NICHOLAS INSTITUTE REPORT

Greenhouse Gas Emissions and Nitrogen Use in U.S. Agriculture

Historic Trends, Future Projections, and Biofuel Policy Impacts

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Executive Summary

The global agricultural and forestry (AF) sectors are experiencing a fundamental transformation characterized by changing demand and supply factors. Demand shifts are driven by growing populations with changing food preferences, bioenergy expansion efforts, and a rapidly developing market for environmental services, including greenhouse gas (GHG) mitigation and water quality improvement. Supply of AF products is constrained by competition for land within and outside agriculture, highly fluctuating energy and other input costs, changing climate patterns and, in some places, diminishing freshwater supplies. Expanded demand, coupled with supply constraints and global climate change, has increased agricultural commodity prices and their volatility.

Agriculture is among the world's largest sources of GHG emissions and is the largest source of certain types of anthropogenic nitrogen (N) pollution, including nitrous oxide (N_2O), nitrate (NO_3), and ammonia (NH_3) (Robertson and Vitousek 2009). But as a source of renewable fuels production and carbon sequestration, agriculture could also be part of the solution to energy security and climate change problems. Similarly, improved management of agricultural N use could be the key to managing N pollution in surface- and groundwater systems.

If policy makers are to determine how best to develop and implement effective policy interventions to correct environmental problems in agriculture, the critical linkages among demand, supply, land use, N use, and GHG emissions must be captured. To that end, this paper projects GHG emissions and N use from AF practices under baseline and alternative biofuel scenarios in the United States, while accounting for land use competition, production heterogeneity, and a full suite of biofuel production possibilities. Although other studies have examined the impact that policy-induced demand for biofuels could have on the land base, commodity production, and greenhouse gases, this report makes many unique contributions:

1. **Connecting the past, present, and future.** This analysis, like some others, makes projections of land use, commodity production, greenhouse gases, and other key sectoral outcomes several decades into the future under baseline and alternative policy scenarios. However, the report connects these projections to historic observations of these variables to gauge how biofuel expansion policies could modify medium- to long-term trends in agriculture. *The report finds that most current AF trends in land management, N use, and production will continue under business-as-usual technology, economic, and policy conditions associated with full implementation of the current renewable fuels standard (RFS2).*

2. **Quantifying GHG and nitrogen tradeoffs from biofuel policy.** Biofuel expansion places additional demand on all factors of production for feedstocks: land, labor, machinery, fuel, and material inputs such as N-based fertilizers. In addition to producing a greenhouse gas (N_2O) that will negate some of the direct GHG benefits of biofuels, residuals (runoff) from agricultural use of nitrogen are a significant source of water quality problems in the United States. The Forest and Agriculture Sector Optimization Model with Greenhouse Gases (FASOMGHG) used for this study has unique capabilities for examining N effects through changes in agricultural practices. *The report finds that the substantial increase in N use and intensity during the last half of the 20th century has begun and will continue to moderate under RFS2 baseline conditions. Biofuel expansion will lead to an increase in total N use and intensity per acre, but the incremental effects will be small relative to total use and intensity in the aggregate, though larger for some regions and crops than for others. Further integration of* FASOMGHG *with water quality models is needed to fully quantify the water quality co-effects of N use shifts stimulated by biofuels policies.*

3. **Evaluating biofuel policy reform.** The renewable fuels standard calls for 36 billion gallons of biofuel use by 2022. This analysis focuses on possible variations of the standard should policy makers choose to reform it in the near future. Examination of *scenarios in which the full volume of the biofuel mandate is increased and decreased by 25% reveal that the effects of either change are not directly proportional to the magnitude of the change—i.e., a 25% increase (decrease) in biofuel output does not require exactly 25% more (less) land and other inputs. Moreover, input and emissions responses to these scenarios are non-linear; the percentage increase in the responses associated with the 25% larger mandate is greater than the percentage decrease associated with the 25% smaller mandate. One concern raised by the analysis is the attainability of the cellulosic ethanol share of the total mandate, given cellulosic ethanol's infancy relative to conventional (corn-based) ethanol. Thus this report evaluates a potential shifting of the shares to allow a greater portion of the mandate to be met with conventional ethanol. Such a shifting changes the magnitude of achieved emission reductions and the relative net GHG efficiency of reductions once upstream and indirect land use emissions are taken into account.*

4. **Using an updated model of U.S. agriculture and forestry that applies system-wide accounting to assess the net GHG benefits of biofuel use.** To the extent that biofuel policies are justified by GHG concerns, the full net GHG consequences of changes in policy must be understood. In addition to emissions displaced through substitution of biofuels for fossil fuels, research must capture emissions generated by cultivation of the land on which feedstocks are grown, removal and transport of the feedstock to processing plants, and emissions due to land use changes caused by expanding feedstock production. The analysis contained herein captures all of these emissions effects within the United States and thus provides a robust national accounting of biofuel use. Although it uses the model applied by the EPA in its regulatory impact analysis of the RFS2 (FASOMGHG), its results differ from EPA's in several key respects. *It shows that biofuels in combination do have a net GHG-reducing effect, within the United States, and that they are approximately 40% to 60% efficient in achieving emissions reductions. Although this study may understate indirect land use emissions by confining the land use change to the United States, it notably captures some indirect emissions effects not captured in EPA's 2010 analysis of the RFS2 standard. It accomplishes this task by evaluating the combined effect of simultaneously mandating multiple biofuel volumes, which results in an overall GHG displacement efficiency lower than that suggested by analysis of particular biofuel types individually.*

This analysis of agricultural land use, N use and intensity, and commodity price trajectories also yields results that differ from those of the EPA. One reason for this disparity is that the analysis presented here uses a more recent version of FASOMGHG. This version applies new data, allows for N intensification to boost yields, includes new productivity growth and demand projections for agricultural commodities, and reflects updated bioenergy cost parameters to determine the most cost-effective feedstock options. The second reason for the disparity in results is that the two studies take different approaches to calculate the net displacement efficiency. The EPA study examined the displacement efficiency of various fuel types one at a time. This study examines them simultaneously as a group, thereby capturing substitution among the fuel sources as they collectively meet the broad mandate.

Introduction

Recent U.S. policies and energy market conditions have greatly expanded the use of agricultural and forest feedstocks for energy. Because the United States has relatively ample capacity to produce bioenergy feedstocks (biofuels), a switch to biofuels is thought to enhance domestic production of energy and reduce reliance on imports from often-volatile global energy markets, while supporting agricultural prices. Moreover, this switch is thought to benefit the environment, because the use and combustion of fossil fuels currently transfers large amounts of carbon from secure storage below ground to the atmosphere in the form of carbon dioxide (CO_2), a greenhouse gas (GHG) that warms the atmosphere. In isolation, biomass recycles carbon between the atmosphere and temporary biological stocks and thus on net does not raise GHG concentrations—if fossil fuel inputs in its production are ignored.[1] This consideration has led policy makers concerned about climate change and rising energy prices to advance policies to expand biofuel use. Increasing the demand for energy feedstocks raises the demand for agricultural output and the income of agricultural producers, creating further political impetus for such policies.

Can U.S. agriculture meet this surge in biofuel requirements while also meeting the escalating food and fiber demands of a growing population at home and globally? The sector has a long history of meeting demand growth initially by clearing land to raise production and then by tapping into advances in research and development and engaging in more intensive practices that raise the productivity of agricultural land. However, these responses, especially those involving expanded crop areas and intensified management, may push producers up against land, water, and other resource constraints, which could raise the environmental costs of agricultural production. Thus the sustainability of this approach may be questionable. Moreover, efforts ostensibly aimed at decreasing greenhouse gases through biofuel expansion may simply shift emissions into other parts of the landscape with little net reduction in emissions.

This report addresses these concerns by deploying a comprehensive economic model of the U.S. agriculture and forest sectors to project land use, agricultural production and prices, GHG emissions, and emissions of nitrogen from agricultural production under business-as-usual conditions capturing emerging sectoral demands. It then evaluates scenarios that change policy mandates for biofuels to show how each affects production, land use, and GHG and N emissions. The results allow for a direct assessment of different policy alternatives' effect on agricultural markets, land management decisions, and the environment (including the net GHG implications of the biofuel policies).

U.S. agriculture, demand growth, and biofuels

The U.S. agricultural and forestry (AF) sectors are experiencing a fundamental transformation categorized by changing demand, supply, and environmental factors. Demand shifts are driven by growing populations with changing food preferences, bioenergy expansion efforts, and increasing demand for land-based ecosystem services. Supply of AF products is constrained by competition for land within and outside agriculture, highly fluctuating energy input costs, changing climate patterns and, in some places, diminishing freshwater supplies. Expanded demand, coupled with supply constraints, has increased the level and volatility of commodity prices (Trostle et al. 2008).

In the last several years, U.S. policies and increasing energy prices have created a substantial impetus for liquid biofuels. The Energy Policy Act of 2005 established a renewable fuels standard that mandated the use of at least 7.5 billion gallons of biofuels, primarily corn-based ethanol, by 2012—a target met early as a result of rising energy prices. The Energy Independence and Security Act of 2007 (EISA) increased the renewable fuels requirement to 36 billion gallons by 2022. The second mandate allows less than half of the requirement to be met by conventional (typically corn-based) ethanol. Much of the balance is to be met with ethanol from cellulosic sources, which are not as directly competitive with food supply as corn-based ethanol is. The 2005 standard is commonly referred to as RFS1; the pursuant 2007 standard is RFS2.

In addition to the RFS2 mandate, ethanol use is incentivized by the Volumetric Ethanol Excise Tax Credit (VEETC), through which a tax credit of $0.45 is granted to liquid fuel blenders for each gallon of pure ethanol blended with gasoline.[2] Moreover, ethanol producers can obtain production tax credits, further enhancing the ethanol's attractiveness.

1. As discussed further in this report, the relationship among biofuel production, use, and atmospheric fluxes is not quite as simple as the pure no net change alluded to here. The use of fossil energy to produce biofuels and the change in land use required to expand biofuel production both have GHG consequences that must be accounted for as well.
2. The credit must be first used against the blender's own fuel excise tax liability, but the blender can claim a direct payment from the IRS for any excess over that liability (U.S. Department of Energy Alternative Fuels and Advanced Vehicles Data Center, http://www.afdc.energy.gov/afdc/laws/law/US/399).

An ethanol import tariff of 2.5% plus $0.54 per gallon further drives the demand for domestically produced ethanol, keeping lower-cost foreign suppliers from decreasing the domestic market price.

Agriculture as a sink and source of greenhouse gases and nitrogen emissions

As suggested above, agriculture could be a partial solution to atmospheric GHG problems, as a source of renewable fuels production. Moreover, agricultural practices can be modified to remove carbon from the atmosphere and sequester it in soils and vegetation. However, agriculture itself is among the largest sources of GHG emissions and is the largest source of certain types of anthropogenic nitrogen (N) pollution, including nitrous oxide (N_2O), nitrate (NO_3), and ammonia (NH_3).

Environmental issues enter into the equation on both the demand and supply side in important and complex ways. Policies to address these problems must be based on a comprehensive understanding of the role that greenhouse gases, nitrogen, and biofuels play in the agricultural system. They must also be based on understanding of the ways that and how policy options can affect impact and modify outcomes.

