scenarios because the new set of electricity-generating technologies is more expensive than those in the reference scenario.

The cost of moving to new technologies shows up in economy-wide measures of well-being, such as real (adjusted for inflation) GDP and real consumption. Economists prefer an alternative cost measure, equivalent variation, which is numerically close to the change in real consumption. Equivalent variation is a concept that monetizes the change in consumer utility between a reference scenario and a policy scenario.[12]

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[12] Equivalent variation is the maximum amount a consumer would be willing to pay to avoid a loss in utility. A related measure, compensating variation, is the minimum amount of compensation required by a consumer to accept a loss of utility.

Results for equivalent variation are shown in fig. 12 for the three scenarios. The rank order of costs across scenarios turns out to be the same as scenarios ordered by CO_2 emissions; cap-and-trade has the greatest cost but also the greatest reduction in CO_2 emissions.

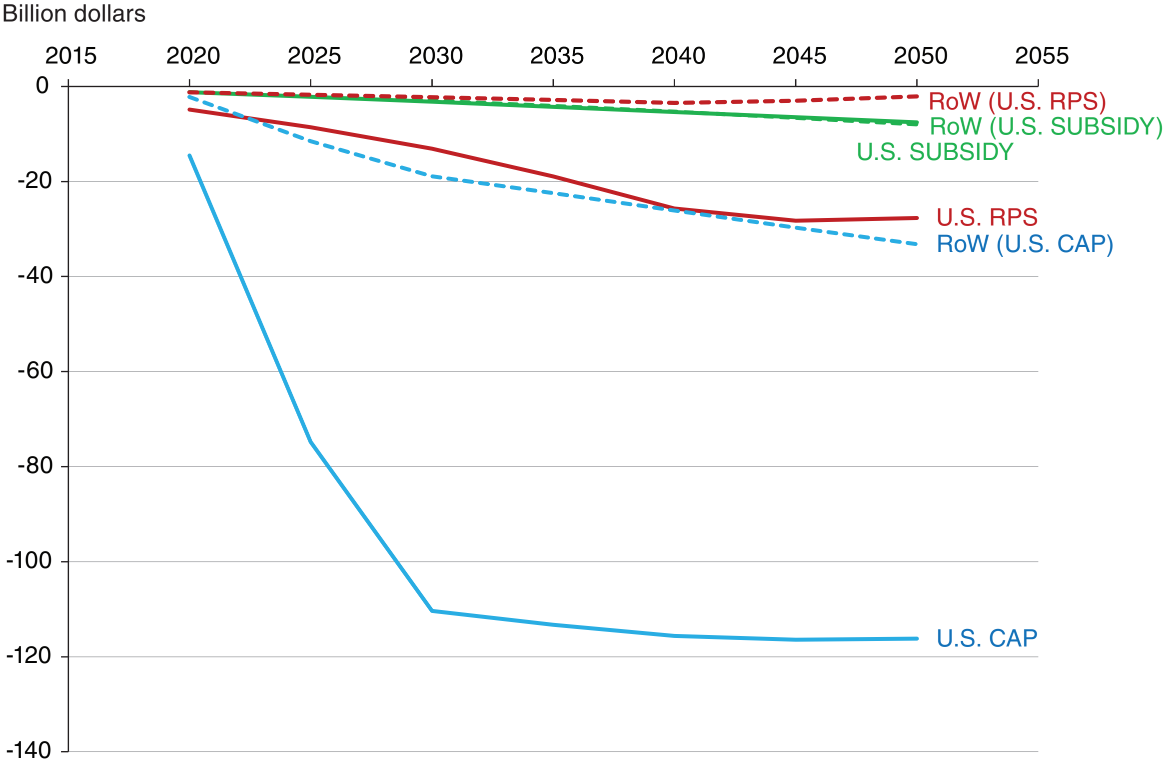
Each scenario shows a unique relationship between U.S. costs and costs induced by the United States on the rest of world. With a bioelectricity subsidy, the cost in the United States is smaller than the other two scenarios, but the rest-of-world cost is nearly the same as the cost in the United States. With RPS, the cost in the United States is substantial, but the total cost to the rest-of-world is small. With cap-and-trade and an emissions cap in the United States, costs to the rest of world are approximately one-fifth of costs in the United States.

Cost Distribution Within United States

The previous section described the cost of each policy in the United States relative to the reference scenario. In this section, we describe how the U.S. cost is distributed among primary factors of production for three policy scenarios. This cost decomposition exploits the identity that GDP can be measured as either the sum of final demands or as the sum of all payments to primary factors of production. We calculate the change in GDP as the sum of changes in payments to owners of the following groups of primary factors: labor, capital, land, natural resources, and a residual change in indirect business taxes (IBT).[13] With IBT included, the decomposition is exact. Labor includes

Figure 12

U.S. annual policy cost (solid lines) and the cost to the rest of world (dashed lines)



RoW = rest of world. RPS = Renewable Portfolio Standard. CAP = cap-and-trade.
Note: Expressed as equivalent variation (costs are negative numbers) in billion dollars per year.
Source: USDA, Economic Research Service using Future Agricultural Resources Model.

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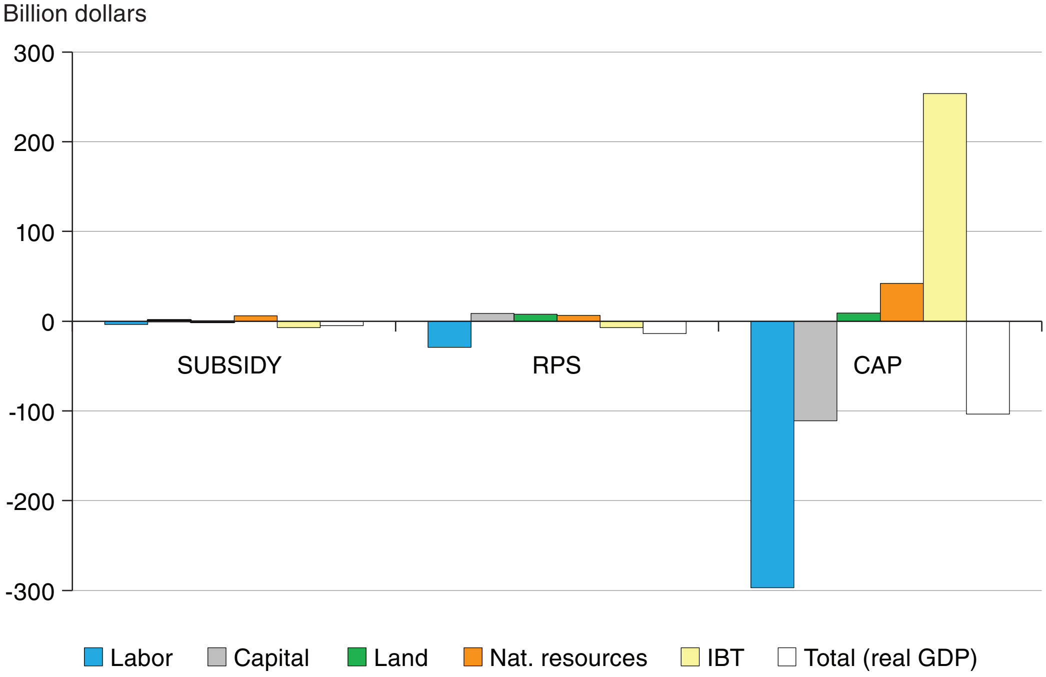
[13] Indirect taxes, such as sales taxes and gasoline taxes, are collected by a firm as part of a purchase and increase the price paid by a consumer. These taxes are paid indirectly by the consumer to the Government through a firm. Direct taxes, such as personal and corporate income taxes, are paid directly to the Government.

skilled and unskilled labor; capital is summed across all production activities; land includes 18 agro-ecological zones; natural resources include fossil energy, wind, and solar resources.

Figure 13 show this decomposition, with cap-and-trade having large, but offsetting, components. In that scenario, owners of land and resources for wind and solar power gain. Providers of labor and capital bear most of the cost, but this is largely offset by increased tax revenues (indirect business taxes, IBT) that are ultimately returned to households.

Figure 13

Cost burden of U.S. energy policy across U.S. primary factors in 2030



Note: IBT = Indirect Business Taxes. RPS = Renewable Portfolio Standard. GDP = Gross Domestic Product.
CAP = cap-and-trade.
Source: USDA, Economic Research Service using Future Agricultural Resources Model.

U.S. Regional Land-Use Effects of Increased Biomass Demand

While some biofuel processes can handle multiple feedstocks, most production systems rely on a single feedstock (e.g., corn grain) or a small set of close alternatives. In contrast, electricity based on combustion of biomass production has a wide range of substitute feedstocks such as switchgrass, crop residue, and forest residue. Crop and forest residues are produced in conjunction with other marketable products, but production of some bioenergy feedstocks compete directly for land and resources with food, feed, and fiber production. As a consequence, the introduction of large-scale planting of crops primarily for energy will displace or shift other agricultural activities.

It is a simple matter to compute the total amount of biomass required to achieve a given level of energy production. Yields and production costs vary between regions, however, so the total area required to produce the needed volume of biomass will depend on where bioenergy crops are planted. Where energy crops will ultimately be planted depends, for the most part, on prevailing national and global demand for nonenergy crops, regional relative yield differences, and other factors, such as proximity to energy production facilities. Bioenergy crops will not necessarily be planted in regions where yields are highest if there is a greater return to planting nonenergy crops in those regions.

While rough estimates of acreage totals can provide some insight into ad hoc methods of estimating where bioenergy crops will be grown, such as a fixed fraction or level of production in each region, they fail to account for the interaction with other crops and alternative land uses and are unable to address many direct and indirect effects from shifting crops between regions. They are also not likely to fully consider the effects of price changes and the extent of land use by underestimating impacts in some regions and overestimating them in others. The ERS national model considers bioenergy crops as one of many crop production options to capture the relationships between the production sectors of an integrated agricultural system.

The central scenario in the national model provides 300 TWh of bioelectricity: 250 TWh using switchgrass and 50 TWh using forest residue, closely approximating the reference scenario in 2030 of the global model. This section addresses the following questions:

- Which USDA regions produce switchgrass at the expense of nonenergy crops and to what extent?
- Which USDA regions increase production of nonenergy crops displaced by switchgrass in other regions?
- What are the water quality implications of shifting crop production patterns?

To examine the sensitivity of cropland shifts to levels of bioelectricity demands, major outputs are compared at 200 TWh and 400 TWh of demand. The year 2030 was chosen as the base year for two main reasons. U.S. domestic climate change policies are geared toward negotiations under the United Nations Framework Convention on Climate Change (UNFCCC), which focus on the 2025-30 timeframe. Also, beyond 2030, climate models begin to diverge in regional climate assessments, which would add a significant additional dimension to the analysis.

Quantitative Modeling of Regional Land Use Consequences

The national model (REAP) computes changes to an equilibrium solution in an analysis year from a shock introduced prior to the analysis year. Thus, the new equilibrium is the consequence of adjustments made before the analysis year. While the model implicitly assumes that a feasible path from the current state to the new equilibrium exists, the model does not specify any particular path. For example, a 1-million-acre reduction to cropland in response to a shock in 2030 would not occur between 2029 and 2030 but rather would happen incrementally from the time of the shock. The outcome is a consequence of changes in farmers' planting decisions and market conditions over the time period. The model also assumes that markets exist for energy crops and that the necessary infrastructure is in place to process, store, transport, and consume biomass for electricity production. Total bioenergy production is exogenous in the national model. Trade volumes for field crops and livestock are fixed at the values calculated in the subsidy scenario of the global model. The amount of bioenergy demand that comes from switchgrass is the total bioelectricity demand less the bioenergy quantity that comes from forest residue.

Land cannot be freely converted between crop production, forestry, and grazing. There is a cost of converting land from one use to another (e.g., forest to agriculture) that reflects direct activities, such as land clearing, and less-direct components, such as foregone revenue during the conversion process. Land area devoted to the primary activities (crops, pasture/range, and forest) is calibrated to a fixed total in the reference year for each activity (see table 7). A shock to market conditions, technology, or policy may create pressure on the land base that may shift the equilibrium, thereby creating movement between land uses. In equilibrium, movement will occur between activities to the point where the marginal value of each land use is equal. Or to put it another way, land use is adjusted in the model until there is no economic value (increase in the objective function) to making any other reallocation of land use.

Table 7

Total land in reference scenario (in 2030) by USDA region

USDA region	Cropland	Pasture	Forest
		Million acres	
Appalachian (AP)	18.5	9.9	56.8
Corn Belt (CB)	103.1	21.1	29.4
Delta States (DL)	16.2	6.9	45.2
Lake States (LA)	42.3	8.2	40.6
Mountain States (MN)	34.7	10.7	24.9
Northern Plains (NP)	68.2	148.4	3.1
Northeast (NE)	13.9	4.4	67.1
Pacific States (PA)	10.0	3.9	39.2
Southeast (SE)	7.6	7.5	61.6
Southern Plains (SP)	41.8	256.5	17.9
U.S. total	**356.4**	**477.5**	**385.8**

Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Agricultural land is partitioned into three categories: cropland, pasture/rangeland, and forest. Each of these land types supports a set of production activities. The sum of the land area used for the three activities is a fixed total for each USDA region. Land for other purposes (e.g., industrial, residential, and recreational) does not compete with agricultural land and remains constant. While the total land available for agriculture cannot change in a region, land is free to redistribute between cropland, pasture, and forest in response to a shock.