Because agriculture currently accounts for 7% to 8% of GHG emissions in the United States (EPA 2009), addressing agricultural emissions should be an important aspect of developing domestic climate policy. Agriculture can provide a significant source of GHG mitigation through terrestrial carbon (CO_2) sequestration, reductions in N_2O emissions, and reductions in methane (CH_4) emissions from rice cultivation and animal agriculture (Murray et al. 2005; Baker et al. 2010).

Increased use of N fertilizer stimulated by bioenergy development or land use intensification presents serious environmental concerns, because potentially harmful N constituents can enter the atmospheric and aquatic environment in many forms through several channels. Nitrous oxide, a byproduct of N fertilizer use, is a greenhouse gas approximately 300 times more potent per unit of weight than carbon dioxide. Along with methane, which is about 21 times as potent as carbon dioxide, nitrous oxide, fossil-based carbon dioxide, and emissions due to land use change are the main constituents of agricultural GHG emissions. Recent literature suggests that N_2O emissions from bioenergy feedstock production might alone be large enough to outweigh GHG benefits to bioenergy (Crutzen et al. 2008). In many parts of the world, nitrogen runoff from agriculture is the predominant source of water pollution, and the problem is worsening (Aneja et al. 2008; Greenhalgh and Sauer 2003). In the United States, Gulf of Mexico hypoxia, caused primarily by upstream agricultural runoff, threatens aquatic ecosystems and critical food supplies (Robertson and Vitousek 2009). Globally, this problem is acute; more than 400 hypoxic zones have been identified, and the total area where hypoxic activity is an issue has increased exponentially since the 1960s (Diaz and Rosenberg 2008). Nitrate contamination in surface water and groundwater systems poses serious health risks and is another environmental cost of agricultural N use (Townsend et al. 2003).

Agriculture is ultimately constrained by the amount of available productive crop, pasture, and forest land—land unused or in other uses. Therefore, continued development in response to energy prices, bioenergy and GHG policies, and associated commodity price surges will likely be manifest both through movement of the extensive margin (conversion of other lands) and through increased production intensity (including higher levels of N application) on AF lands. Thus, N pollution and N_2O emissions can be exacerbated by bioenergy expansion. Water resources will also be pressured by policies that affect land management decisions. In the absence of U.S. biofuel mandates, global water use for irrigation would need to increase by 17% over 2000 levels by 2025 to satisfy growing agricultural demands (de Fraiture et al. 2001).

Purpose and scope of report

If configured effectively, bioenergy production can reduce reliance on fossil fuels (and associated GHG emissions), enhance energy security by increasing domestic fuel production, improve air quality, and provide an additional source of revenue for crop producers. However, the net benefit of bioenergy production is complicated by indirect GHG emissions and other environmental problems, including land clearing, intensified input use, processing, and product transport. Moreover, the rise in income for crop producers comes at the expense of higher prices paid by consumers, raising concerns about whether biofuel expansion policies create food-for-fuel tradeoffs. Given the U.S. role as a major producer and consumer of agricultural commodities, the demand for biofuels could increase prices, cultivation, and production intensity around the world.

Global efforts to reduce GHG emissions and dependence on fossil fuels further complicate matters by altering competition for land. In particular, policy incentives to produce renewable bioenergy, increase afforestation, and reduce deforestation all have the net effect of reducing the amount of land available for conventional agriculture. In turn, programs spawned by such incentives, if not matched by agricultural productivity increases, can lead to higher commodity prices and greater incentives for farmers not directly involved in the programs to increase agricultural lands by alterations in land use. This induced land use change (ILUC) is of particular concern. Land diversion for bioenergy or sequestration may induce land clearing to replace forgone production, generating GHG emissions. Some studies suggest that emissions from ILUC might outweigh the emission reductions achieved by the original mitigation activity (Fargione et al. 2008; Piñeiro et al. 2009; Searchinger et al. 2008). Thus, analysis of the environmental effects and full life-cycle GHG benefits of bioenergy or sequestration should consider land use competition among cropland, forests, native grassland, and conservation lands. Given these concerns, capturing the critical linkages among demand, supply, land use, production intensification, N use, and GHG emissions associated with biofuels policy is important. By understanding these linkages, policy makers can determine how best to develop and implement effective interventions to correct and manage environmental problems in agriculture.

This report projects GHG emissions and N use from AF practices under baseline and alternative biofuel scenarios in the United States while accounting for land use competition, production heterogeneity, and a full suite of biofuel production possibilities. A modeling of this sort allows for novel insights into agricultural GHG emissions, N use, water use, and pollution under various market and policy scenarios. Because the unique simulation scenarios discussed here can affect land management decisions in very different ways on the extensive and intensive margins, they allow for a detailed examination of the net consequences of the renewable fuels standard (RFS2) in relation to alternative scenarios that require more (or less) biofuels from the system. Sensitivity analysis of this kind is important for understanding the direct and indirect environmental consequences of policy.

This report uses an integrated model of U.S. AF sectors to simulate land use change and agricultural production responses to U.S. biofuel expansion efforts. It analyzes policy scenarios that are upward and downward variations on the RFS2 passed by the U.S. Congress as part of the Energy Independence and Security Act of 2007 to determine the effects of relaxing or tightening those restrictions on land use, commodity production, emissions of greenhouse gases, and nitrogen use. Several aspects of this study are unique:

- The connection of past, present, and future trends in land management (including N use) and GHG emissions from U.S. agriculture
- Explicit quantification of the N use impacts of the RFS2 and of deviations from current biofuel legislation
- Evaluation of alternative biofuel growth futures in which mandate levels and biofuel mixes vary
- Comprehensive accounting of the domestic GHG impacts of altering the RFS2 mandate
- Comparison of the key results of this study with those of the EPA's regulatory impact analysis of the RFS2

This study uses an updated version of the U.S. Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG), a model used by the EPA and other organizations for GHG and biofuels analyses. This version also has been enhanced in several important ways:

- Nitrogen intensification options are reflected to account for nitrogen application levels as high as 115% of current levels.
- Technological growth parameters are updated to represent commodity-specific yield growth projections.
- New commodity-specific demand projections based on population and income are facilitated.
- Bioenergy transport and storage cost parameters are updated.

The remainder of this report

- reviews historic trends in U.S. agricultural land use, N use and intensity, and GHG emissions;
- introduces the empirical model used for simulation analysis (FASOMGHG) and discusses baseline assumptions;
- presents results from a baseline simulation in which the RFS2 biofuel mandates are imposed on the AF system;
- explores alternative biofuel scenarios by varying the total volume and the biofuel mix of the mandate;
- uses the results from simulations of these scenarios to assess the net domestic fossil fuel emissions-displacement potential of biofuels as well as land use, N use, and GHG emissions in response to alternative biofuel production levels; and
- discusses key differences between the results of this analysis and those of EPA's RFS2 analysis.

Trends in Agricultural Land Use, GHG Emissions, and Nitrogen Use

To provide context for alternative policy scenarios, current trends in agricultural land use, GHG emissions, and N use are discussed below.

GHG emission sources in U.S. agriculture

Agricultural activities contribute directly to emissions of greenhouse gases through many activities. These activities include fossil fuel use, agricultural soil[3] management, enteric fermentation from the raising of domestic livestock, livestock manure management, rice cultivation, field burning of agricultural residues, liming of soils, and nitrogen fertilization of soils with urea. The primary greenhouse gases emitted through these activities are carbon dioxide, nitrous oxide, and methane. Table 1 and Figure 1 summarize and quantify these emissions sources from 2000 to 2009 in the United States. In 2009, net emissions from the agriculture sector (excluding emissions from farm machinery and buildings and including net increases in agricultural soil carbon stocks) comprised 6.8% of net U.S. emissions (U.S. EPA 2011).

Table 1. U.S. agricultural sector GHG emissions, 2000–2009 (Tg CO_2e)[a]

Gas and source	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Methane (CH_4) emissions	**186.7**	**187.7**	**188.5**	**183.5**	**186.5**	**190.1**	**191.6**	**198.1**	**197.5**	**196.8**
Enteric fermentation	136.5	135.7	136.1	134.3	134.4	136.5	138.8	141	140.6	139.8
Manure management	42.4	44.2	45.4	42.1	44.3	46.6	46.7	50.7	49.4	49.5
Rice cultivation	7.5	7.6	6.8	6.9	7.6	6.8	5.9	6.2	7.2	7.3
Field burning of agricultural residues	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.2
Nitrous oxide (N_2O) emissions	**223.5**	**236.9**	**225.7**	**218.7**	**228.1**	**228**	**226.3**	**226.9**	**228**	**221.9**
Agricultural soil management	206.3	219.8	208.2	201.7	211.1	210.6	208.2	208.7	210	203.9
Manure management	17.1	17	17.4	16.9	16.9	17.3	18	18.1	17.9	17.9
Field burning of agricultural residues	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Carbon dioxide (CO_2) emissions from liming and urea fertilization of soils[b]	**7.5**	**7.8**	**8.5**	**8.3**	**7.6**	**7.9**	**7.9**	**8.2**	**8.7**	**7.8**
Net CO_2 flux from changes in soil carbon stocks	(107.6)	(61.6)	(77.8)	(45.7)	(45.8)	(45.6)	(46.1)	(46.3)	(44.4)	(43.4)
Soil carbon flux occurring on croplands	(27.8)	(8.7)	(6.7)	(11.8)	(12.2)	(12.4)	(13.2)	(13.8)	(12.2)	(11.5)
Soil carbon flux occurring on grasslands	(79.8)	(52.9)	(71.1)	(34.00)	(33.6)	(33.3)	(33.00)	(32.6)	(32.3)	(31.9)
Net GHG emissions from agriculture[c]	**310.1**	**370.8**	**344.9**	**364.8**	**376.4**	**380.4**	**379.7**	**386.9**	**389.8**	**383.1**
Total U.S. GHG emissions	**7112.7**	**6998.6**	**7038.5**	**7065.1**	**7174.8**	**7213.5**	**7166.9**	**7263.4**	**7061.1**	**6633.2**
Net U.S. GHG emissions (sources and sinks[d])	**6536.1**	**6336.8**	**6173.7**	**6059.3**	**6122.3**	**6157.1**	**6102.6**	**6202.5**	**6020.7**	**5618.2**

a. The abbreviation *Tg* denotes the teragram. One teragram = 1 megaton (1 million metric tons).
b. Includes small amounts of emissions from applications of these materials on non-agricultural lands.
c. Does not include emissions from on-farm energy use (i.e., machinery and buildings).
d. Sinks refer to land or land management practices that sequester carbon.
Source: U.S. EPA 2005.

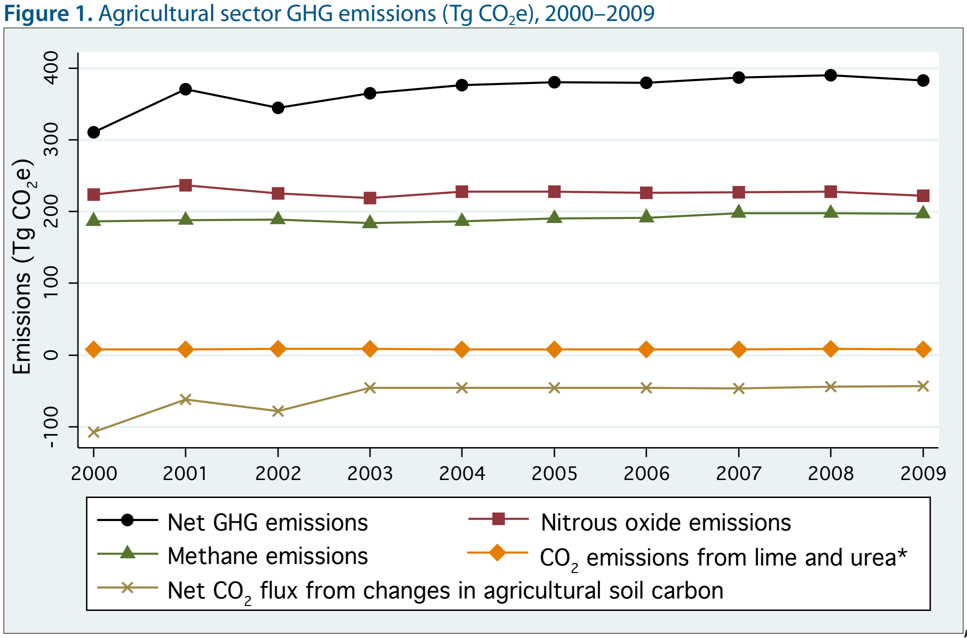
Several agricultural activities and processes can generate greenhouse gases, including the following:

- *Agricultural soil management*—Nitrous oxide is produced directly (in soil) through the natural microbial processes of nitrification and denitrification and indirectly (in the atmosphere and in water bodies) following volatilization of nitrogen into the atmosphere or leaching and runoff of soil nitrogen into ground or surface water. Agricultural processes that add nitrogen to the soil and thereby increase the amount of N_2O emissions include fertilization, application of managed livestock manure, deposition of manure by domesticated animals on pastures, production of nitrogen-fixing crops, retention of crop residues, and drainage and cultivation of organic cropland soils.
- *Enteric fermentation*—Methane is produced during digestion as microbes in an animal's digestive system ferment consumed food—a process referred to as enteric fermentation—releasing methane as a byproduct. Beef cattle are by far the largest contributor of CH_4 emissions from enteric fermentation, accounting for 71% of these emissions in 2009; CH_4 emissions from dairy cattle in the same year accounted for 24% (U.S. EPA 2005).

3. Two broad categories of agricultural soils are recognized. The first, croplands, is a land cover/use category that includes areas used for the production of adapted crops for harvest. This category includes both cultivated and non-cultivated lands. The second, grasslands, is a land use category on which the plant cover is composed principally of grasses, grass-like plants, forbs, or shrubs suitable for grazing and browsing. This category includes both pastures and native rangelands. See U.S. EPA 2011.

- *Manure management*—Management of livestock manure, apart from the application of manure on fields, produces both CH_4 and N_2O emissions. Methane is produced primarily from anaerobic decomposition occurring in liquid storage or treatment systems. N_2O emissions are produced as part of the N cycle through nitrification and denitrification of the organic nitrogen in livestock dung and urine. These processes occur mostly in dry manure handling systems.
- *Rice cultivation*—Rice is cultivated in the United States using a flooded field technique, which produces an anaerobic soil environment. Under these conditions, methane is produced through anaerobic decomposition of soil organic matter by methanogenic bacteria.
- *Field burning of agricultural residues*—The burning of agricultural residues, though not common in the United States, produces nitrous oxide and methane, both of which are released during combustion. Burning of agricultural residues also produces carbon dioxide. However, these emissions are not considered to be a net source of carbon dioxide because the carbon released into the atmosphere is assumed to be reabsorbed during the next growing season.
- *Liming of soils and urea fertilization*—Land managers, mainly in the Mississippi River basin, apply lime, in the form of crushed limestone and dolomite, to agricultural soils to ameliorate acidification. On contact with acid soils, these compounds degrade, releasing carbon dioxide. The use of urea as a fertilizer is another source of agricultural CO_2 emissions. CO_2 emissions from urea are produced in soils as the urea is broken down by microbial enzymes into ammonium and other byproducts.
- *Soil carbon sequestration*—This process is influenced by land use change and farm management practices, as discussed below.

Figure 1. Agricultural sector GHG emissions (Tg CO_2e), 2000–2009



* Includes a relatively small amount of emissions that occur from applications of these materials on non-agricultural lands.
Source: U.S. EPA 2005.

Emissions from fossil fuel use in agriculture

Agricultural practices require direct fossil energy use as well as energy-intensive inputs. Data on emissions from these sources are typically not reported as agricultural emissions, because standard accounting practices include these emissions in the energy sector (through carbon dioxide emitted from the combustion of fossil fuels). Hence, emissions from upstream energy are not reflected in Table 1 and Figure 1. Yet tracking these emissions allows this analysis to better capture the full net effects of biofuel policy. The USDA estimated that emissions from energy consumption in the U.S. agricultural sector (2008) amounted to roughly 71.6 million t CO_2e. Of the total, diesel consumption and electricity consumption each accounted for roughly 38% of total emissions. Gasoline consumption accounted for 11%; the remainder was split between liquefied petroleum gas and natural gas.

Energy is used throughout the cultivation and processing phases of agricultural production. Major sources of *direct* agricultural energy consumption include irrigation systems, grain drying, transportation and distribution of agricultural products, processing operations, and farm or field operations. *Indirect* sources of energy consumption in agriculture include the energy required to produce energy-intensive inputs such as nitrogen fertilizer and crop protection agents. Emissions from ammonia and urea for nitrogenous fertilizer production averaged approximately 12.6 million t CO_2e per year between 2005 and 2009 (U.S. EPA 2011).

Agricultural soil carbon storage

In addition to generating GHG emissions through the activities outlined above, the practice of agriculture can change the amount of carbon stored in agricultural soils. This change arises through anthropogenic activities that together act with natural processes occurring in soils, resulting in a net gain or loss in soil carbon. That gain or loss is referred to as the *net CO_2 flux from changes in soil carbon* in Table 1.

When soils are converted from their native state to agricultural use, an increased amount of the soil's organic matter becomes available to microbial decomposition, resulting in CO_2 emissions and a loss of soil carbon over time. This phenomenon is particularly pronounced in what are known as organic soils, which are soils containing more than 12% to 20% organic carbon by weight (Brady and Weil 1999). Carbon inputs to agricultural soils include decayed plant matter, roots, and organic amendments such as manure and crop residues. Ongoing agricultural practices, including clearing, drainage, tillage, planting, grazing, crop residue management, fertilization, and flooding, affect both organic matter inputs and rates of decomposition, thereby resulting in a net flux of carbon to or from the pool of soil carbon.

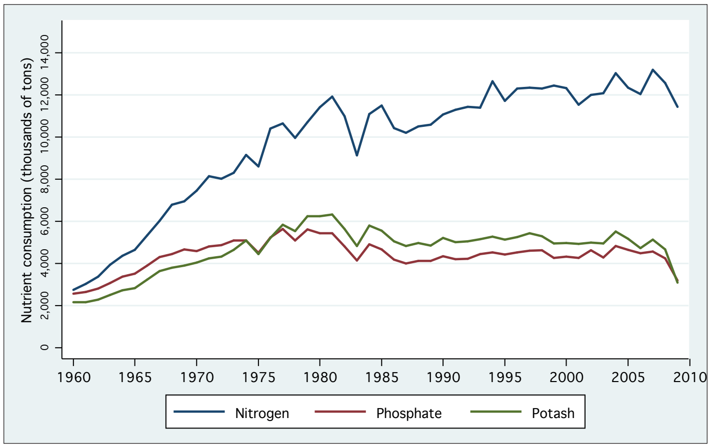
Changes in soil carbon sequestration are influenced primarily by land use change and management choices. Converting grasslands into cultivated cropland, for example, can reduce total soil carbon in grasslands. Likewise, large-scale enrollment of lands in the Conservation Reserve Program can temporarily increase agricultural soil carbon stocks, but re-cultivation of these lands can release a significant amount of the sequestered carbon. How agricultural land is managed also influences the carbon stock. If conservation (strip, ridge) tillage is adopted or tillage is eliminated on cropland, farmers can increase the amount of carbon stored on their farms. Ultimately, however, soil carbon stocks saturate at a new steady state, so the amount of additional soil carbon that can be obtained by changing tillage practices is finite.

During the 2000–2009 period, much of the temporal variability in total net U.S. agricultural-sector GHG emissions stemmed from a decrease in the rate (60%) of soil carbon sequestration on agricultural lands (see Table 1). For croplands, the U.S. EPA attributes the declining soil carbon accumulation rate to the decreasing influence of annual cropland enrolled in the Conservation Reserve Program. Beginning in the 1980s, the amount of land in the program became relatively constant, and soil carbon reached equilibrium. Moreover, adoption of conservation tillage decreased, and land sequestration began reaching equilibrium (Horowitz et al. 2010). For grasslands, changes in weather patterns and associated interaction with land management activities are implicated (U.S. EPA 2005).

Nitrogen use in U.S. agriculture

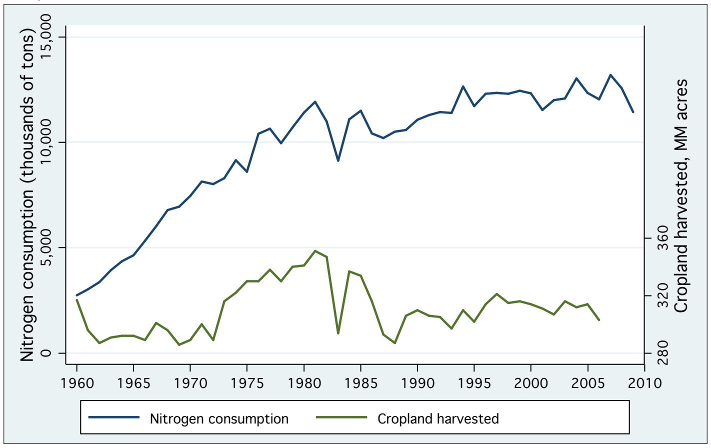
Total application and use of applied nutrients (fertilizer), especially nitrogen, in U.S. agriculture began to increase dramatically in the early 1960s, although the rate of both has stabilized since the mid-1990s. Figure 2 shows roughly a doubling of phosphate and potash application from the early 1960s to the mid-2000s, and about a *fourfold* increase in nitrogen use. Figure 3 shows that N application rates on cropland have risen over time, while the area of cropland in production has remained fairly stable. Accordingly, most of the trend in N use can be attributed to a rise in application intensity per unit area (Figure 4).