Ideally, feedstocks used to meet demand for bioelectricity come from the most economic sources between planted crops and forest residues in each region. For native grasses, the relative competitiveness with other crops determines the location and quantity. However, the national model does not have a wood product market, so the model is unable to calculate a value for forest products. The total quantity of nonenergy forest products (lumber, pulp, and paper) is not allowed to adjust in response to changes in bioelectricity demand. Likewise, harvest rates (cubic feet of economic forest product removed per acre) are fixed and do not adjust to changes outside the forest sector. Therefore, any contraction of forest land in one region must be compensated for by an increase in at least one other region so that the total production target is achieved. The net change in forest acreage may be different from zero because of differences in productivity between regions. The portion of total bioelectricity production that comes from forest residue is fixed at the 2030 level of 50 TWh.

Conventional forest harvest is focused on removal of the commercially useful parts of the tree. Harvest for biomass entails removing a greater amount of wood. Forest residue and thinnings are roughly proportional to the volume of growing stock and distribution of species in a region. As noted in the *U.S. Billion-Ton Update* (U.S. DOE, 2011), “nutrient removal is much greater in biomass harvesting systems than in conventional harvesting systems relative to the actual amount of biomass harvested. Therefore, it is important to manage the retention of portions of the biomass to ensure long-term productivity through leaving residues or [sic] time of harvest.” The extent of productivity impacts varies regionally due to soil, slope, and species variation. Little information is available on the specific cost and productivity effects of large changes to biomass harvest. In this study, the amount of forest material available for bioelectricity in a region is limited to a quantity equivalent to 10 percent of the mass of total growing stock. This quantity implicitly includes biomass available from downstream (off the land) processing of forest products (i.e., residue from pulp and paper production).

Crop yields are computed using the Environmental Policy Integrated Climate (EPIC) model (Williams, 1995). EPIC is also used to compute edge-of-field soil, water, nutrient, and pesticide fate. Regional rotation-specific EPIC crop yields are adjusted to match the national reference yield. The national crop yields for the 2030 reference year are derived by extrapolating yield growth assumptions of the USDA projections (USDA, 2015). Table 8 shows the reference crop yields for 2030 for the crops covered by the USDA projections. Switchgrass yields are generated by EPIC using production information from USDA's Natural Resources Conservation Service (Marshall and Sugg, 2010). The regional ranges of yields for switchgrass are shown in fig. 14. Switchgrass for biomass can be grown in every region except the Pacific.

Table 8

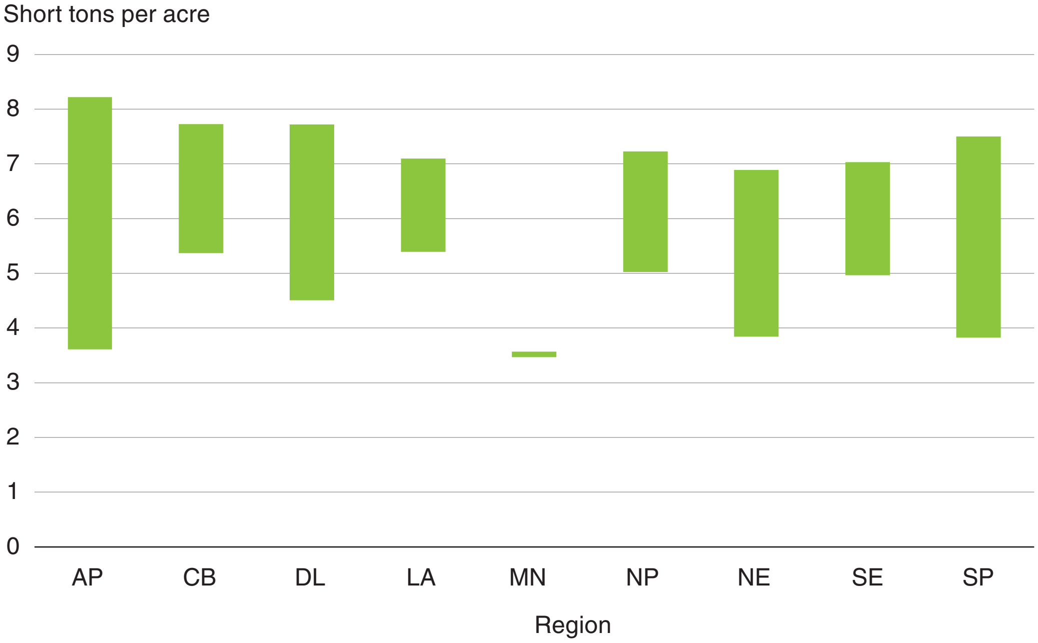
National yields for nonenergy crops in 2030

Crop	Yield per harvested acre	Unit
Corn	200.4	bu/acre
Sorghum	63.4	bu/acre
Barley	78.2	bu/acre
Oats	71.5	bu/acre
Wheat	50.0	bu/acre
Rice	84.4	cwt/acre
Soybeans	51.0	bu/acre
Cotton	1,020.0	lb/acre

bu = bushel. cwt = hundredweight. lb = pound.
Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Figure 14

Switchgrass yields by USDA region in 2030



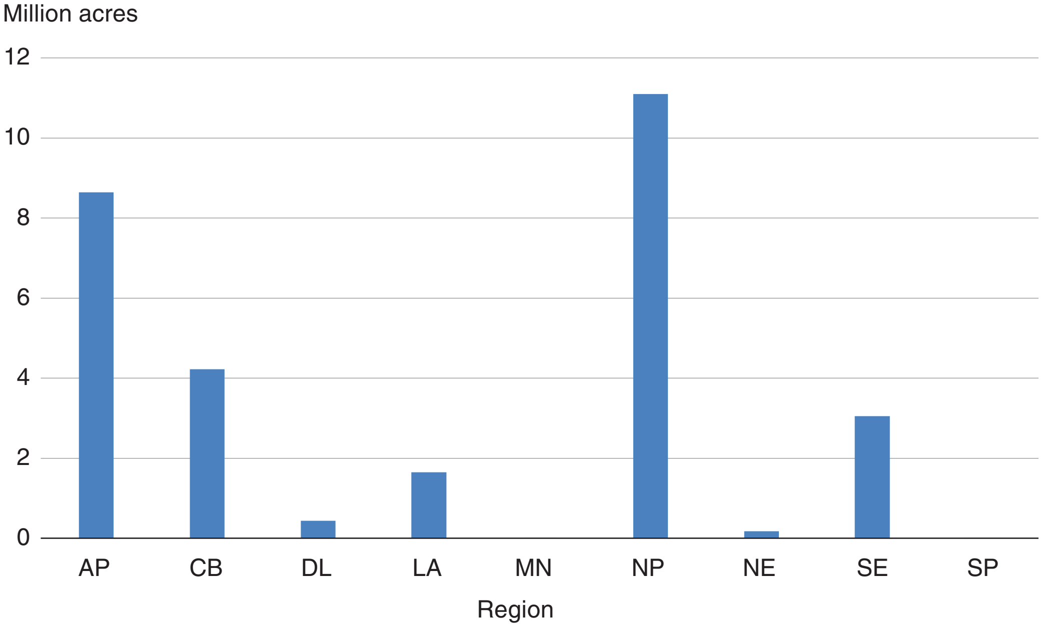
See USDA region list in table 7.
Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Crops Shift Between Regions To Adjust to Biomass Demand

At 250 TWh of switchgrass electricity generation (consistent with global model scenarios), switchgrass is mostly planted in regions with high switchgrass yields but which do not have a comparative advantage in growing other crops (fig. 15). The displacement of nonenergy crops by switchgrass in the Appalachian, Southeast, and Northern Plains regions is shown in fig. 16. In the Appalachian region, the crop most affected is hay, with smaller reductions in corn and soybeans. In the Southeast and Northern Plains, acreage reductions are shared among the crops more uniformly.

Figure 15

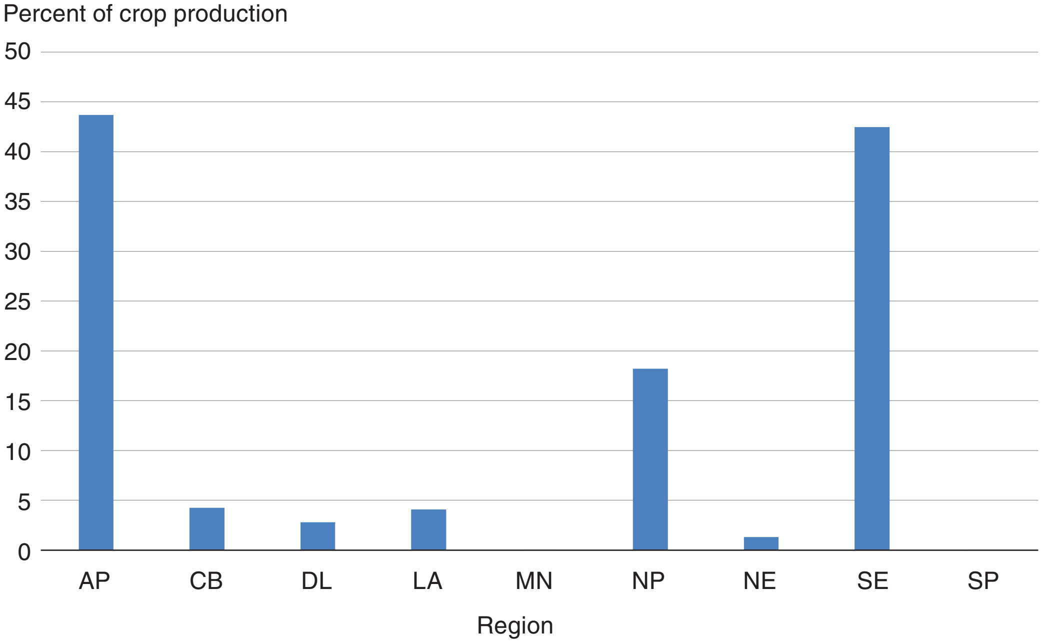
Switchgrass area by USDA region at 250 TWh of bioelectricity generated using switchgrass



See USDA region list in table 7. TWh = terawatt hours.
Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Figure 16

Switchgrass share of cropland within USDA region at 250 TWh of bioelectricity generation using switchgrass



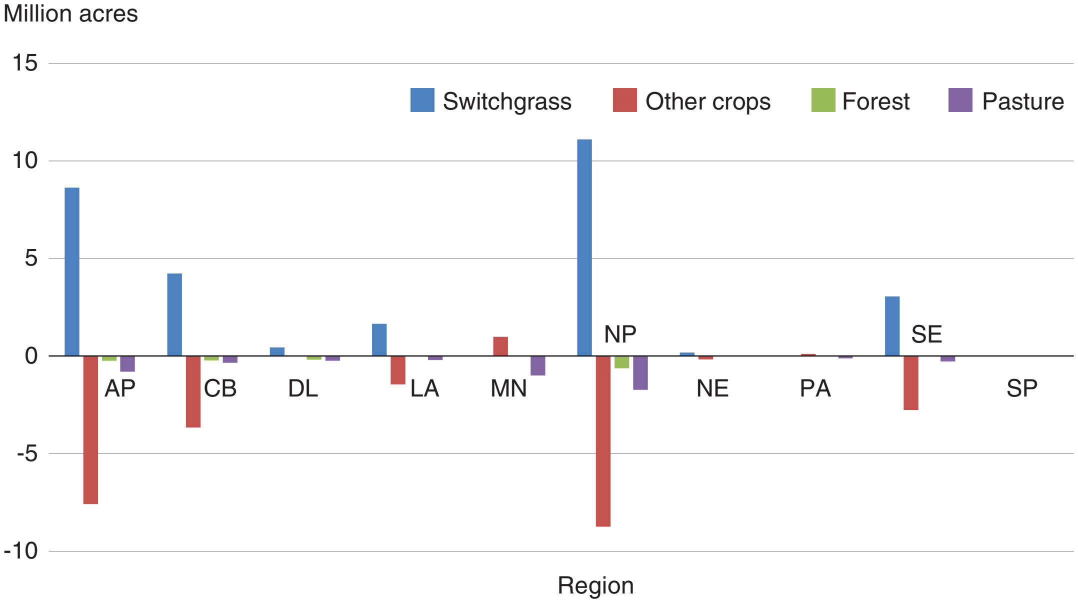
See USDA region list in table 7. TWh = terawatt hours.
Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Land for switchgrass comes mostly from replacement of nonenergy crops (fig. 17) in the 300-TWh scenario. Conversion of pasture is also modest at this level of switchgrass production. All regions increase total cropland because the increase in switchgrass acreage is greater than the acreage loss in other crops as bioelectricity demand is increased, except for a small decrease of total cropland in the Corn Belt. Forest conversion is negligible at bioelectricity demand of 300 TWh. A small amount of forestland conversion to cropland is evident in the Appalachian region.

With biomass production to meet a 300-TWh demand, production of nonenergy crops is reduced as relative returns favor acreage moving to switchgrass. National yields for all crops increase as a consequence of crops shifting from lower yielding regions. Competition for land puts a premium on maximizing production on less land, encouraging substitution of switchgrass for nonenergy crops in regions with lower nonenergy crop yields, while increasing production of nonenergy crops in higher yielding regions. Regional variability of crop yields and costs of production allows redistribution of crops in such a way that minimizes consequences to producers and consumers. As shown in table 9, the pattern of reductions in nonenergy crops differs by region. Each region typically has one or two crops with relatively high reductions, with the remaining crops showing only modest reductions. Some region-crop combinations show an acreage increase in response to energy crop production due to higher yields and lower costs of production relative to other regions. Much hay production shifts to the higher yielding subregions of the Southern Plains.[14]

Figure 17

Land substitution by USDA region, 300-TWh scenario



See USDA region list in table 7. TWh = terawatt hours.
Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

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[14] No switchgrass is produced in the Southern Plains, even though switchgrass yields in that region are similar to those of other USDA regions. However, hay yield is considerably higher in the Southern Plains relative to other regions.

Table 9

Crop displacement in 2030 by region at 300 TWh of bioelectricity generation (million acres)

	Acreage shifts at 300 TWh												
Region	Switchgrass	Corn	Wheat	Soybeans	Hay	Sorghum	Barley	Oats	Rice	Cotton	Fallow	Pasture	Forest
AP	8.6	-1.46	-0.32	-1.10	-4.05	-0.00	-0.00	0.00	0.00	-0.08	-0.25	-0.79	-0.24
CB	4.2	-0.48	-0.21	-0.6	-1.81	-0.06	0.00	-0.01	-0.10	-0.19	-0.36	-0.34	-0.22
DL	0.4	0.12	0.04	0.47	-0.77	0.01	0.00	0.00	0.07	0.30	-0.35	-0.24	-0.18
LA	1.6	0.22	0.13	0.20	-1.11	0.00	0.00	-0.04	0.00	0.00	-0.25	-0.20	0.00
MN	0.0	1.43	-0.91	0.00	-0.87	-0.24	0.08	0.21	0.00	0.21	0.74	-0.99	0.00
NP	11.1	-2.15	-0.67	-2.67	-1.93	-0.52	-0.06	0.08	0.00	0.00	-0.83	-1.73	-0.62
NE	0.2	0.45	0.08	0.11	-0.58	0.00	0.00	0.01	0.00	0.00	-0.02	-0.02	0.00
PA	0.0	0.15	0.08	0.00	0.09	0.00	-0.17	-0.00	-0.06	-0.11	0.15	-0.11	0.00
SE	3.0	-0.46	-0.09	-0.45	-0.91	-0.01	0.00	0.00	0.00	-0.46	-0.18	-0.28	0.00
SP	-0.0	0.47	-1.00	-0.31	2.55	-0.74	0.00	-0.50	-0.01	-0.22	-0.31	0.00	0.00
U.S. total	**29.2**	**-1.71**	**-2.88**	**-4.41**	**-9.40**	**-1.56**	**-0.15**	**-0.25**	**-0.11**	**-0.56**	**-1.67**	**-4.67**	**-1.26**

See USDA region list in table 7. TWh = terawatt hours.

Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Market Impacts Limited by Diversity of U.S. Production System

Prices for all crops increase from the reference as a consequence of increased bioenergy crop production (table 10). In the same scenario, the magnitude of acreage reductions (in percentage terms) is greater than the increase in price for each crop. As crops shift from lower yielding regions, total production does not decline as much as acreage. Prices for oats and hay, which are consumed almost entirely by livestock, rise the most as bioenergy crop production increases.

Table 10

Prices for all crops increase at 300 TWh bioelectricity generation

	Change from reference		
	Price	**Acreage**	**Production**
		Percent	
Corn	1.0	-2.1	-0.8
Sorghum	1.4	-23.4	-23.1
Barley	1.3	-6.0	0.4
Oats	2.9	-9.1	-0.7
Wheat	1.4	-5.4	-4.4
Rice	0.2	-3.5	-4.3
Soybeans	1.9	-5.8	-5.7
Cotton	0.8	-4.8	-2.1
Silage	1.0	-7.0	3.1
Hay	2.0	-14.9	-1.4

TWh = terawatt hours.

Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Bioelectricity production is specified exogenously at 250 TWh using switchgrass and 50 TWh using forest residue. Because the national model has limited capacity to capture the societal costs or benefits of implementing a policy, it is difficult to directly measure welfare impacts. Taxes, subsidies, changes in energy prices, and other costs and benefits are not explicitly calculated in the national model, but impacts are reported based on results in the previous chapter. The national model can estimate the net change in returns from nonenergy crops, which is a measure of the impact to crop producers in a region (table 11). The reduction in nonenergy crop production is more than made up for by increases in price and revenue from switchgrass, resulting in greater per acre returns in all regions. Producers in regions that are best able to grow switchgrass in place of other crops benefit the most. While producers benefit, consumers could face slightly higher costs for food products due to small increases in commodity and livestock prices.

Energy crop production is facilitated by a reduction in pasture in some regions, although the overall effect is moderated by a movement of pasture land from lower to higher productivity regions. Lower grazed cattle inventory, due to higher prices of livestock feed constituents, results in lower national pasture demand. (fig. 18). Higher feed prices also reduce production of beef from feedlot cattle. Exports of animal products are reduced significantly, which keeps domestic consumer price impacts smaller than would be expected due to the loss of pasture.

Table 11

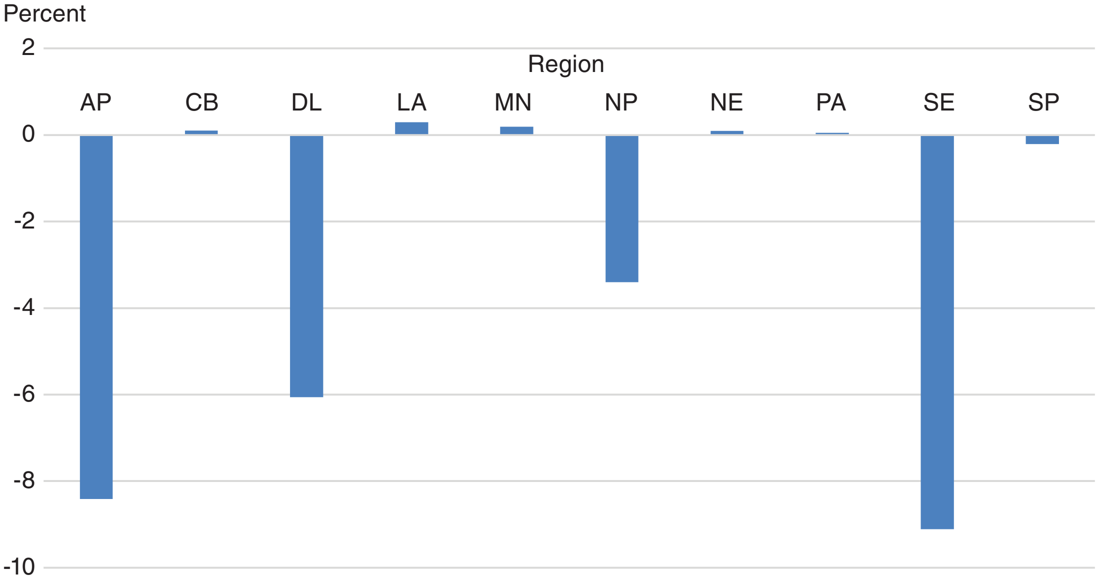
Returns to crop production increase in all regions (switchgrass price = $75/ton, 300 TWh bioenergy generation)

Region	Change in per acre returns	Switchgrass	Change in nonenergy cropland
	$/acre	*Million acres*	
AP	147.6	8.6	-7.6
CB	17.1	4.2	-3.7
DL	25.1	0.4	0.0
LA	18.4	1.6	-1.4
MN	22.9	0.0	1.0
NP	39.4	11.1	-8.7
NE	18.6	0.2	-0.2
PA	11.6	N/A	0.1
SE	100.6	3.0	-2.8
SP	19.7	0.0	0.0
U.S.	31.0	29.3	-23.3

See USDA region list in table 7. TWh = terawatt hours. N/A = not applicable.
Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Figure 18

Change in grazed cattle inventory



See USDA region list in table 7.
Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

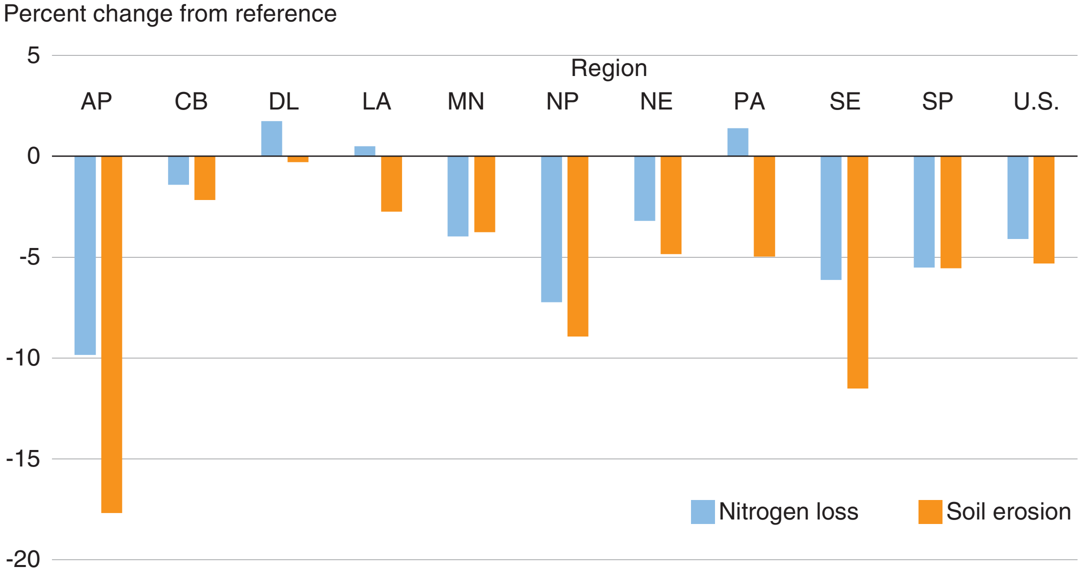
Erosion and Nitrogen-Loss Benefits Coexist With the Intensification of Nonenergy Crops

There are significant differences between the soil and nutrient retention properties of native grasses and annual crops. Native grasses, including switchgrass, have extensive root networks that reach deep into the soil and increase water filtration, nutrient holding capacity, and erosion control. Large-scale commercial planting of switchgrass has yet to be established, so predominant production practices must be inferred. This is particularly important with regard to nitrogen application. Nitrogen application rates were determined based on expert judgment and available field-level studies (Marshall and Sugg, 2010).

Extensive planting of switchgrass coupled with reduction of acreage of nonenergy crops produces large benefits in terms of reduced erosion, especially in regions with high energy-crop plantings (fig. 19). As cropland area increases, nitrogen fertilizer use intensifies. More fertilizer is used for switchgrass as well as for nonenergy crops (fig. 20). However, the increase in acreage is accounted for entirely by introduction of native grasses with high nutrient retention. Combined with the decrease in acres of nonenergy crops, the amount of nitrogen lost to water declines compared to the reference scenario even as cropland acreage increases. This is true for many regions, particularly those that increase their acres of switchgrass. However, in regions (Pacific, Northeast, and Delta) where cropland increases but little of it is switchgrass, nitrogen loss to water increases. Nonetheless, nationally, the overall impact of switchgrass is more nutrient retention. All regions increase nitrogen application per cropland acre (fig. 20) except the Pacific region, which shows a small decrease. Regions that become major switchgrass producers intensify production much more than minor switchgrass regions. As seen in figure 21, Appalachia has the largest increase in applied nitrogen per acre, four times the rate at which acreage expands in the region.

Figure 19

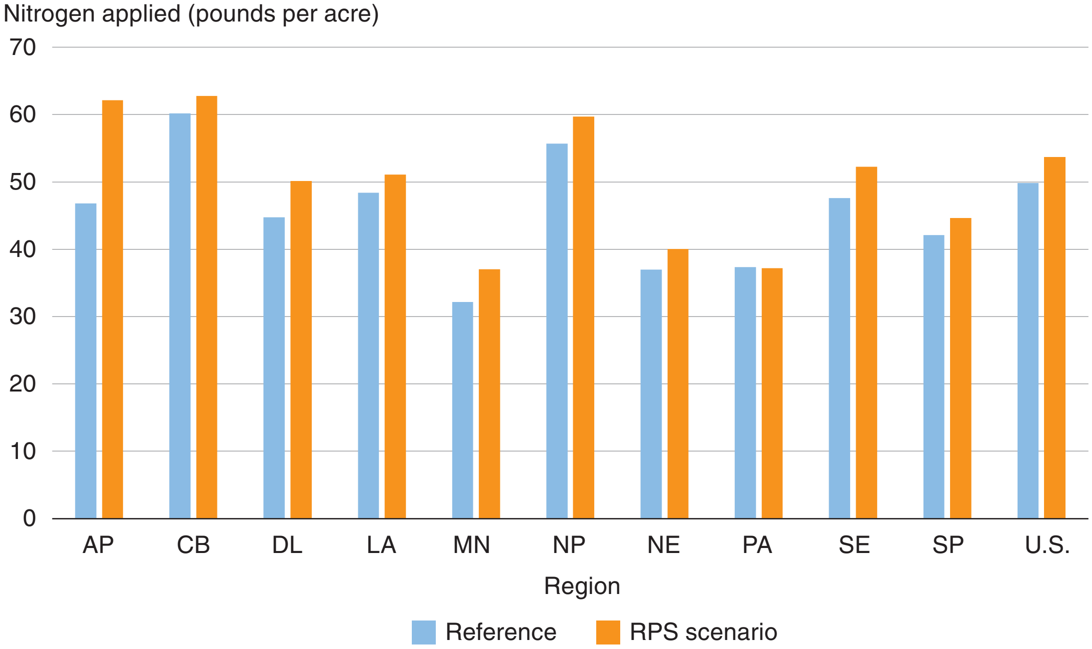
Greater planting of switchgrass in place of nonenergy crops reduces soil erosion and nitrogen loss (300 TWh bioelectricity demand)