Figure 2. U.S. nutrient consumption by type (1,000 nutrient tons), 1960–2009



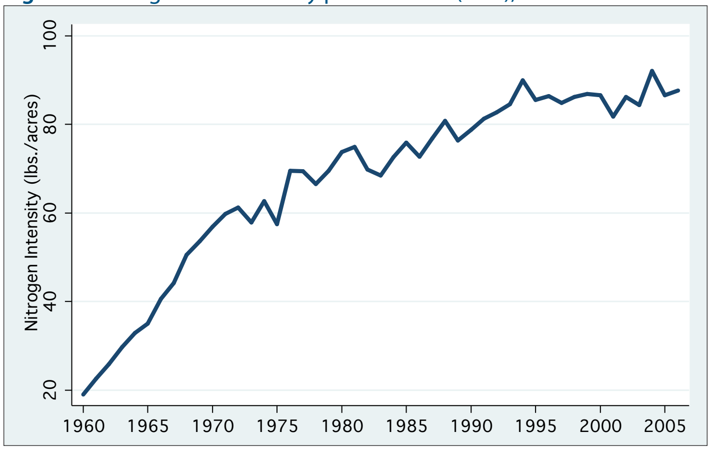
Sources: USDA Economic Research Service; Tennessee Valley Authority; Association of American Plant Food Control Officials; The Fertilizer Institute.

Figure 3. Relationship between harvested acres and total nitrogen use, 1960–2009



Note: Cropland harvested series extends only to 2006.
Sources: USDA Economic Research Service; Tennessee Valley Authority; Association of American Plant Food Control Officials; The Fertilizer Institute.

Figure 4. Nitrogen use intensity per unit area (acre), 1960–2006



Note: Plot shows total U.S. consumption of nitrogen (lbs.) divided by total area of U.S. harvested cropland (acres) over time.
Sources: USDA Economic Research Service; Tennessee Valley Authority; Association of American Plant Food Control Officials; The Fertilizer Institute.

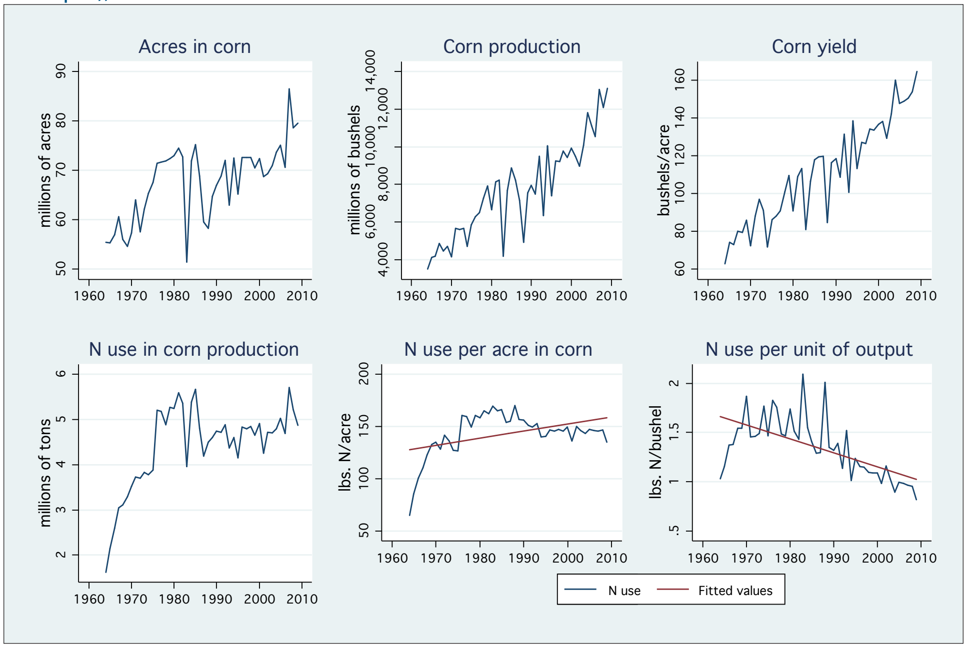
Nitrogen use and intensity by key crop

Figures 5 through 8 illustrate nitrogen application for four key U.S. crops—corn, wheat, soybeans, and cotton—since 1960. Each figure separately shows total production, yield per acre, total N use, N use intensity (per acre), and N use efficiency (output per unit of N use). By far the most substantial user of applied nitrogen is corn, which is of further interest here because of corn ethanol's large role in the U.S. biofuel portfolio. Corn production and yields have risen dramatically, with a more than threefold increase in production and a roughly doubling and a half of per-acre yields. This growth has been driven in part by a substantial increase in N use intensity per acre, especially in the 1960s. Since 1980, a small net decrease in N use for corn and a steep decrease in N use per unit output is evident. Moreover, corn output has risen faster than N use. However, improvement in the N use efficiency of other crops, such as soybeans and cotton, is less than that of corn. In the case of wheat, N application rates have outpaced yield growth, indicating a decrease in N use efficiency (i.e., nitrogen per unit output).

Together, these patterns indicate a period of substantial and continued reliance on N use as an agricultural input. By and large, this use has stabilized and has corresponded with an increase in per-acre yields that has helped reduce the amount of land required for a given level of output. But N use comes with environmental consequences in the form of increased N_2O emissions and the introduction of nitrogen to surface and groundwater, where it can degrade water quality. A full analysis of the water quality implications of increased N use from agriculture is beyond this report's scope.[4] However, the report includes projections of future N use under baseline conditions and under variations of U.S. biofuel policy as a proxy for potential environmental consequences of policy alternatives.

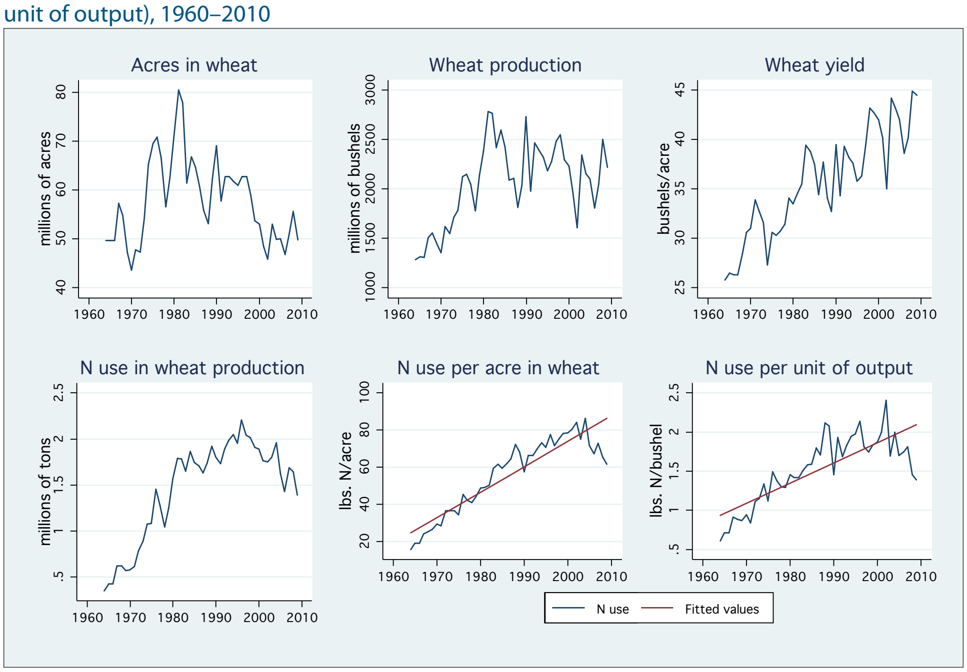
4. See Pattanayak et al. 2005 for an example of policy-induced changes in nitrogen and water quality.

Figure 5. U.S. corn production, yield, nitrogen use, and nitrogen use intensity (per acre and unit of output), 1964–2009



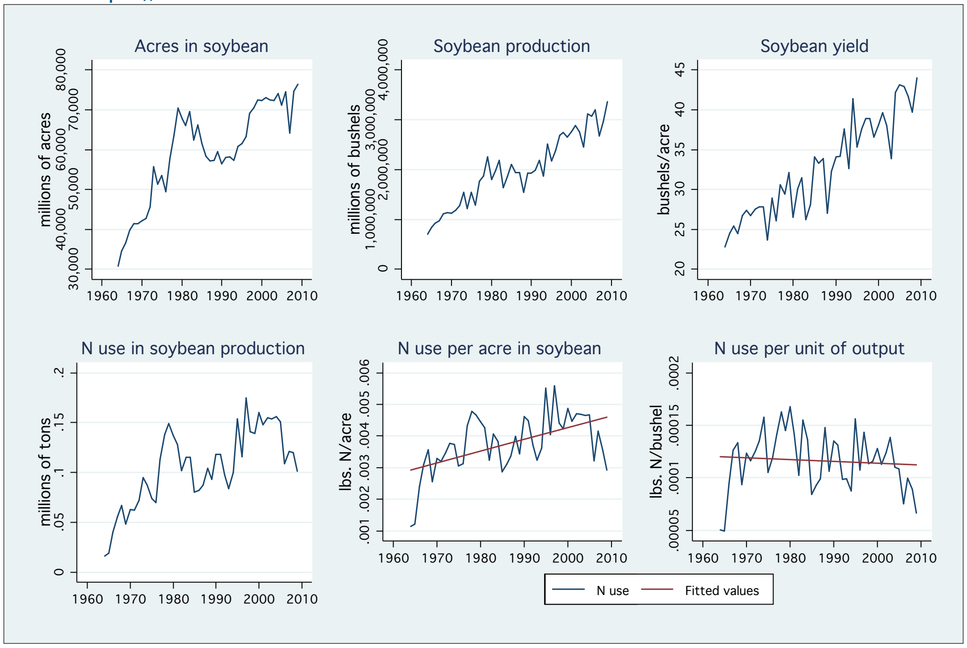
Source: USDA Economic Research Service.

Figure 6. U.S. wheat production, yield, nitrogen use, and nitrogen use intensity (per acre and unit of output), 1960–2010



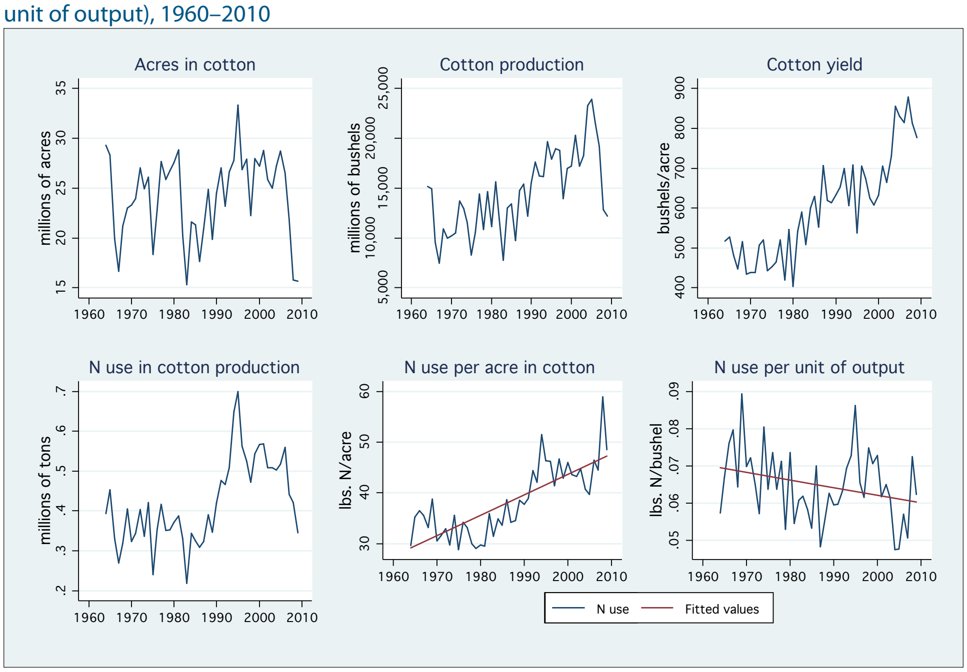
Source: USDA Economic Research Service.