See USDA region list in table 7. TWh = terawatt hours.
Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Figure 20

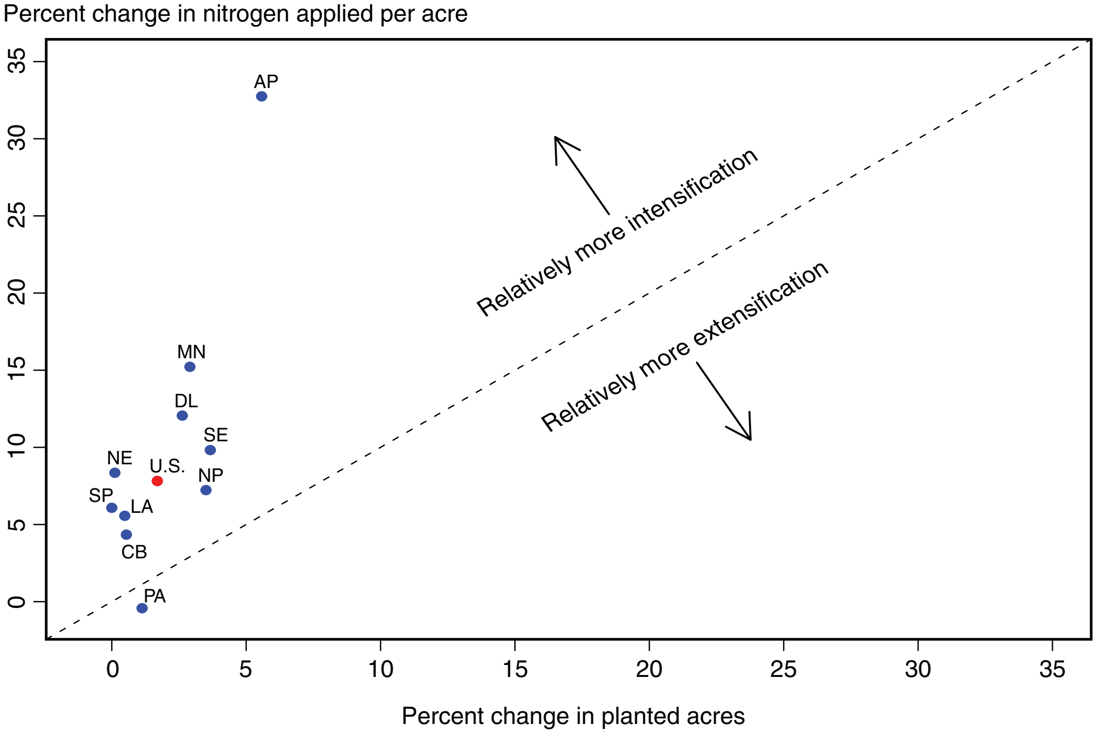
Nitrogen application rates increase relative to the reference scenario



See USDA region list in table 7. RPS = Renewable Portfolio Standard.
Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Figure 21

Regions differ in degree of intensification



See USDA region list in table 7.
Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

The Northern Plains and the Southeast expand acreage, but the rate of nitrogen application does not increase very much, in line with the regions that do not produce significant amounts of switchgrass. The balance between intensification and extensification of nonenergy crops is shown in figure 22. All regions reduce acreage and increase nitrogen application per acre; however, the rate of increase in nitrogen application is larger in magnitude than the reduction of crop acreage.

Impact on Agricultural Production Varies With Bioelectricity Demand

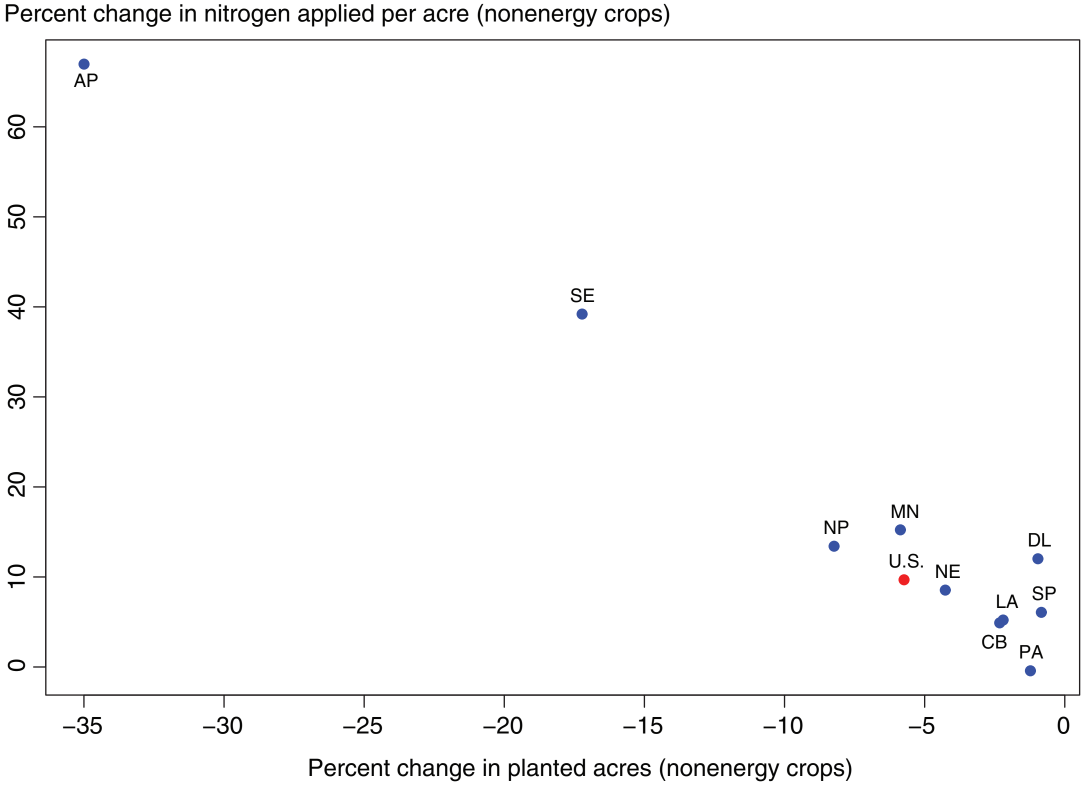
Each unit of biomass production for bioelectricity causes changes in the agricultural system from crop redistribution. Bioelectricity demand much higher or lower than 300 TWh would result in a different set of outcomes. Table 12 shows the values for several important indicators at bioelectricity production levels of 200 TWh and 400 TWh. Bioelectricity production at these levels represents, respectively, an 11.8-million-acre decrease or a 12.0-million-acre increase in land dedicated to switchgrass, compared to the 300 TWh case. At bioelectricity demands above 200 TWh, crop prices on average increase by 0.6 percent for every additional 100 TWh of bioelectricity demand. The price change from 0 to 200 TWh is about the same as the price change from 200 TWh to 300 TWh, indicating the price effects get larger as more switchgrass is planted.

Above 300 TWh, the rate at which planting switchgrass comes from land for nonenergy crops remains fairly constant—each acre of switchgrass planted comes from about two-thirds of an acre of nonenergy crops and about one-third acre of land from pasture or forest. Greater demand for land dedicated to switchgrass leads to greater nitrogen fertilizer application on nonenergy crops.

Additional land planted to switchgrass results in increases in total nitrogen application, as well as a greater intensification of nitrogen application per acre. Increasing switchgrass acreage does continue to provide erosion and nutrient loss benefits. Up to 300 TWh, total soil erosion declines as nonenergy crops are replaced by switchgrass in regions with high erosion potential. As greater amounts of switchgrass are planted, erosion benefits reverse due to a redistribution of nonenergy crop acreage into regions with higher erosion potential.

Figure 22

Regions differ in degree of intensification of nonenergy crops as land shifts to switchgrass



See USDA region list in table 7.

Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Table 12

Agricultural production measures at different levels of biomass demand

Item		Reference	Bioelectricity demand (TWh)			Percent change from 300 TWh	
			200	300	400	200 to 300	300 to 400
Switchgrass	*Million acres*	0	17.5	29.3	41.3		
Northern Plains		0	9.5	11.1	12.4		
Appalachian		0	3.9	8.6	14.5		
Southeast		0	0.0	3.0	4.6		
Nonenergy crops		314.0	300.4	292.2	284.2	-2.7	-2.8
Corn		89.0	87.6	87.1	86.7	-0.5	-0.5
Soy		76.0	73.1	71.6	69.9	-2.1	-2.3
Wheat		52.5	50.3	49.7	49.1	-1.2	-1.2
Total crop acreage		314.0	317.8	321.5	325.5	1.2	1.2
Crop price index		1.000	1.004	1.010	1.015	0.6	0.5
Corn	*$ per bushel*	3.65	3.67	3.69	3.70	0.5	0.4
Soy		9.3	9.39	9.48	9.58	1.0	1.0
Wheat		4.7	4.72	4.77	4.81	1.0	0.8
Total erosion	*Million tons*	1,673.6	1,646.0	1,632.8	1,638.4	-0.8	0.3
Nitrogen applied (total)		8.9	9.4	9.7	10.1	4.0	3.7
Nitrogen applied (per acre)	*Pounds per acre*	56.6	59.0	60.6	62.1	2.8	2.4
Nitrogen lost to water	*Million tons*	7.1	6.8	6.7	6.6	-1.7	-1.4

TWh = terawatt hours.

Source: USDA, Economic Research Service using the Regional Environment and Agriculture Programming model.

Conclusions

We use two economic models to assess the competitive potential of dedicated energy crops in the United States. On the supply side, energy crops compete for land with other crops, pasture, and forest. On the demand side, bioelectricity competes in the electricity market with other generating technologies. The global model provides an international context, an energy and climate policy framework, and covers other sectors of the economy that interact with agriculture, such as electricity generation. Bioelectricity provides a link between energy and agriculture, as well as a link between models. The national model takes bioelectricity demand as given and calculates the least-cost way to simultaneously supply land for crops, livestock, forest products, and biomass for electricity generation. The strength of the national model is the regional breakout for U.S. agriculture and the use of crop simulation modeling to capture variation in crop and switchgrass yields across USDA regions.

There are some areas of model overlap that can be compared: the range of switchgrass yields, the area of U.S. land used to grow switchgrass, the impact on crop prices, the impact on production of crops, and land allocation. When comparing results between models, note that bioelectricity is introduced gradually over time in the global model, while all scenarios in the national model compare alternative levels of bioelectricity for a single year (2030). The primary coordinated scenario between models is a bioelectricity subsidy, with 50 TWh of electricity generation from forest residue and 250 TWh from switchgrass. Electricity-generation targets, using forest residue and switchgrass as feedstocks, are exogenous inputs to the national model.

Obtaining guidance from the literature on switchgrass yield is complicated by the wide range of estimates. To cover most of this range, we use three cases for yield of dry switchgrass in the global model: low (8 t/ha = 3.6 st/acre), medium (12 t/ha = 5.4 st/acre), and high (16 t/ha = 7.1 st/acre). The high case is approximately the same as 16.8 t/ha used by Winchester and Reilly (2015) and is near the high end of the switchgrass yield distribution in the national model (see fig. 14). The low case is at the low end of the distribution of switchgrass yields in the national model.

Just as important are assumptions of yield growth over time for switchgrass and other crops. Winchester and Reilly (2015) use a yield growth rate of 1 percent per year for all crops in the base case but also have a low-yield scenario with 0.75 percent growth per year. In the global model, we assume an increase in yield of 1 percent per year for switchgrass. This is at the high end of yield growth rates projected by the International Food Policy Research Institute from 2010 through 2050 for major field crops in the United States (see fig. 3).

Several important areas are beyond the scope of this study: crop residues as an energy feedstock, the effect of land use change on carbon stocks in soils and forests, and the impacts of climate change in 2030. Crop residues, including corn stover, are an important potential source of biomass. The quantities of residue available will depend on the intensity of tillage and the tradeoff between retained residues and crop yield. Crop residues could be introduced to the global model in the same way as forest residues, as a joint product with crop production. CO_2 emissions data from land-use change, in response to an energy or climate policy, are necessary to assess the full environmental impact of a policy. Land-use change can be indirect and occur outside the United States through international markets in agricultural products. Calculation of carbon stocks by world region and AEZ can be done in the global model using data from Gibbs et al. (2014). However, carbon stocks by AEZ should not be considered static, as forest productivity changes over time and this requires further model development of the forestry sector. Climate change will affect the competitive potential of switchgrass relative to food crops, pasture, and forests, and this will vary by food production region.

The long-term potential for dedicated energy crops depends on two major uncertainties: (1) if and under what conditions cellulosic biofuels become competitive with other liquid fuels; and (2) the cost of carbon dioxide capture and storage (CCS) technology and the scale of the geologic storage resource. We did not consider cellulosic biofuels in this report. Other modeling studies have assumed that CCS will be available by 2050 at large scale, but our year of analysis is 2030 and our cap-and-trade scenario includes bioelectricity without CCS.

A comparison of outputs between the global and national models is provided in appendix B. The following activities would be useful extensions to this report: consider competition from forests for supplying bioenergy; introduce calculation of carbon stocks to better understand the conditions required for carbon neutrality of biomass; and consider the potential impacts of climate change on future productivity of food crops, energy crops, and forests.

In this study, we provide three “what-if” scenarios that incentivize switchgrass as another crop to expand agriculture. Economic simulation indicates that the quantity of biomass produced in each scenario, about 250 million short tons per year, is both technically and economically feasible. However, the competitive potential of switchgrass depends on the policy environment and some important areas of technology development, including yield growth over time and the interaction of bioelectricity with wind and solar power as competing renewables.

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Appendix A: Abbreviations

AEZ	agro-ecological zone
AgMIP	Agricultural Model Intercomparison and Improvement Project
bu	bushel
BECCS	Bioelectricity with carbon dioxide capture and storage
CCS	Carbon dioxide capture and storage
CO_2	Carbon dioxide
CRP	USDA Conservation Reserve Program
cwt	hundredweight (100 pounds)
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EJ	exajoule
EPA	U.S. Environmental Protection Agency
EPIC	Environmental Productivity and Integrated Climate model
FARM	Future Agricultural Resources Model
GHG	greenhouse gas
GTAP	Global Trade Analysis Project
gal	U.S. gallon
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
ha	hectare
kg	kilogram
L	liter
lb	pound
LHV	low heating value
Mha	million hectares
MSW	municipal solid waste
MWh	megawatt hour
PJ	petajoule
REAP	Regional Environment and Agriculture Programming model
RFS	Renewable Fuel Standard
RPS	Renewable Portfolio Standard
SSP	Shared Socio-economic Pathway
st	short ton (2,000 pounds)
t	metric tonne (1,000 kilograms)
TWh	terawatt hour (same as billion kWh)

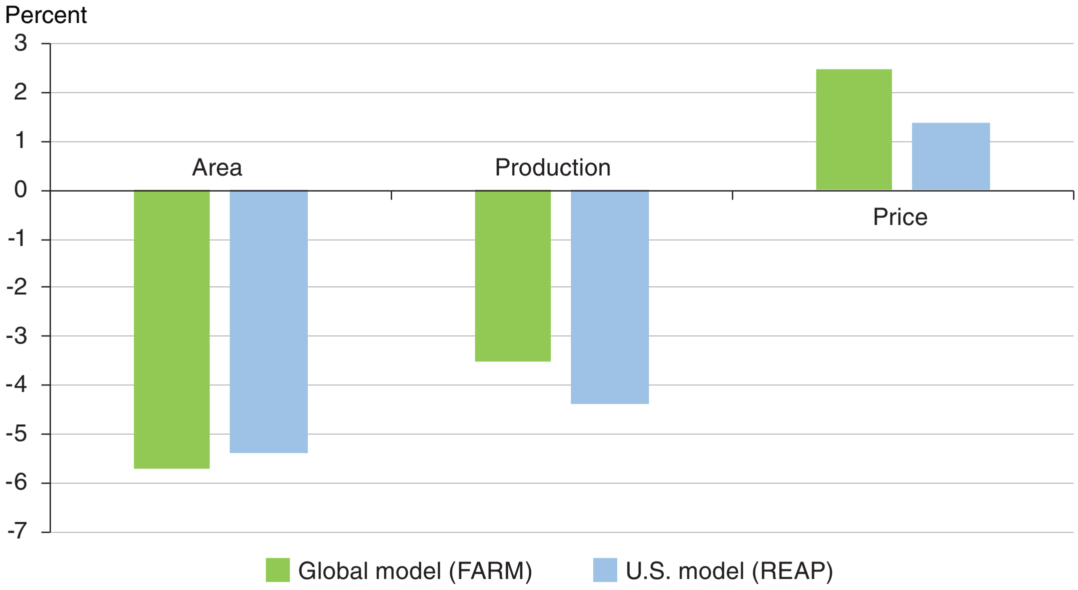
Appendix B: Comparison of Output Between Models

Appendix figure B1 provides a comparison between the ERS global and national models of changes in harvested area, production, and price for wheat. In both models, the decline in wheat production is less than the decline in harvested area due to intensification of production on land. Appendix tables B1, B2, and B3 provide the underlying data for appendix figure B1 and for two other scenarios in the Future Agricultural Resources Model.

The primary difference between output in global and national models is the price response to scenarios in this report. Percentage changes in harvested area and production are relatively similar between the two models. Percentage increases in the price of field crops in the global model were roughly double those in the national model. The greatest increase in prices was in the cap-and-trade scenario, as seen in appendix table B3 and appendix figure B2.

Appendix figure B1

Comparison between models of changes in area, production, and price for U.S. wheat SUBSIDY scenario in global model (year = 2030)



FARM = Future Agricultural Resources Model. REAP = Regional Environment and Agriculture Programming model.
Source: USDA, Economic Research Service.

Appendix table B1

Comparison between models of changes in area, production, and price for major crop groups

SUBSIDY scenario in FARM (year = 2030)

	Harvested area		Production		Price	
	FARM	REAP	FARM	REAP	FARM	REAP
Wheat	-5.7%	-5.4%	-3.5%	-4.4%	2.5%	1.4%
Coarse grains (Corn)	-3.6%	-2.1%	-0.6%	-0.8%	1.9%	1.0%
Oilseeds (Soybeans)	-6.0%	-5.8%	-3.2%	-5.7%	2.8%	1.9%

FARM = Future Agricultural Resources Model. REAP = Regional Environment and Agriculture Programming model.
Source: USDA, Economic Research Service.

Appendix table B2

Comparison between models of changes in area, production, and price for major crop groups

RPS scenario in FARM (year = 2030)

	Harvested area		Production		Price	
	FARM	REAP	FARM	REAP	FARM	REAP
Wheat	-6.4%	-5.4%	-4.0%	-4.4%	2.9%	1.4%
Coarse grains (Corn)	-4.2%	-2.1%	-0.7%	-0.8%	2.3%	1.0%
Oilseeds (Soybeans)	-7.2%	-5.8%	-3.9%	-5.7%	3.5%	1.9%

FARM = Future Agricultural Resources Model. REAP = Regional Environment and Agriculture Programming model.
RPS = Renewable Portfolio Standard.
Source: USDA, Economic Research Service.

Appendix table B3

Comparison between models of changes in area, production, and price for major crop groups

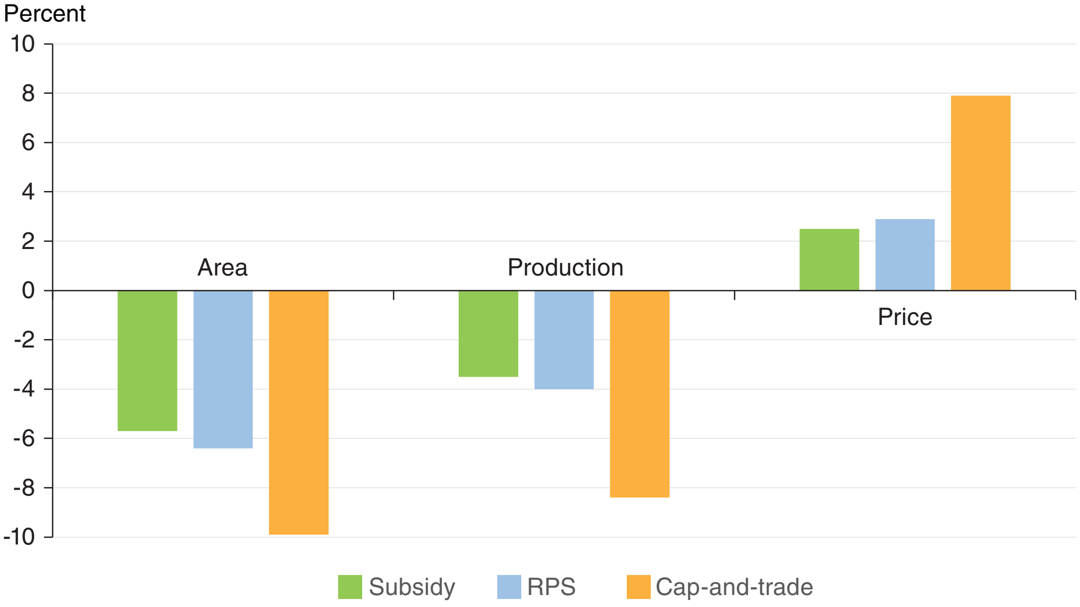
Cap-and-trade scenario in FARM (year = 2030)

	Harvested area		Production		Price	
	FARM	REAP	FARM	REAP	FARM	REAP
Wheat	-9.9%	-5.4%	-8.4%	-4.4%	7.9%	1.4%
Coarse grains (Corn)	-5.0%	-2.1%	-1.7%	-0.8%	5.8%	1.0 %
Oilseeds (Soybeans)	-8.3%	-5.8%	-4.8%	-5.7%	5.7%	1.9%

FARM = Future Agricultural Resources Model. REAP = Regional Environment and Agriculture Programming model.
Source: USDA, Economic Research Service.

Appendix figure B2

Comparison between scenarios of changes in area, production, and price of U.S. wheat in global model (year = 2030)



RPS = Renewable Portfolio Standard.
Source: USDA, Economic Research Service.

Appendix C: FARM Documentation

The Future Agricultural Resources Model (FARM) is a global computable general equilibrium (CGE) economic model with 13 world regions that operates in 5-year steps from 2007 to 2052. Land use can shift among crops, pasture, and forests in response to population growth, changes in agricultural productivity, and policies such as a renewable portfolio standard or greenhouse gas cap-and-trade. See Hertel et al. (2009a) for a comprehensive overview of modeling land use in CGE models.

The first version of FARM was constructed in the early 1990s by Roy Darwin and others at ERS (Darwin et al., 1995). By partitioning land into land classes, this model provided a unique capability among CGE models to simulate land use on a global scale. Early versions of the FARM model were used to simulate the impact of a changed climate on global land use, agricultural production, and international trade.

Data requirements include a base-year social accounting matrix from the Global Trade Analysis Project (GTAP) at Purdue University, energy balances from the International Energy Agency (IEA), land use from the Food and Agriculture Organization of the United Nations (FAO), and agricultural production from FAO.

Data Processing

We begin with social accounts in GTAP version 8.2 as the primary economic framework. GTAP data provide social accounting matrices for 140 world regions and 57 production sectors. These data are then aggregated to 13 world regions, corresponding to region definitions of the Agricultural Model Intercomparison and Improvement Project (AgMIP), and 38 production sectors. The production sectors retain all GTAP information related to primary agriculture, food processing, energy transformation, energy-intensive industries, and transportation (appendix table C1).

Appendix table C1

Production sectors in FARM after aggregating GTAP social accounts

	Group	Subgroup	Symbol	Description
1	Primary agriculture	Crops	wht	Wheat
2			pdr	Paddy rice
3			gro	Other grains
4			osd	Oilseeds
5			c_b	Sugar (cane and beet)
6			v_f	Vegetables and fruits
7			pfb	Plant-based fibers
8			ocr	Other crops (including forage crops)
9		Animal products	ctl	Cattle and other ruminants
10			rmk	Raw milk
11			wol	Wool
12			oap	Other animal products
13		Fisheries	fsh	Fish
14		Forestry	frs	Forestry
15	Food processing		vol	Vegetable oils
16			pcr	Processed rice
17			sgr	Sugar
18			b_t	Beverages and tobacco products
19			ofd	Other food
20			cmt	Meat from cattle and other ruminants
21			mil	Dairy products
22			omt	Other meat products
23	Energy	Production	ecoa	Coal
24			eoil	Crude oil
25			egas (2)	Natural gas
26		Transformation	ec_p	Refined coal and petroleum products
27			eely	Electricity
28	Energy-intensive industries		lum	Wood products
29			ppp	Paper and pulp
30			crp	Chemicals, rubber, and plastic
31			nmm	Nonmetallic minerals
32			i_s	Iron and steel
33			nfm	Nonferrous metals
34	Other industry		oth_industry (12)	Other industry
35	Transportation		otp	Land transportation
36			wtp	Water transportation
37			atp	Air transportation
38	Services		svs (8)	Services

Note: Symbols followed by an integer in parentheses indicate the number of original GTAP production sectors aggregated to this FARM sector. Fifty-seven GTAP sectors were aggregated to 38 FARM production sectors. GTAP = Global Trade Analysis Project. FARM = Future Agricultural Resources Model.

Source: USDA, Economic Research Service.

The GTAP data distribution has the same number of production activities as products for consumption. However, it is convenient to maintain a distinction between produced commodities and production activities, allowing for the possibility of joint products or multiple activities producing the same product. For example, the FARM model considers oil and gas as joint products from a combined oil and gas production activity. FARM also considers milk and ruminant meat as joint products of a ruminant animal production activity.

Recent GTAP datasets are constructed to maintain consistency between energy values in the GTAP dataset and energy quantities from energy balances distributed by the International Energy Agency (IEA). This provides energy values consistent with the law of one price for each energy carrier: within each world region, all consumers of energy pay the same price net of tax and transport margins. The GTAP data distribution includes supplemental energy quantity data aggregated from detailed IEA energy balances, which provide sufficient energy information for calculating carbon dioxide (CO_2) emissions from energy combustion.

Further data processing expands the number of production sectors: the single electricity production sector in GTAP is expanded to include nine electricity-generating technologies; household transportation is removed from final demand to create a new transportation services sector; and household energy consumption is also removed from final demand to create a new energy services sector. Dedicated biomass production is introduced as a new field crop, which is then combusted in a bioelectricity activity. Biomass therefore becomes a link between agricultural and energy systems.

Agricultural products are mostly consumed after processing into vegetable oils, sweeteners, dairy products, meat products, and other food products. Many of these products are not consumed directly at home but are purchased along with services as food away from home.