Figure 7. U.S. soybean production, yield, nitrogen use, and nitrogen use intensity (per acre and unit of output), 1960–2010



Source: USDA Economic Research Service.

Figure 8. U.S. cotton production, yield, nitrogen use, and nitrogen use intensity (per acre and unit of output), 1960–2010



Source: USDA Economic Research Service.

Empirical Model: U.S. Forest and Agricultural Sector Optimization Model with Greenhouse Gases

This analysis applies an updated and enhanced version of the U.S. Forest and Agricultural Sector Optimization Model with Greenhouse Gases (FASOMGHG). FASOMGHG is a dynamic partial equilibrium economic model of the U.S. AF sectors that has been applied in a wide range of policy settings. FASOMGHG explicitly models conventional commodity production and resource use from AF practices, and it includes many biofuel- and bioenergy-processing options (Murray et al. 2005; Schneider and McCarl 2007).

FASOMGHG uses a price-endogenous mathematical programming approach developed by Takayama and Judge (1973) and McCarl and Spreen (1980). In this approach, an optimization problem is defined and solved using a set of equations that depict competitive market equilibrium under a given set of supply-and-demand conditions. The objective function is the summation of all areas beneath product demand curves minus the sum of all areas under import and factor supply curves. This objective function criterion maximizes total intertemporal welfare across the AF sectors, or the sum of producer surplus (area below the equilibrium price) and consumer surplus (area above the equilibrium price).

Commodity and most factor prices are endogenous, that is, determined by the supply-and-demand relationships in all markets included within the model. The price-endogenous model accounts for market adjustments to systematic policy shocks by depicting changes in equilibrium prices and the supplied quantities of all primary and secondary commodities. Because commodity markets within agriculture and forestry are highly interdependent, a systematic shock that disrupts the optimal production portfolio of one commodity (e.g., corn) can cycle through other primary or secondary commodity markets (such as ethanol and livestock, which use corn, or corn substitutes such as alternative feed grains).

FASOMGHG contains near-comprehensive GHG accounting within the AF sectors, including biological sequestration of carbon in agricultural soils and forest stands, emissions from alternative crop and livestock production practices, and emissions from bioenergy feedstock transportation and production. The gases represented are carbon dioxide, methane, and nitrous oxide. Forest carbon balances are tracked using a methodology consistent with the forest carbon accounting system, FORCARB (Birdsey et al. 2000). Forest carbon is tracked in trees, soils, understory, and end products. Forest management offset opportunities are endogenously modeled in FASOMGHG and include avoided deforestation, rotation extensions, altered species mix, partial thinning, and reforestation.[5]

FASOMGHG accounts for a comprehensive range of land use categories consistent with land classifications. The model allows for explicit land use competition among cropland, grazing lands, conservation lands (CRP), and forests on the basis of expected returns to alternative uses over dynamic intervals. This capability allows simulation of potential land-use-change impacts of policy drivers that increase the relative value of land holdings in a particular use or of multiple uses simultaneously (Alig et al. 1998; Alig et al. 2010).

FASOMGHG includes most sources of cropland, grazing lands, rangeland, and private timberland throughout the conterminous United States.[6] The model tracks both area used for production and idled (if any) within each land category. In addition, the model tracks the movement of forest and agricultural lands into developed uses. The recently updated land use categorization system accounts for a comprehensive range of land use categories. The system now includes expanded coverage of pasturelands to explicitly represent multiple forms of public and private grazing lands (each with different animal unit month [AUM] grazing potential per unit of land). The new land use categorization system includes sources of cropland, cropland pasture, pasture, rangeland, public and privately grazed forest, and managed timberland. The FASOMGHG land base was developed on the basis of land classifications from multiple sources, including the Natural Resources Inventory (USDA NRCS 2003; USDA NRCS 2007), the Major Land Use Database (USDA ERS 2010), and agricultural census (USDA NASS 2010).

FASOMGHG is disaggregated into 63 minor production units in the lower 48 states and 11 main agri-forestry regions. Table 1 displays all major regions with accompanying production units. With the exception of the Great Plains and Southern Plains (which includes most of Texas and Oklahoma), these regions are candidates for crop and forestry production opportunities.

5. Further information on forest GHG accounting in FASOMGHG can be found in Beach et al. 2010.
6. Although public timberland is not explicitly modeled because the focus of the model is on private decision-maker responses to changing incentives, FASOMGHG includes an exogenous timber supply from public forestlands.

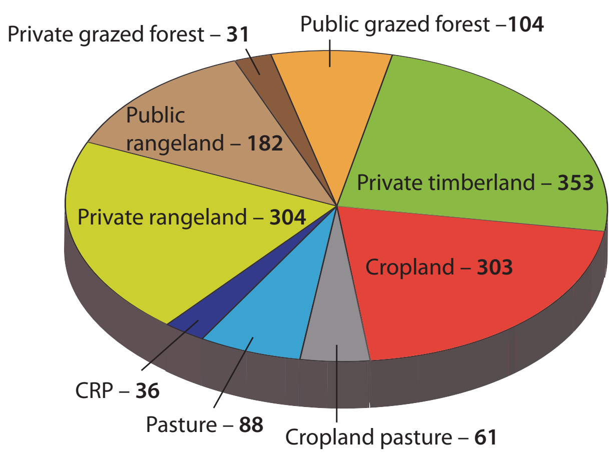
Table 2. FASOMGHG regional aggregation (definition and geographic scope)

Aggregated region	Market region	Production region (states/subregions)
Northeast	Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia
Midwest	Lake States	Michigan, Minnesota, Wisconsin
Midwest	Corn Belt	All regions in Illinois, Indiana, Iowa, Missouri, Ohio (Illinois N, Illinois S, Indiana N, Indiana S, Iowa W, Iowa Cent, Iowa NE, Iowa S, Ohio NW, Ohio S, Ohio NE)
Plains	Great Plains	Kansas, Nebraska, North Dakota, South Dakota
Southeast	Southeast	Virginia, North Carolina, South Carolina, Georgia, Florida
Southeast	South Central	Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Tennessee, Eastern Texas
Plains	Southwest (agriculture only)	Oklahoma, all but East Texas (Texas High Plains, Texas Rolling Plains, Texas Central Blacklands, Texas Edwards Plateau, Texas Coastal Bend, Texas South, Texas Trans Pecos)
Western United States	Rocky Mountains	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming
Western United States	Pacific Southwest	All regions in California (California N, California S)
Western United States	Pacific Northwest—East side (agriculture only)	Oregon and Washington, east of the Cascade mountain range
Western United States	Pacific Northwest—West side (forestry only)	Oregon and Washington, west of the Cascade mountain range

Land-to-development transfers are modeled on a regional basis by land type and are drawn from recent data prepared for the 2010 Resources Planning Act (RPA) Assessment (Alig et al. 2009). These parameters point to an AF land base that is decreasing in the baseline due to development pressures. Accounting for land-to-development pressures in a AF sectoral modeling framework is important, because varying levels of development pressures can affect land use competition between agriculture and forestry, GHG mitigation potential, and commodity prices.[7]

Figure 9 shows the base-year land allocation in FASOMGHG at the national level across each of the land categories defined above.

Figure 9. Baseline FASOMGHG land use by category (in millions of acres)



7. See Alig et al. 2010 for additional discussion.

The baseline used in this study incorporates dynamic trends in important exogenous variables using a variety of data. These data include energy prices (AEO 2009), demand and yield productivity growth consistent with historic and projected trends using USDA NASS data (USDA NASS various years) and technological progress in bioenergy processing.[8] Parameters defining land use and land use change potential are modeled after the Natural Resources Inventory (USDA NRCS 2007), and the USDA Major Land Use Data-Base (USDA ERS 2007). The baseline is estimated over a 70-year horizon (2000 to 2070) to fully capture changes in forestry investment decisions and the dynamic interactions of AF land use.

The RFS2 policy baseline incorporates the latest version of the EISA-RFS rules (referred to as RFS2) into the model by setting minimum and maximum biofuel production requirements for ethanol, cellulosic ethanol, and biodiesel at mandated levels (Table 3). The model is allowed to choose an optimal AF feedstock mix to satisfy these constraints. Requirements are phased in over time until a total of approximately 30 billion gallons of ethanol, cellulosic ethanol, and biodiesel annually is reached in 2022.[9] As in the baseline, long-term ethanol production is locked in at RFS-mandated levels beyond 2022, given uncertainties in future energy demand projections and transportation sector infrastructure.

In this study, implementation of the RFS2 mandates mimics EPA legislative requirements as well as modeling assumptions (and outcomes) from EPA's RFS2 analysis. Corn ethanol is locked in at 15 billion gallons per year, and roughly 16.67% of total grain ethanol production is assumed to come from corn wet-mill processing. Remaining grain ethanol is not assumed to come from corn, though only a very small portion (30–50 million gallons) is currently produced from barley or sweet sorghum. Total cellulosic ethanol is set at 13.7 billion gallons per year at the pinnacle of the RFS2. This constraint is based on the RFS2 requirement of 16 billion gallons of cellulosic or "advanced" biofuels and on the EPA assumption that 2.3 billion gallons of this requirement will be satisfied with municipal and industrial waste-derived biofuels. No restrictions on feedstock mix for cellulosic ethanol are imposed.

Table 3. EISA-RFS2 biofuel mandates (billion gallons per year)

	2010	2015	2020	2025
Crop ethanol	12.94	15.0	15.0	15.0
Cellulosic ethanol (agriculture and forestry)	0.44	4.7	13.7	13.7
Cellulosic ethanol (forest)	0.0	0.1	0.1	0.1
Total biodiesel	0.86	1.32	1.47	1.47

Baseline Projections to 2030

Baseline simulations of the RFS2 legislation indicate the potential resource allocation and land management trends resulting from a regime characterized by the RFS2 requirements for biofuels, in addition to business-as-usual commodity demand and supply. The RFS2 requirements for ethanol, cellulosic ethanol, and biodiesel are satisfied through a mix of feedstocks. In 2025, after the RFS2 reaches maturity, corn ethanol is produced from dry- and wet-mill processing: approximately 12.5 billion gallons per year (bgy) are produced from dry-mill processing, and 2.5 bgy, from wet-mill processing. Cellulosic feedstocks are produced from a variety of sources, including switchgrass (8.4 bgy), hybrid poplar (0.59 bgy), sugarcane bagasse (0.58 bgy), corn stover (3 bgy), and hardwood and softwood pulp and milling residues. By contrast, in EPA's RFS2 analysis, feedstock mix is primarily based on switchgrass (7.9 bgy), corn stover (4.9 bgy), and other crop and forestry residues. The baseline is simulated over the 2000–2070 time horizon. Although the focus of this discussion is on results for the 2010–2030 time frame, the longer horizon is needed to accurately simulate forestry investment decisions and land use decisions that occur in a dynamic fashion.

Baseline market conditions

Table 4 displays baseline commodity prices (in decadal averages) for several important agricultural commodities. Baseline prices increase over the first two decades of the simulation horizon under the influence of the RFS2 (relative to the historic 2000 base period) and other demand drivers. The latter include expected population and income growth. In the simulation, 2010 is a projection period, not an observation.