CGE Framework

New tools and data have become available since the first version of FARM was constructed, most notably the GTAP dataset (Hertel, 1997) and tools for using GTAP data in the General Algebraic Modeling System (GAMS) programming language (Rutherford, 2010). Therefore, development of the new FARM model did not start from scratch; the starting point was code in GAMS provided by Rutherford (2010). This software provides a comparative-static global CGE model fully compatible with GTAP 8 social accounts and bilateral trade between world regions. The software also provides utilities for converting GTAP data into the GAMS programming environment.

The FARM model has been extended in many ways beyond the model in Rutherford (2010): conversion from comparative-static to a dynamic-recursive framework with 5-year time steps; conversion of the consumer demand system from constant-elasticity-of-substitution (CES) to the Linear Expenditure System (LES); allowing for joint products in production functions; introduction of land classes for agricultural and forestry production; and introduction of electricity-generating technologies.

The FARM model is solved using the PATH solver in GAMS, with each model equation paired with a model variable. Most model equations are one of three types: market clearing, zero-profit (efficiency) conditions, and income balance. Market-clearing equations are paired with market prices, zero-profit conditions are paired with production quantities, and income balance equations are paired with expenditure by a representative agent (appendix table C2).

Appendix table C2

Matched variables and equations in FARM

Variables (unknowns)	Equations
prices of produced commodities (by region of production)	market clearing (domestic supply equals domestic demand plus foreign demand)
rentals of primary factors (capital, labor, natural resources) in each region	market clearing
land rents by land class (in each region)	market clearing
scale of production (by region and commodity)	zero-profit conditions (price received equals total cost of production)
expenditure of representative agent (in each region)	income balance

FARM = Future Agricultural Resources Model.

Source: USDA, Economic Research Service.

Demand

An economic simulation of per capita food consumption relies on behavioral parameters, especially income and price elasticities. An ERS study (Muhammad et al., 2011) addresses the question: How is an additional dollar of income split among various food commodities? The authors of this study estimated income and price elasticities using data from the International Comparison Program (ICP) of the World Bank. These data clearly show a declining share of food in an extra dollar of total expenditure across countries ranked from low to high per capita income. Further, cereals are a declining share of marginal food expenditure as per capita income increases. This study provides empirical support for income elasticities that can be used in economic models such as FARM.

Consumer demand for individual commodities is calculated in FARM using the LES. Equations (B1) and (B2) are based on Sydsaeter et al. (2010). The LES is derived from a shifted Cobb-Douglas utility function.

$$u(\mathbf{x}) = \prod_{i=1}^{n} (x_i - \gamma_i)^{\beta_i} \qquad \beta_i > 0 \qquad \sum_i \beta_i = 1 \tag{C1}$$

Demand for an individual commodity is given by

$$x_i(\mathbf{p}, m) = \gamma_i + \frac{1}{p_i} \beta_i \left(m - \sum_i p_i \gamma_i \right) \tag{C2}$$

The beta parameters are value shares of income remaining after minimum quantities of each commodity have been purchased. Income elasticities of demand and own-price elasticities of demand can be calculated from equation (C2) by differentiating with respect to income (C3) and prices (C4), respectively.

$$\varepsilon_{im} = \frac{\beta_i m}{p_i x_i} = \frac{\beta_i}{S_i} \tag{C3}$$

$$\varepsilon_{ii} = -\frac{\beta_i}{p_i x_i} \left(p_i \gamma_i + m - \sum_k p_k \gamma_k \right) \tag{C4}$$

Base-year calibration requires setting the gamma and beta parameters in (C2) so that FARM replicates base-year data from GTAP, including value shares for each commodity in total expenditure *m*. A convenient method of calibration is to set the ratio γ_i / x_i, and then β_i parameters are calculated to match GTAP value shares. The ratio γ_i / x_i must be in the interval [0,1] and can be used to indirectly set income elasticities, especially for agricultural products. Note that income and price elasticities cannot be set independently in the LES: once the ratio γ_i / x_i is set, then income and own-price elasticities are already determined. Levels of the ratio γ_i / x_i close to 1 imply low income and own-price elasticities.

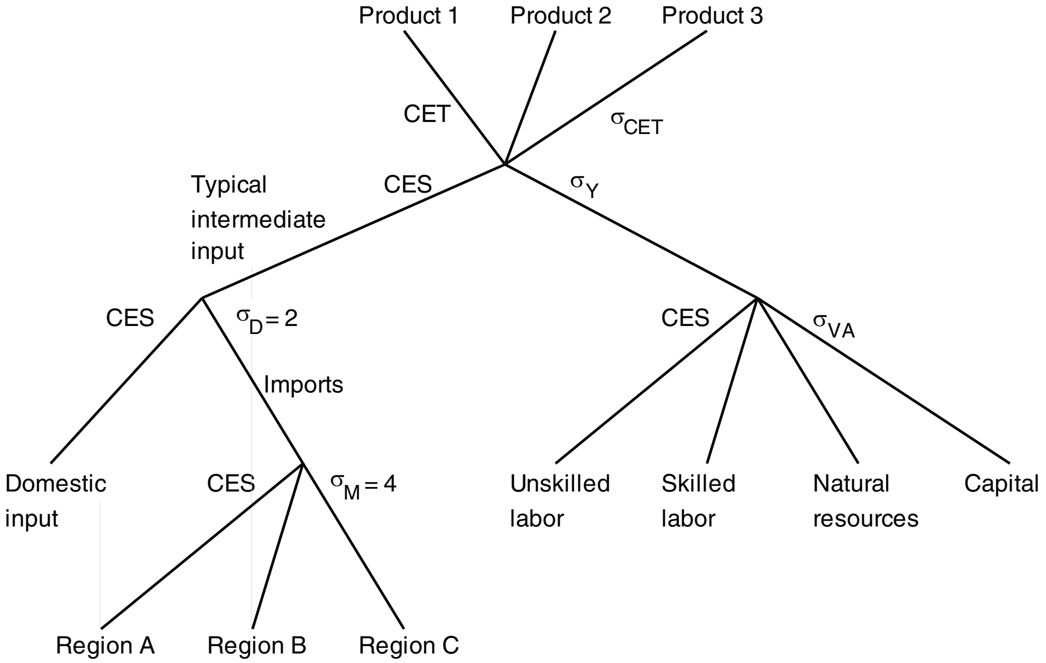
Production

Each production sector is modeled as a nested CES production function as shown in appendix figure C1. The top CES nest is an aggregate of intermediate inputs and nested value added. Each intermediate input is distinguished by source: from domestic production or imports from other world regions.

Output from each production activity passes through a constant-elasticity-of-transformation (CET) function before it can be consumed or exported. A CET function has the same functional form as a CES production or cost function, but with an elasticity less than or equal to zero. Most production activities have only one product, but there are exceptions such as oil and natural gas as joint products from a single production activity. More complex production structures can be created by combining two or more generic production structures connected by an intermediate product.

Appendix figure C1

Generic production structure in Future Agricultural Resources Model



CET = constant elasticity of transformation. CES = constant elasticity of substitution.
Source: USDA, Economic Research Service.

Technical Change

We use technical change parameters to construct a plausible global reference scenario for energy, agriculture and land use through 2050. All technical change parameters are input specific and are considered as input augmenting. For example, labor productivity parameters are used to produce GDP pathways for each region that closely approximate target pathways from Shared Socio-economic Pathways (SSPs). These parameters vary over four dimensions: model time step, input to production, production sector, and world region. Productivity improvements are reflected in input-output ratios that decline over time.

Land-augmenting technical change parameters are taken directly from the AgMIP reference scenario. The efficiency of energy use by production sector is set exogenously to provide plausible scenarios of energy consumption by energy carrier: coal, refined petroleum, natural gas, and electricity. Capital-augmenting technical change is set to zero for all production sectors and regions, with two exceptions: electricity from wind and electricity from solar. This is done to keep the economy-wide investment-GDP ratio from falling over time. Technical change is captured through all inputs other than capital.

Each land-using production function (e.g., wheat, rice, coarse grains) has a technical coefficient associated with land that varies over time. A reference scenario was constructed for this report using exogenous changes in yield through 2050 provided through the AgMIP project by the International Food Policy Research Institute (IFPRI). These changes in yield were applied only to the land input, as land-augmenting technical change. Crop yield is also influenced in FARM by changes in prices of agricultural products and inputs to agricultural production. Therefore, simulated crop yield in FARM is a combination of exogenous and price-induced effects.

IFPRI has constructed yield projections through 2050 for a reference scenario and eight climate impact scenarios. These scenarios of yield growth are used by 10 global economic modeling teams in the AgMIP project, including FARM. The climate impact scenarios are based on output from two climate models and several crop growth models.

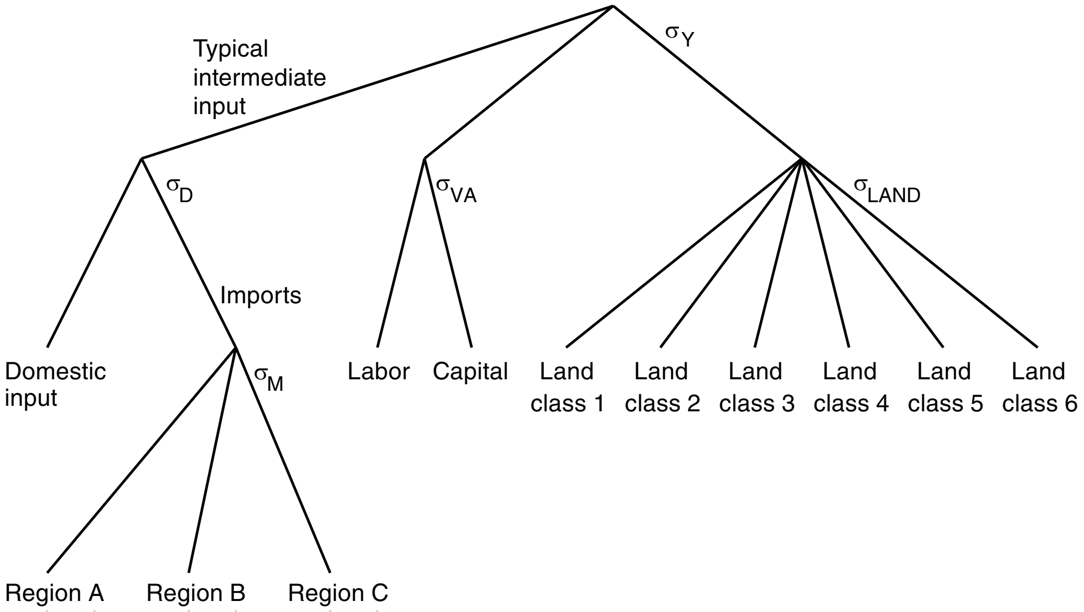
Land as an Input to Production

Land use can shift among crops, pasture, and managed forests in response to population growth and changes in income, with behavioral responses determined by price and income elasticities. The GTAP 8 database distributed by Purdue University includes supplemental data on physical quantities from FAO. The base year is 2007, and the GTAP dataset includes a global social accounting matrix with economic values, land cover for aggregate land types, harvested area for eight crop types, and production quantities for five types of field crops. Further, the GTAP dataset provides land use by 18 agro-ecological zones (AEZs). See Monfreda et al. (2009) for background on construction of AEZs for GTAP. Lee et al. (2009) provide a description of the land-use database provided by GTAP. FARM operates with up to 18 land classes in each region, which correspond to 18 AEZs provided in GTAP land-use data.

The FARM production structure with land as an input is shown in appendix figure C3. Each land class allocates land to 1 of 11 land-using production sectors: 5 field crops, 1 energy crop, 3 other crop types, pasture for ruminant animals, and managed forests. Within each land-using production sector, land from land classes is combined into a land aggregate in a CES nest. Other nesting structures bring intermediate inputs and value added into the production function. Input groups compete within the top-level CES nest. The nesting structure for animal feed is shown in appendix figure C3, which is a special case of appendix figure C2. Feed for ruminant animals is a combination of pasture and crops.

Appendix figure C2

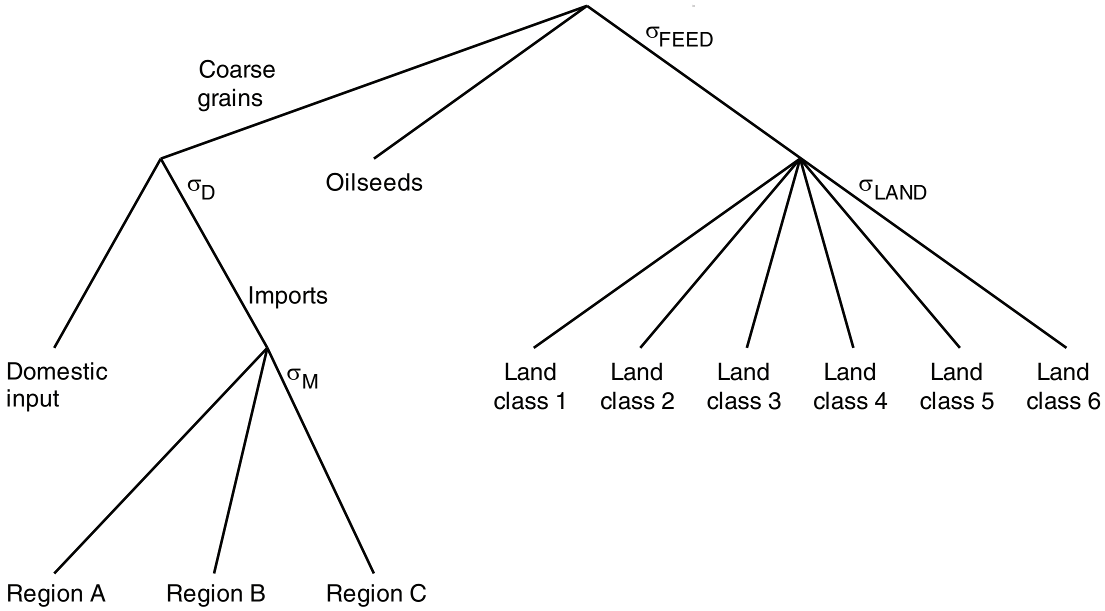
Production structure for crops and forestry



Source: USDA, Economic Research Service.