8. See Beach and McCarl 2010 for more detail on bioenergy processing.
9. The total is reached, in part, through allowances for imported ethanol and other "advanced" biofuels from non-AF biomass.

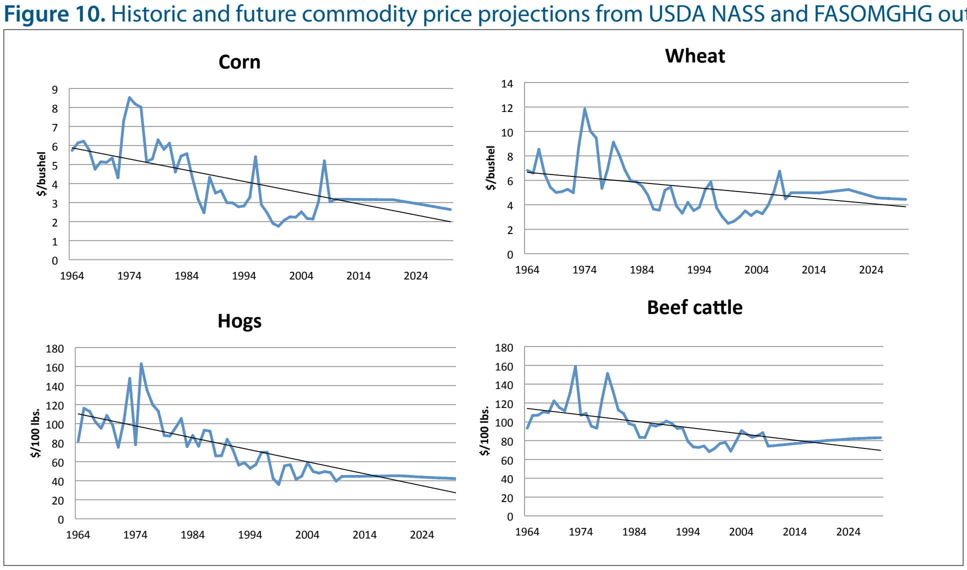
Prices of corn, wheat, and soybeans immediately increase, though they begin to taper as the RFS2 reaches maturity and as productivity enhancements begin to outpace demand growth.[10] When the RFS2 matures in 2022, the corn price is projected to be roughly $3.15 per bushel, which is significantly lower than the EPA estimate (though endogenous corn N intensification allows for greater productivity, hence relaxing the corn price effects of the RFS2 relative to the EPA estimate). Soybean prices are projected to reach approximately $9.19 per bushel; the EPA estimate is $10.87 per bushel. Higher grain prices increase the costs of livestock feeds, which drive up meat prices. Fed-beef and chicken prices continue to rise throughout the horizon, reflecting rising demand projections for meat, both domestically and abroad. Cotton prices rise substantially, reflecting anticipated demand growth. In general, commodity prices initially increase, reflecting a baseline that is shocked by a variety of factors (including the biofuel mandate). Later, these prices decrease (or slightly increase), reflecting historic trends.

Table 4. Baseline commodity price projections (2004 dollars)

	2000	2010	2020	2030
Corn ($/bushel)	2.09	3.18	3.15	2.89
Soybeans ($/bushel)	6.11	9.03	9.19	8.46
Wheat ($/bushel)	2.99	5.93	6.01	5.56
Rice ($/bushel)	6.42	7.33	5.82	4.70
Cotton ($/bale)	206.44	206.16	263.81	297.55
Fed beef ($/cwt)	115.59	122.82	131.81	136.70
Pork ($/cwt)	60.83	61.01	62.20	58.04
Chicken ($/cwt)	68.11	63.90	71.10	71.61

In general, price projections reflect past commodity price trends. Figure 10 shows projections of real (2004 dollars) prices for key commodities through 2030. These prices for corn and wheat remain relatively flat or modestly decrease over time after increasing initially. This result may appear at odds with recent (e.g., 2008–2011) commodity price spikes, but consider that a structural economic model such as FASOMGHG is best suited to project long-term price trends, not to predict short-run outcomes determined by a variety of short-term shocks to the market. Moreover, Figure 10 shows that projections are largely consistent with the long-run decrease in agricultural commodity prices observed over time. (A slight increase is observed over time for the price of beef cattle, which is driven by anticipated demand growth).

Figure 10. Historic and future commodity price projections from USDA NASS and FASOMGHG output



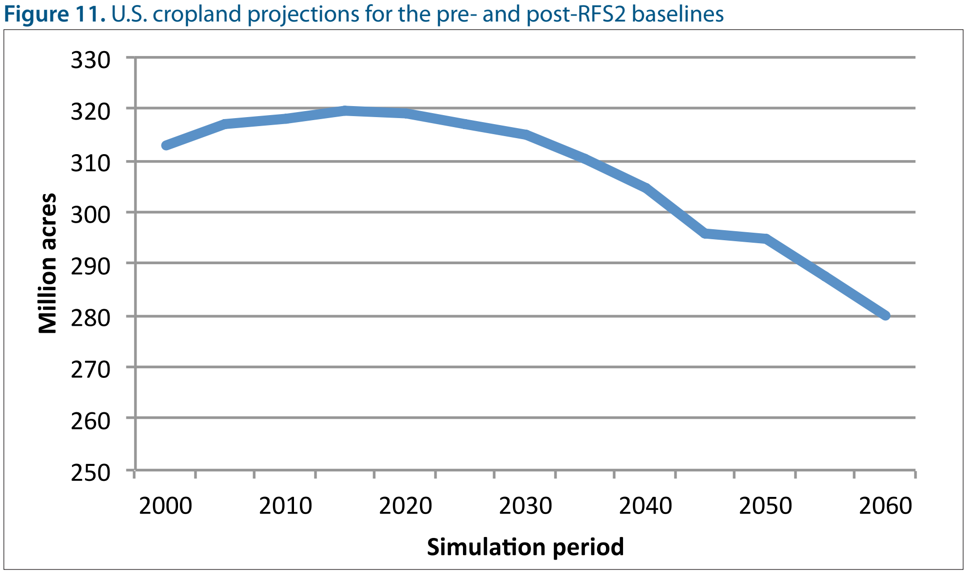
10. FASOMGHG productivity growth parameters are commodity specific and were estimated using USDA NASS observed yields from 1960 to 2009. The estimation procedure tested the statistical fit of multiple functional forms, with and without structural break points in time, given that productivity growth for many commodities has begun to taper since the 1980s.

RFS2 baseline land use projections

The following land use results are displayed relative to the 2000 base period. FASOMGHG is calibrated to the 2000 and 2005 historic periods, which represent average conditions from 2000 to 2004 and 2005 to 2009, respectively. The 2010 period is simulated and should be interpreted as average projected conditions between 2010 and 2014, and not as a solution that attempts to replicate land use and market conditions observed in 2010. The following land use results are evaluated in reference to the 2000 base period to yield projected deviations from historically observed AF land use trends.

U.S. cropland expands from the base year (2000) level by approximately 2%, approaching 320 million acres at the height of the RFS2 mandates in the 2020 time period. The initial rise in cropland is attributable to several simultaneous factors, including biofuel mandates and rising export demand for some primary agricultural commodities (such as rice and beef cattle). As the mandates are held constant beyond the maturation date of the RFS2 (2022), yield growth outpaces the demand increases and total use of cropland as a primary input begins to decline. This trend, coupled with transfers of land to developed uses, causes the U.S. cropland base to shrink over time, as indicated by Figure 11. The Great Plains and Southeast regions experience the greatest increases in total cropland—3% and 5%, respectively—relative to the base period (2000). This expansion occurs as the bulk of the dedicated energy crops for cellulosic ethanol production are grown in the Great Plains and Midwest. Simultaneously, production of conventional commodities (including corn, soybeans, and cotton) increases in the southeastern United States. This expansion is an indirect implication of additional energy production as traditional crop production (and associated emissions) shift elsewhere within the country. Peak cropland levels (320 million acres) are approximately 2% higher than the EPA estimate (314 million acres) due to increased reliance on energy crops (instead of crop residues) for cellulosic ethanol.

Figure 11. U.S. cropland projections for the pre- and post-RFS2 baselines



Over the long run, land used for AF production decreases due to productivity improvements and the bidding away of land for development.[11] Figure 12 displays cumulative land use transitions by major land use account. Forestry experiences the greatest decrease relative to the base period (2000). Cropland pasture also decreases significantly over time. Development transfers total approximately 40 million acres—approximately 13 million acres from cropland, 22.7 million acres from forestry, and the remainder from range and pastureland—by 2030. However, as Figure 12 shows, cropland initially expands, implying that pasture and forests are moving into crop production at rates that surpass development transfers.

11. FASOMGHG includes exogenous projections of land use, consistent with the most recent Resources Planning Act (RPA) Assessment by the U.S. Forest Service (Alig et al. 2010) Between 1982 and 2007, the U.S. agricultural and forestry land base lost approximately 40 million acres to development, or roughly 1.6 million acres per year (USDA NRCS 2007). Under FASOMGHG projections, the sectors combined are expected to lose an additional 1.33 million acres a year by 2035.

Figure 12. Cumulative projected land use transitions by major land use account

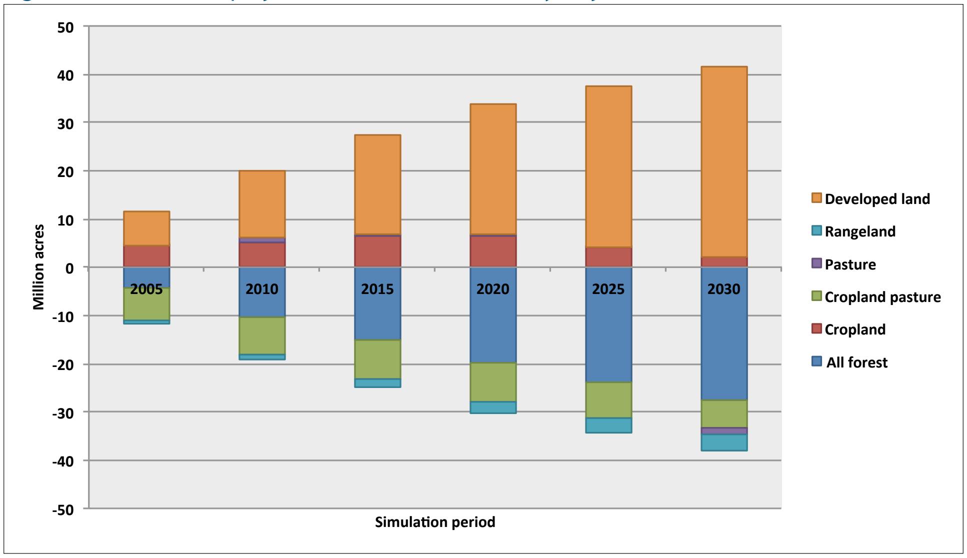


Table 5 displays cumulative land use transfers by type (not including development) by 2020 and 2030. In the early part of this simulation horizon, cropland acreage expands as a significant area of land in alternative uses is cultivated, including roughly 10 million acres of cumulative deforestation and an additional 10 million acres of cropland pasture recultivation. An additional 3.4 million acres of land initially enrolled in the Conservation Reserve Program (CRP) is also projected to be cultivated.[12] In summary, transfers of land into crop production from alternative uses more than compensate for cropland lost to development and thus, on net, crop area grows. Deforestation (including forest-to-pasture movement) continues to expand from 2020 to 2030, increasing agricultural emissions and loss of ecosystem services associated with forestland.