Appendix figure C3

Feed production structure for ruminant animals



Source: USDA, Economic Research Service.

Hertel et al. (2009a) provide a discussion of land use in CGE models using GTAP data. The most common approach is to allocate total land in each land class, to its uses, using a CET function. The main drawback of this approach is that land quantities are not preserved: the quantity of land going into a CET nest does not equal the sum of land quantities allocated to production sectors. Land values are preserved, but not land quantities.

This presents a dilemma for CGE modelers, especially for analysis where land use is an important output. For example, carbon emissions from land-use change are an important component of global greenhouse gas emissions. In the FARM model, we consider each land class a primary factor of production with a market-clearing condition. Market clearing assures that land quantities are preserved. Each land class has its own land market, where the rental per hectare of land is the same regardless of land use. We impose this condition on the data, when calibrating to benchmark data in the base year.

The assumption of equal land rents can be justified by the land allocation theory in Sands and Leimbach (2003). This has been used successfully in a partial equilibrium framework where the yield for each land use, within a land class, is described by a joint probability distribution including a correlation coefficient for yield between land uses. If the land use with the highest profit rate is always selected, then the share of land allocated to each land use can be calculated. Surprisingly, the average land rent is the same across land uses within a land class, regardless of the share of land going to each land use.

Hertel et al. (2009b, pp. 126-128) state the conditions where a single crop production function, with land inputs from several land classes, is equivalent to having a production function for each crop x land class combination. One of the conditions is that land rents, for a given crop, are proportional to yield across land classes. This follows from (1) the price received per unit of output is the same regardless of land class; and (2) the cost per unit of output for non-land inputs is the same regardless of land class. Then, the expenditure on land, per unit of output, is the same across land classes. If land rents are proportional to yield, then low yields are offset by low land rents, and high yields are matched with high land rents.

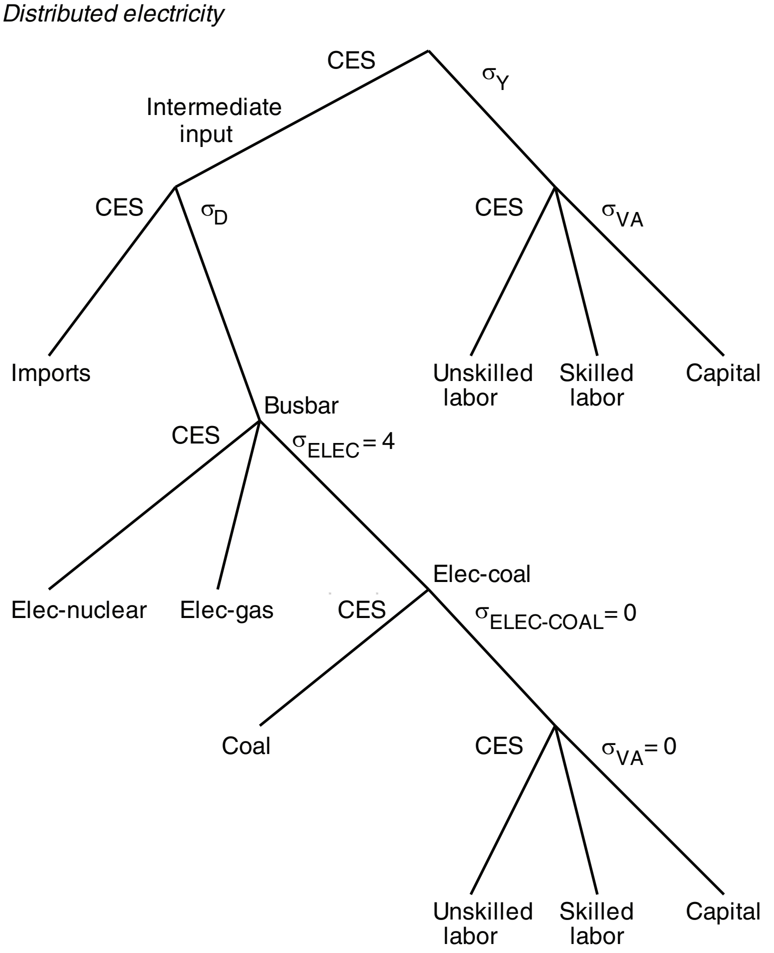
In summary, we have two efficiency conditions that are imposed algebraically on the input dataset. The first is that average land rents, within a land class, are equal across land uses. The second is that land rents, across land classes for a given land use, are proportional to yield.

Electricity Generation

Electricity generation is a good example of combining generic production structures, where outputs of each generating technology are combined into a CES nest (appendix fig. C4). Each electricity generation technology is a fixed-coefficient nest of fuel, other intermediate inputs, and value added. The electricity generated by each technology is consumed by a “busbar” technology, which is simply a CES nest that combines output from all electricity-generating technologies. All of the output from “busbar” is consumed as an intermediate product to “distributed electricity” with the capital and labor needed to transmit electricity from the generating plant to industrial, commercial, and residential customers. The electricity structure in appendix figure C4. combines three production activities, where each activity is a special case of the generic production structure of appendix figure C1.

Appendix figure C4

Electricity generation and distribution in Future Agricultural Resources Model



CES = constant elasticity of substitution.
Source: USDA, Economic Research Service.

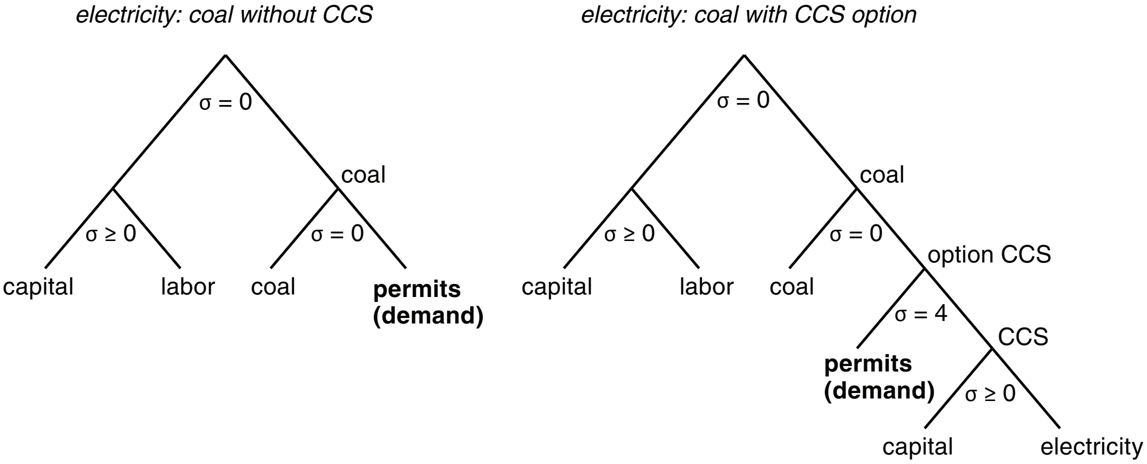
Bioelectricity With CO_2 Capture and Storage (BECCS)

CO_2 capture and storage is a stand-alone production technology that can be used by any fossil electricity-generation technology or bioelectricity. The nest on the left side of appendix figure C5 applies to any fossil-generating technology without CCS. In this case, coal is the fuel, and the ratio of electricity generated to coal energy input is fixed through the zero rate of substitution in the top level of the nest. The ratio of coal to the quantity of CO_2 emission permits is also fixed, with the cost of permits varying directly with the CO_2 price.

The following discussion of CCS operating with electricity generation is in the context of a CO_2 cap-and-trade system where permits are purchased to cover CO_2 emissions. The discussion could also be placed in the context of a carbon tax: the carbon tax would be paid directly to the Government in place of purchasing permits in a market.

Appendix figure C5

Nesting structure for electricity generation from coal



CCS = carbon dioxide capture and storage.
Source: USDA, Economic Research Service.

The right side of appendix figure C5, a generalization of the left side nest, can turn the CCS option on or off depending on the CO_2 price. Instead of purchasing CO_2 permits directly, activities that generate electricity from fossil fuel purchase permits indirectly through an economic switch (option CCS) that buys permits if the CO_2 price is below the breakeven cost of CCS, and buys CCS otherwise. If the CO_2 price is equal to the breakeven cost of CCS, then purchases are split equally between permits and CCS. The economic switch is a CES function with a high elasticity of substitution, equal to 4 in this case. The benchmark (base year) price of CO_2 permits is $1 per metric ton, as demand would be undefined if the permit price were zero. The primary motivation for this nesting structure is that it can be further generalized to apply to bioelectricity with CCS.

Appendix figure C6 provides nesting structures for bioelectricity, a technology that combusts biomass to raise steam for electricity generation. However, there are important differences in the bioelectricity nests relative to the coal-electricity nests in appendix figure C5. First, CO_2 emissions from biomass combustion in the left nest of appendix figure C6 are not taxed: these emissions represent CO_2 that was recently removed from the atmosphere through photosynthesis. Second, the generalized nesting structure on the right side of appendix figure C6 was designed to operate as the left nest at low CO_2 prices, but provide an opportunity for negative CO_2 emissions when CO_2 prices are above the breakeven price for CCS.

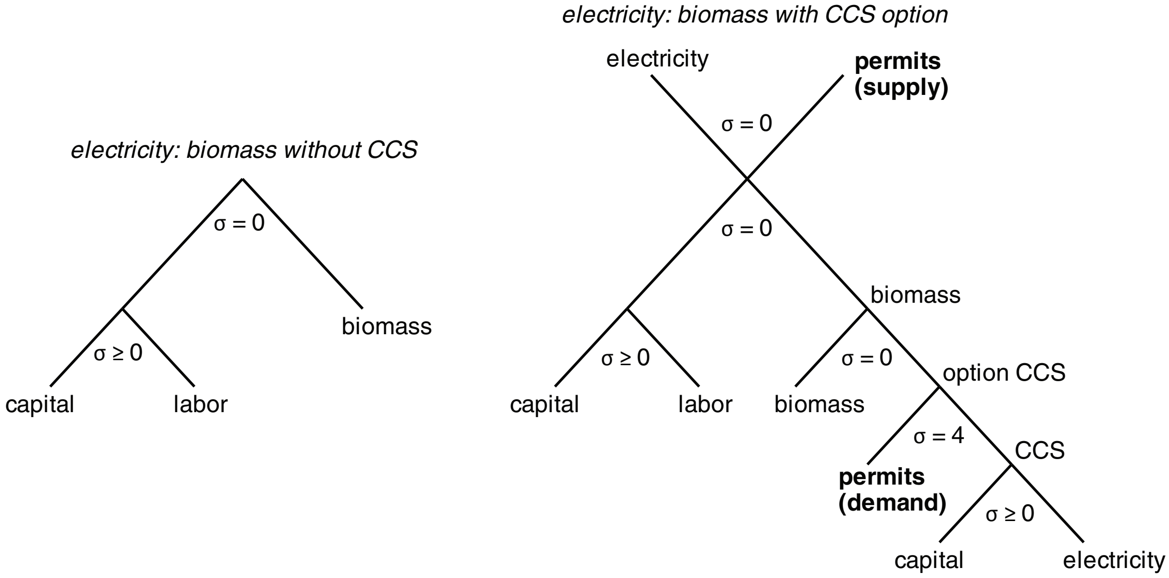
The generalized nesting structure in appendix figure C6 can simultaneously demand from, and supply permits to, a CO_2 market. Supply of permits is made possible as one of two joint products: electricity and CO_2 permits. Permit supply and demand are calculated as the quantity of CO_2 emitted by combustion of biomass. With low CO_2 prices, supply and demand for permits exactly cancel, providing the same behavior as the simple bioelectricity nest.

At CO_2 prices greater than the breakeven price for CCS, this production process switches from buying permits to buying CCS, as this is the less expensive option. This process continues to supply CO_2 permits based on the carbon content of the biomass combusted. However, supply of permits comes at a cost, as electricity used by the CCS process offsets some of the bioelectricity generated.

Revenue from permit supply acts as a subsidy for bioelectricity, allowing land for biomass production to expand relative to other land uses. If the market carbon price is much greater than the break-even cost of CCS, then the subsidy becomes large with rents accruing to landowners. Bioelectricity with CCS is described further in Sands et al. (2014a).

Appendix figure C6

Nesting structure for electricity generation from biomass



CCS = carbon dioxide capture and storage.
Source: USDA, Economic Research Service.

Appendix D: The Regional Environment and Agriculture Programming (REAP) Model

The Regional Environment and Agriculture Programming (REAP) model is a static, partial equilibrium optimization model of the agricultural sector that quantifies agricultural production and its associated environmental outcomes for 48 regions in the United States. The regions are defined by the intersection of USDA's farm production regions (defined by State boundaries) and land resource regions (defined by predominant soil type and geography).

Data and Model Structure

REAP employs survey data (from USDA's Agricultural Resource Management Survey (ARMS)) and simulated input data (from the Environmental Productivity and Integrated Climate (EPIC) model) at the regional level on crop yields, input requirements, costs and returns, and environmental parameters to estimate long-run equilibrium outcomes. Other data sources are employed as shown in appendix table D1. Regional production levels are determined for 10 crops and 12 livestock categories, and national production levels are determined for 20 processed products (appendix table D2). For each REAP region, land use, crop mix, and acreage allocations by multiyear crop rotation and tillage practice are endogenously determined by REAP's constrained optimization process. Input use and national-level prices are also determined endogenously. The model has been applied to address a wide range of agri-environmental issues, such as soil conservation and environmental policy design, environmental credit trading, climate change mitigation policy, and regional effects of trade agreements.

Appendix table D1

Data sources and their use in REAP

Source	Use
USDA Projections	Reference acreage, national crop yields, crop prices
Ag Census	Regional crop acreage, livestock inventories, and transformation coefficients
ARMS	Enterprise production costs
NRI	Crop rotations and rotation distribution
EPIC	Enterprise crop yields, soil and water impacts

ARMS = Agricultural Resource Management Survey. NRI = National Resources Inventory. EPIC = Environmental Productivity and Integrated Climate. REAP = Regional Environment and Agriculture Programming model.
Source: USDA, Economic Research Service.

Appendix table D2

Major Products in REAP

Crops	Livestock	Processed
Corn	Dairy cows	Ethanol
Sorghum	Layers	Cheese
Barley	Broilers	Milk
Oats	Turkey	Butter
Wheat	Hogs (cull sows, feeder pigs)	Soybean meal
Rice	Grazed cattle	Soybean oil
Soybeans	Feedlot cattle	Livestock rations
Cotton	Stocker, calves, yearlings	Bioelectricity
Silage		
Hay		
Switchgrass		

REAP = Regional Environment and Agriculture Programming model.
Source: USDA, Economic Research Service.

REAP models production agriculture in the United States as a geographically distributed set of production units. Each unit represents the aggregate of all farmers in the region that produce the products modeled in REAP. Currently, the products include the crop and livestock categories outlined in the USDA Projections for agriculture, plus several products processed from the primary commodities. The primary products that are produced on the farm are transformed into products consumable by humans, livestock, or other products. Appendix figure D1 shows the basic information flow from land use to final consumption. Production is regional (but not spatial as there is no transportation or any geographically meaningful relationship between regions) and consumption is national, with the exception of animal feed. REAP is a price endogenous model, meaning prices for each product are determined by the model as the intersection of a demand curve and a supply curve that adjusts to keep the material flow in balance and optimizes the objective function. REAP is a partial equilibrium model, meaning there are no endogenous markets for input factors such as fertilizer or labor. The objective is to maximize consumer plus producer surplus.

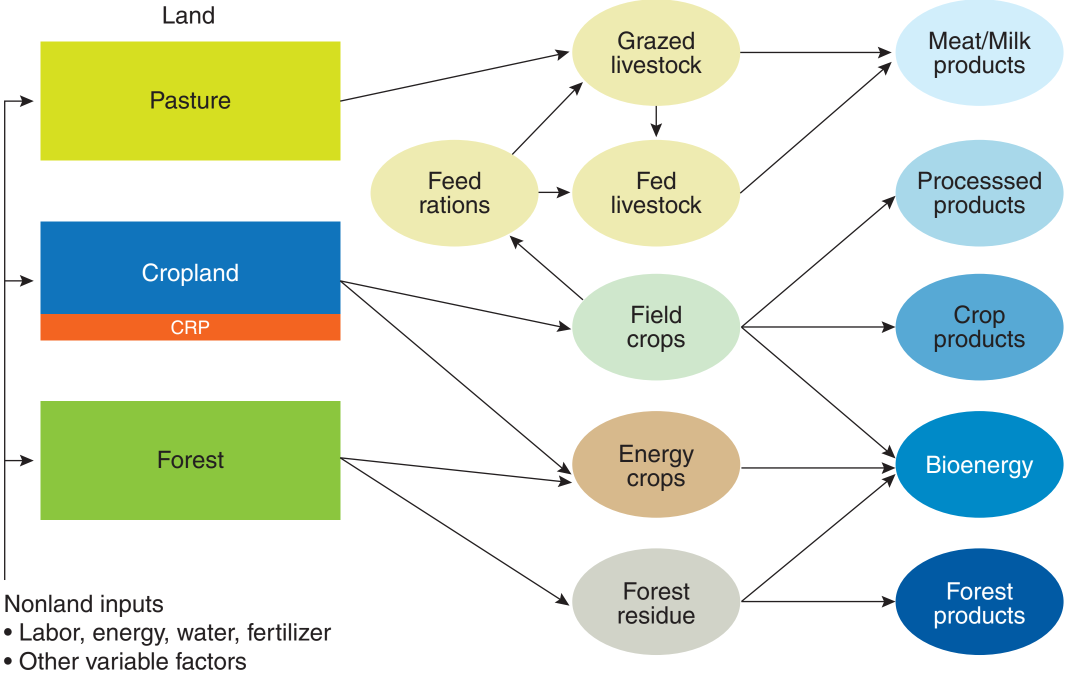
Production "shocks" under policy, technical, or environmental scenarios can be introduced through changes or additions to constraints, modifications of baseline data assumptions, adjustments in objective function terms, or some combination of approaches. Changes in policy, commodity demand, or production technology can be imposed on the model and the results examined to determine their effects on:

- Regional supply of crops and livestock;
- Commodity prices and returns to crop production;
- Crop management and production input use;
- Environmental indicators, such as nutrient and pesticide runoff, soil loss, greenhouse gas emissions, soil carbon fluxes, and energy use.

For more information on REAP and its applications, see model documentation in Johansson et al. (2007).

Appendix figure D1

REAP model structure



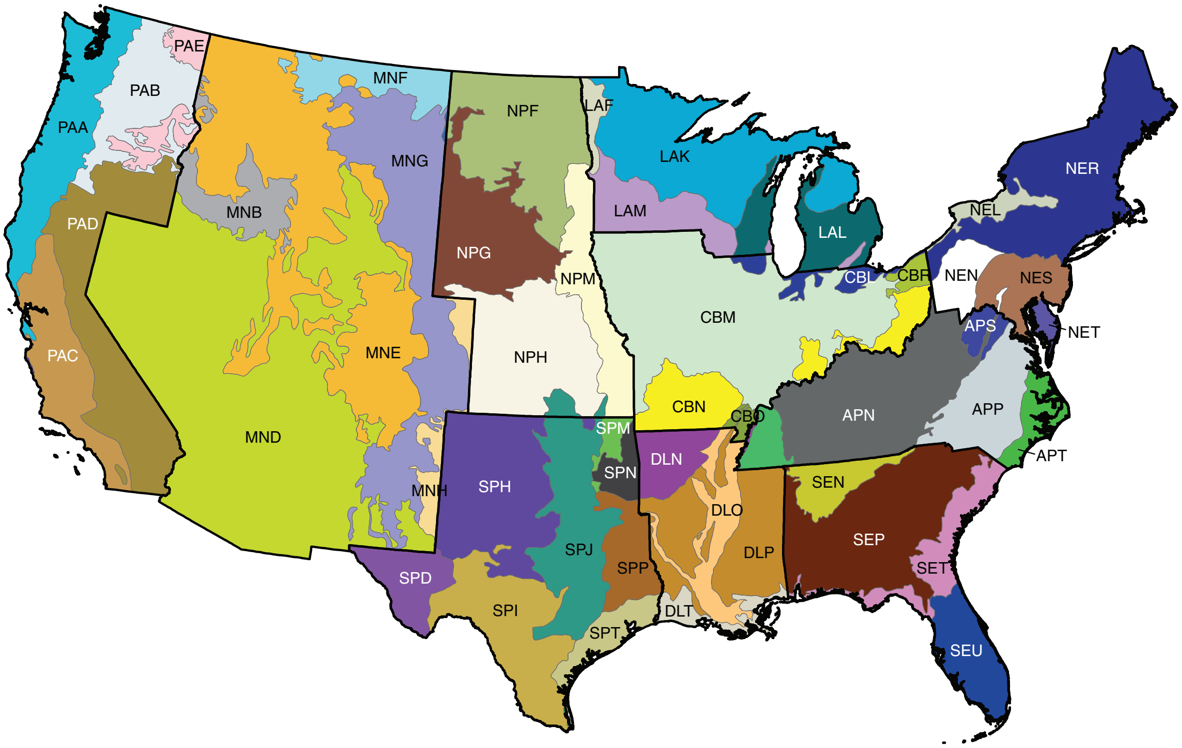
REAP = Regional Environment and Agriculture Programming model. CRP = Conservation Reserve Program.
Source: USDA, Economic Research Service.

An important assumption in REAP is that agricultural production is homogeneous within a given region. The great diversity of soils, climate, and predominant production practices in U.S. agriculture would require an enormous number of regions to ensure homogeneity. This is impractical from a data collection perspective as well as computational considerations. However, regions need to be small enough to minimize variation in growing conditions and resource availability between producers but large enough to facilitate data collection and reduce computational burden. REAP achieves this balance by employing regions delineated by the intersection of USDA's farm production regions (FPR) and the Land Resource Regions (LRR) defined by USDA's Natural Resources Conservation Service. Because of the importance of soil erodibility in conservation and its effect on crop productivity, each geographic region is further divided into highly-erodible (HEL) and non-highly-erodible (NHEL) components. Appendix figure D2 displays the geographical arrangement of the REAP regions.

The basic decision unit in REAP is the acreage planted to each of a set crop rotations in each region. Not all crops are grown in every region, and not all rotations are economically or agronomically feasible, even in regions where the constituent crops are produced. We identify for each region the feasible rotations and estimate the frequency distribution using the National Resources Inventory (NRI) (app. table D3). Rotations with a small amount of acreage in a region are excluded. The observed rotations become a fixed feature of REAP. The initial distribution determined from the NRI is adjusted to be consistent with other REAP input data. Rotations are designated in REAP with a label "RXXX," where X indicated one of the 10 field crops (B=soybeans, C=corn, G=silage, H=hay, L=barley, O=oats, R=rice, S=sorghum, T=cotton, W=wheat). The order of the labels is not relevant—for example, the corn/soybean/wheat rotation RCBW accounts for all rotations that include corn, soybeans, and wheat planted sequentially.

Appendix figure D2

Regional Environment and Agriculture Programming regions



Note: The three-letter region labels are defined by the two-letter Farm Production Region abbreviation (see region list in table 7) and the one-letter designation for USDA, NRCS Land Resource Region.
Source: USDA, Economic Research Service.

A key (and perhaps unique) feature of REAP compared to other large-scale agricultural systems models is the inclusion of environmental impact drivers that are directly associated with each production unit. The environmental drivers are derived from soil and production practices predominant in the region. Each production unit has associated nutrient loss, soil erosion, and greenhouse gas measures that are based on crop (rotation), soil type, tillage system, climate, and input use. Output values of these parameters for each enterprise are aggregated at the regional level to identify potential consequences to air and water quality from changes to U.S. agricultural production.

REAP is implemented as a nonlinear mathematical program using the General Algebraic Modeling System (GAMS). The model determines a welfare-maximizing set of crop, livestock, and processed-product production levels subject to land constraints and production balance requirements. Production activities for crops within a region (defined by crop rotation and tillage) are allocated in the model solution based on a constant-elasticity-of-transformation (CET) relationship. The CET specification helps to avoid unrealistic “corner point” solutions by accounting for cost and risk considerations embedded in observed acreage allocations but not explicitly included in the model. The model is calibrated to USDA baseline production levels over a multiyear timeframe using the Positive Mathematical Programming (PMP) method.

Appendix table D3

REAP rotations in each farm production region

Rotation	AP	CB	DL	LA	MN	NP	NE	PA	SE	SP
RBBB	x	x	x	x			x		x	x
RBR		x	x							x
RBS	x	x	x			x			x	x
RBT	x		x						x	
RBW	x	x	x	x		x			x	x
RBWR			x							
RBWS		x				x				x
RCB	x	x	x	x		x	x		x	x
RCBL	x					x	x			
RCBO		x		x		x				
RCBOH		x		x		x				
RCBS		x				x				x
RCBW	x	x		x		x	x		x	
RCBWH	x	x		x		x	x			
RCBWL						x				
RCBWO				x		x				
RCCC	x	x	x	x	x	x	x		x	x
RCH	x	x		x	x	x	x			
RCO		x		x		x	x			
RCOH		x		x		x	x			
RCS						x				x
RCT	x		x					x	x	x
RCW	x	x		x	x	x	x	x		x
RGGG	x	x	x	x	x	x	x		x	x
RGH				x			x			
RHHH	x	x	x	x	x	x	x	x	x	x
RLF					x			x		
RLH				x	x					
RLLL					x	x		x		
ROOO					x	x		x		x
RRRR			x					x		x
RSSS			x		x	x				x
RST			x							x
RTTT	x	x	x		x			x	x	x
RWF				x	x	x				x
RWH		x		x	x	x	x	x		x
RWL				x	x	x		x		
RWLF					x	x		x		
RWOF						x				
RWOH						x				
RWS					x	x				x
RWSF					x	x				x
RWT					x			x	x	x
RWWW	x			x	x	x		x	x	x

REAP = Regional Environment and Agriculture Programming model. See USDA region list in table 7.
Source: USDA, Economic Research Service.