Table 5. Cumulative land transfers by type

	Cumulative LUC by 2020	Cumulative LUC by 2030
Forest converted to cropland	10.42	12.85
Forest converted to pasture	5.00	5.54
Cropland pasture converted to cropland	10.27	10.27
CRP converted to cropland	3.41	3.41
Cropland converted to cropland pasture	0.26	3.68

Examination of crop acreage by commodity (see Table 6) reveals that the greatest initial shift occurs in corn and soybean acreage, which grows with the volume of the corn ethanol and biodiesel mandate in the initial simulation periods. Much of this corn and soybean expansion comes at the expense of wheat acreage, which decreases by approximately 20% in the first decade of the simulation horizon (and continues to decrease in later periods). However, once the mandated peak volumes of conventional ethanol and biodiesel are reached in 2015, corn and soybean acreage begins to decrease. This trend is attributed to productivity improvements and crop mix shifts to dedicated energy crops and other conventional commodities with high growth in export demand and relatively low growth in productivity, such as rice and cotton.

Dedicated energy-crop acreage, which is used to meet cellulosic ethanol requirements, increases rapidly, exceeding 20 million acres in 2020 (or roughly 6.6% of the total cropland base for that period). By 2020, this dedicated energy-cropped area includes approximately 12 million acres of switchgrass in the Great Plains, 9 million acres of switchgrass in the Midwest, and more than 1 million acres of willow in the western United States; hybrid poplar plantations comprise a very small share of the total at 0.2 million acres. Energy-cropped acreage expands greatly in the Southeast as well, but only in later periods of the simulation horizon (2030 and beyond).

12. In this simulation, the CRP is maintained at 32 million acres, consistent with 2008 Farm Bill targets. This constraint is not binding in the baseline, meaning that the base CRP area (~37 million acres), less total CRP reversion to crop production, does not reach the 32 million acre threshold. Allowing additional CRP acreage back into production could theoretically reduce deforestation and pasture cultivation rates, but the majority of cropland expansion occurs in regions with limited CRP participation, such as the southeastern United States.

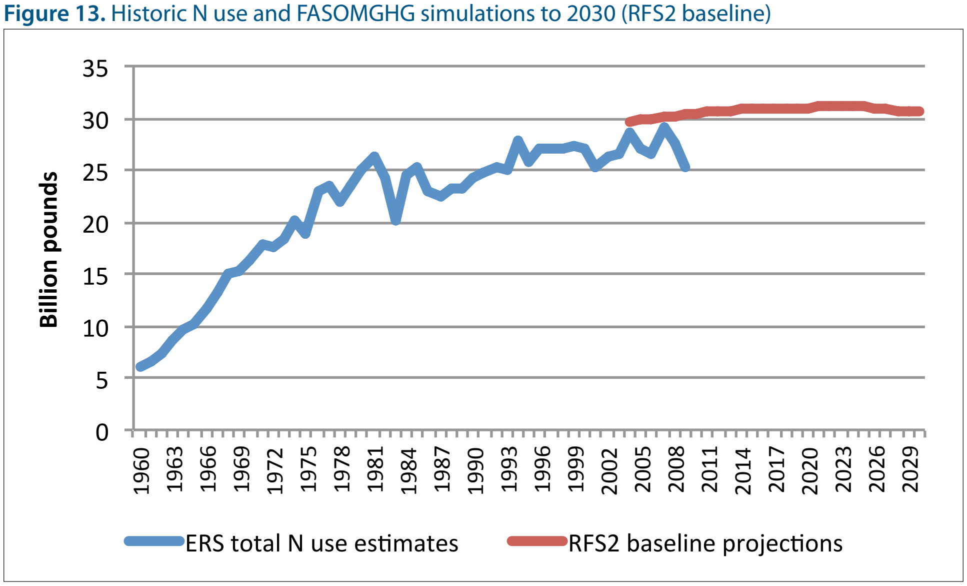
Table 6. Baseline land use projections by major crop (million acres, decadal averages)

	2000	2010	2020	2030
Corn	75.98	82.03	72.62	65.61
Soybeans	66.37	73.28	68.09	65.78
Wheat	61.69	49.29	43.99	42.18
Cotton	14.17	16.61	18.55	18.69
Hay	50.04	53.47	51.74	56.95
Rice	3.75	4.34	5.08	5.17
Oats	3.43	4.04	3.69	3.85
Energy crops	0.00	2.61	22.67	21.24

Nitrogen use and intensity projections

In general, baseline N use projections align with historically observed trends in nutrient application. Figure 13 plots observed N use totals with FASOMGHG baseline projections of N use. It indicates a slowing expansion in total N use. Total N use peaks in 2020 at 31.2 billion pounds, higher than the EPA estimate of 27.7 billion pounds. This 12.6% difference can be explained by a couple of factors. First, this analysis points to an additional 1% to 3% in total cropped acreage, which boosts total input use. Second, it incorporates the 115% N intensification option. Therefore, the model is intensifying N use under the baseline for the higher accompanying yields. In fact, in the baseline, N application for corn is at 115% of base-level application for all regions.

Figure 13. Historic N use and FASOMGHG simulations to 2030 (RFS2 baseline)

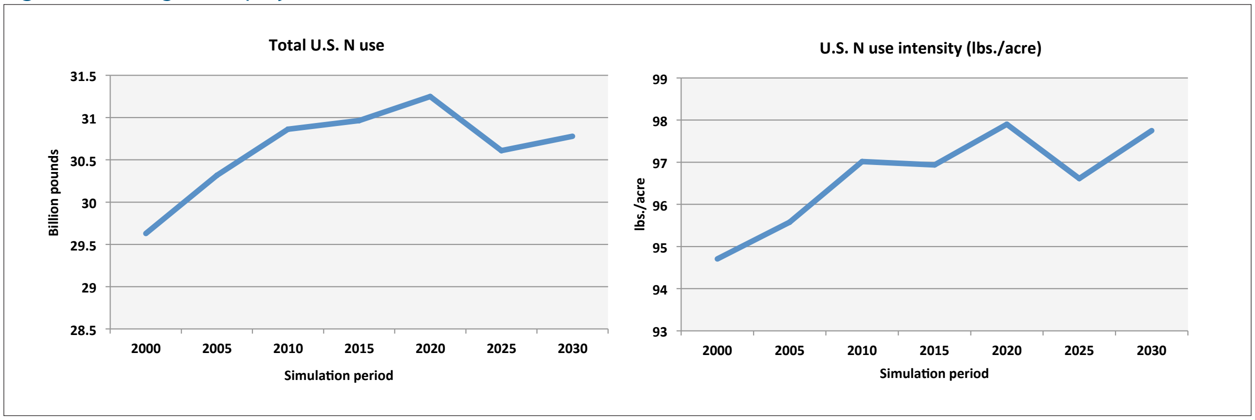


A change in total N use can occur in several ways. The first is through cropland expansion. As land moves to the extensive margin, more inputs are needed for crop production, and thus new acreage requires additional nutrient application. The second is through shifts in the national crop mix, which are influenced by biofuel mandates. A shift to high N-input crops such as corn and wheat could increase total N use and average intensity per acre, whereas a shift to N-fixing crops like soybeans or to low-input energy crops could reduce total N use. The third way a change in total N use can occur is through input intensification, which has driven much productivity growth. FASOMGHG includes parameters reflecting *exogenous (predetermined) rates of yield growth*. These yield-growth rates are *coupled with elasticity parameters that require additional input use as yields increase* (i.e., an increase in inputs required to achieve successively higher crop yields). Consistent with observed trends in crop management, the model uses crop-specific input-use elasticities to define the percentage change in input use necessary to achieve a percentage increase in yields.[13] Finally, FASOMGHG reflects *endogenous* N use intensification by choosing among alternative N application rates for each region/crop combination entering the solution set, including base application, plus 85%, 70% and 115%of the baseline use rate.

13. The N use elasticity for corn is set at zero, because the N use efficiency of corn has increased dramatically, requiring lower levels of N application per acre.

Like land use, baseline nutrient application increases in the beginning of the time horizon as production expands (see left-hand side of Figure 14). Additionally, N use intensity per unit area rises over time relative to the base period. This trend implies that total N use rises more rapidly than cropland expands, or that the *intensive* margin shift for N use is more pronounced than *extensive* margin land-use shifts.

Figure 14. Nitrogen use projections for the RFS2 baseline



Expansion and intensification in N use over time varies by region, as shown in Table 7 and Table 8. The greatest rates of expansion and intensification occur in the Midwest. Although these rates begin to subside by 2030, they remain a near-term policy concern in the Midwest, because this region is a predominant source of N pollution that contributes to the worsening of Gulf Coast hypoxia and fears about ground water infiltration. N use and intensity also increase substantially in the Great Plains, which has waterways draining into the Gulf. N use and intensity decrease in the southeastern United States, in part due to a shift in N-fixing soybean and low-input energy crop acreage. Such a shift could ameliorate water quality concerns of N use expansion in the Midwest. However, to fully evaluate net water quality implications of regional shifts in N use and intensity, simulation output must be linked to a detailed U.S. hydrologic model explicitly reflecting water quality considerations (Pattanayak et al. 2005). In summary, total N use and intensity per acre are expected to rise modestly, though this change varies substantially by region, depending on land use and crop mix decisions.

Table 7. Absolute and percent changes in total N use (relative to the 2000 base period)

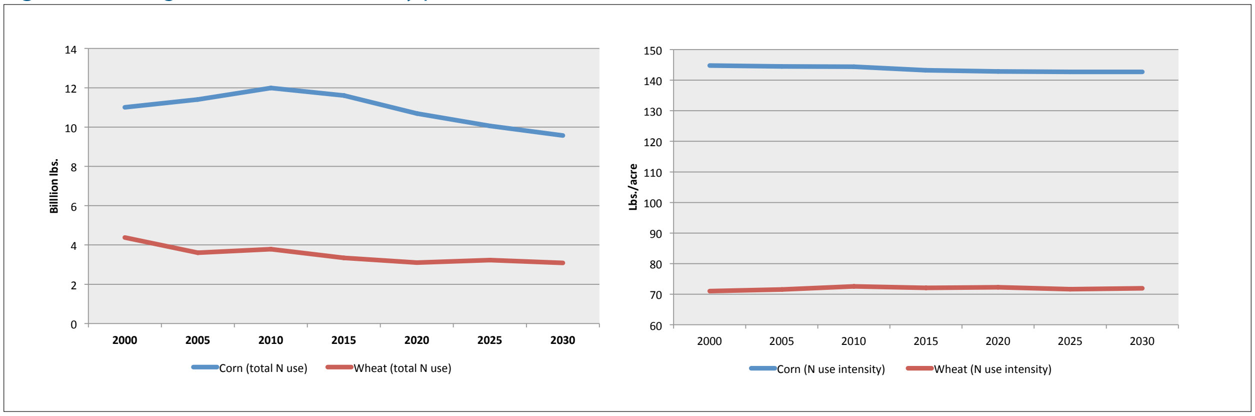
	Absolute change 2020 (million lbs. of N applied)	Percent change by 2020	Absolute change 2030 (million lbs. of N applied)	Percent change by 2030
Midwest	1121.27	10.44%	552.37	5.14%
Northeast	0.16	0.01%	76.45	6.11%
Great Plains	585.66	7.01%	636.10	7.61%
Southeast	-158.53	-3.73%	-110.14	-2.59%
Western United States	71.42	1.42%	-5.70	-0.11%
Total United States	**1619.98**	**5.47%**	**1149.08**	**3.88%**

Table 8. Absolute and percent changes in N use intensity per acre (relative to the 2000 base period)

	Absolute change 2020 (lbs. of N per acre)	Percent change by 2020	Absolute change 2030 (lbs. of N per acre)	Percent change by 2030
Midwest	8.18	9.08%	6.98	7.75%
Northeast	-5.23	-5.18%	2.19	2.16%
Great Plains	3.01	3.40%	3.90	4.41%
Southeast	-6.31	-6.89%	-7.25	-7.92%
Western United States	3.98	3.19%	3.54	2.84%
Total United States	**3.98**	**3.19%**	**3.54**	**2.84%**

Crop-specific changes in N use vary little over time, as indicated by Figure 15, which represents N use and intensity for the two largest users of N fertilizers (corn and wheat). N use and intensity for corn production actually decrease over time, consistent with recently observed trends. Total N use for wheat decreases as well, and intensity per acre remains relatively flat. These results imply that the RFS2 is not a significant driver of corn or wheat N use. Given that corn and wheat are the two largest N users, total N use does not rise substantially. However, changes in crop mix change the composition of N use. N use for dedicated energy crops expands greatly, increasing demand for non-energy conventional commodities such as cotton. Rice also increases N use in the baseline. Total N use increases in the baseline, implying that the additional N burden is coming from other conventional and bioenergy crops for which production expands. For example, cotton acreage expands in the baseline, and by 2030, N use for cotton expands by approximately 0.54 billion pounds (a 40% increase from the base period). Switchgrass expands by more than 20 million acres and uses an additional 1.79 billion pounds of nitrogen. Rice expansion requires an additional 0.24 billion pounds of nitrogen (a 38% increase from the base period).

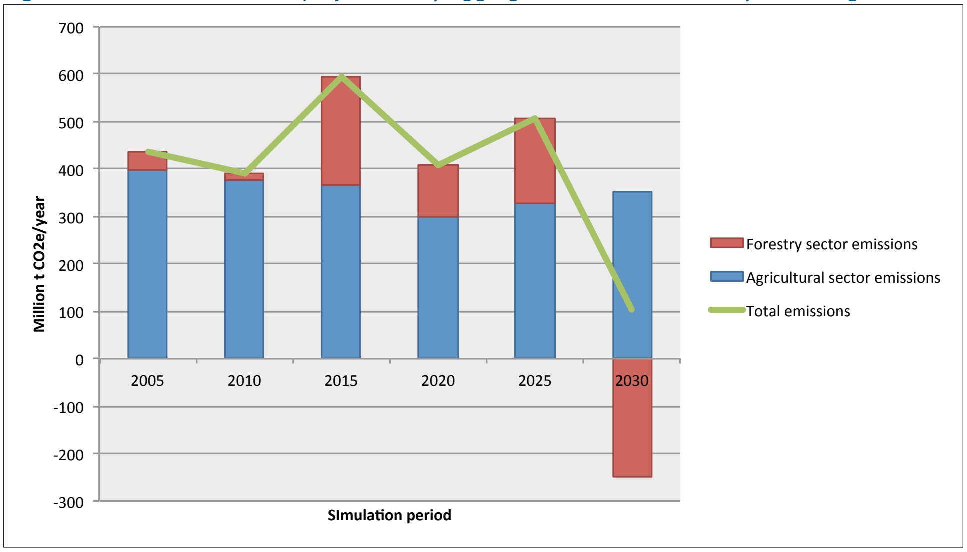
Figure 15. Changes in N use and intensity per acre for corn and wheat



GHG emissions trajectories

Figure 16 displays net GHG emissions resulting from baseline agricultural activities (the data represent the average annual flux over each five-year time step). Here, positive values indicate a net source of emissions, whereas negative values indicate that the account is a sink (such as carbon sequestered in soils or biomass) or a source of emissions displacement (including biofuel replacement of fossil fuels). Projected net emissions (plotted by the green line) represent the sum of all sources of emissions and sequestration accounted for in FASOMGHG. Net emissions from U.S. agriculture and forestry average 474.4 million t CO_2e from 2005 to 2030, or roughly 7.15% of total U.S. anthropogenic emissions in 2010 (U.S. EPA 2011). Emissions projections vary over time, due primarily to projected land use changes, forest carbon sequestration (discussed in additional detail below), and the increasing emissions displacement effect of biofuels.

Figure 16. Baseline emissions projections by aggregate GHG account (five-year average)



U.S. agricultural sector emissions

Figure 17 disaggregates agricultural sector GHG accounts to distinguish the various sources of emissions and sequestration that form the baseline solution. Agricultural methane (CH_4) emissions, which include emissions from rice cultivation, livestock manure management, and enteric fermentation from livestock feeding, average 154 million tons[14] of CO_2e per year (2010–2030). Rice cultivation alone accounts for an average of 10.8 million t CO_2e per year, or approximately 7% of CH_4 emissions. CH_4 emissions from enteric fermentation from livestock feeding account for an additional 85 million t CO_2e per year, while methane from manure at hog, dairy, and cattle operations average 58.6 million t CO_2e. CH_4 emissions rise consistently as rice cultivation and cattle production expands.

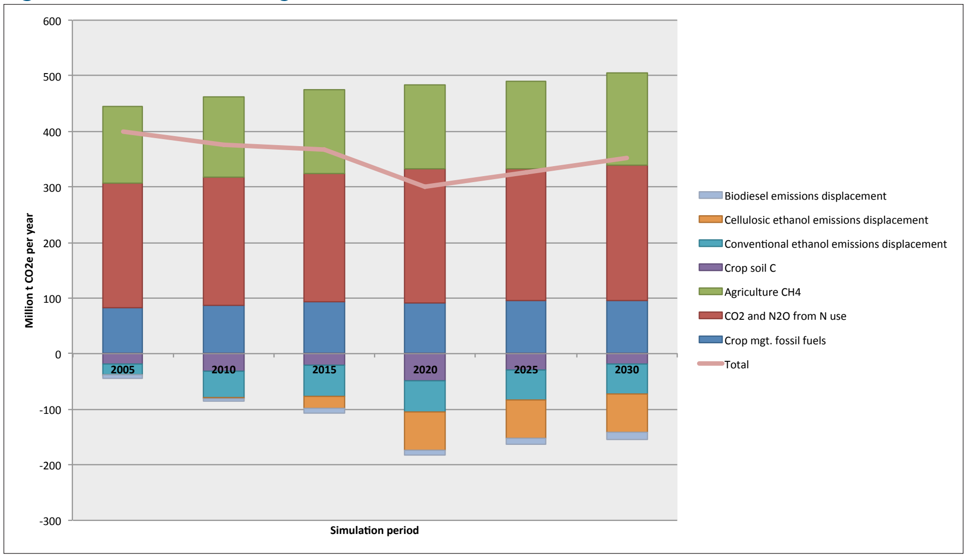
Nitrous oxide (N_2O) and CO_2 emissions from N fertilizer use amount to approximately 236 million t CO_2e per year by 2030; the EPA GHG Inventory estimate is approximately 200 million t CO_2e per year (EPA 2009).[15] Increased emissions from N fertilizer use is not surprising given that N use intensifies in the baseline above historically observed levels. N_2O emissions from N use include those directly associated with fertilizer use as well as indirect N_2O emissions from soil volatilization or N leaching. Like CH_4 emissions, total emissions from fertilizer use rise slowly as agricultural production practices intensify.

Crop soil C sequestration is variable, reflecting soil carbon dynamics, differences in tillage practices, land use shifts into and out of crop production, and changes in overall crop mix strategies. For example, movement into no-till or conservation tillage increases the agricultural soil C account, as does increased area of perennial energy crops such as switchgrass that increase belowground biomass. However, movement out of crop production into development, pasture, or forestry will debit that agricultural soil C account. In all, agricultural C sequestration averages approximately 30 million metric tons in the 2010–2030 period. Crop soil C sequestration does increase as the RFS2 matures (by the 2020 period) due to the additional belowground carbon storage obtained through growth of switchgrass. Expansion in energy crops boosts the terrestrial C stock and adds to the GHG displacement benefit of the mandates. However, this sequestration diminishes as soil C accumulation from energy crop systems begins to saturate for those systems.

In summary, emissions from agricultural activities decrease by 2020 (the height of RFS2 implementation) as liquid biofuel emissions displacement and increased soil C sequestration outweigh higher emissions from other crop management accounts during the same time frame (however, this net emissions metric ignores international leakage effects due to potential indirect land use change.) Nevertheless, emissions eventually start to increase again, because biofuel mandates are held constant over time and production intensifies, thereby limiting emissions displacement potential. Additionally, soil C stocks saturate and production intensifies to achieve higher yields and meet rising export demands for key commodities (hence increasing net emissions from agricultural cultivation).

14. The term *ton* (abbreviated *t*) in this report refers to the metric ton. One ton = 1 megagram (Mg) = 1,000 kg = 2,204.62 lbs.
15. However, FASOMGHG N_2O emissions estimates exclude N use for specialty crops as well as pasture N_2O.

Figure 17. Emissions from agricultural sector activities



Finally, emissions from biofuels mandated by the RFS2 include all emissions from transportation, storage, processing, distribution, and combustion of the final fuel, as simulated through FASOMGHG. The value of the liquid biofuels GHG "sink" is the emissions displacement of transportation fossil fuels that are replaced with energy-equivalent volumes of biofuels. At the height of the RFS2, total GHG displacement from biofuels is approximately 134 million t CO_2e per year: 54.8 million t CO_2e from conventional ethanol, 69 million t CO_2e per year from cellulosic ethanol, and 10.5 million t CO_2e per year from biodiesel.

Ethanol net emissions displacement effects

What does this displacement represent in conventional fossil fuel terms? Consider conventional (corn-based) ethanol, cellulosic ethanol, and biodiesel. Assuming that a gallon of conventional ethanol has the energy equivalence of 0.7 gallons of gasoline, the RFS2 could potentially replace 10.5 billion gallons of gasoline (=15 billion gallons x 0.7, assuming no market rebound effects or fuel switching), as shown in Table 9. Because unleaded gasoline has an average CO_2 footprint of approximately 8.91 kg/gallon, this direct emissions displacement (minus emissions from biofuels production) would amount to 93.5 million t CO_2e per year. Once the FASOMGHG-projected emissions displacement of 54.8 million t CO_2e is deducted, production of 15 billion gallons emits approximately 38.7 million t CO_2e per year, implying that across the RFS portfolio conventional ethanol is roughly 58.6% efficient in reducing greenhouse gases (54.8/93.45). As shown in Table 10, cellulosic ethanol produces a net displacement of approximately 69 million t CO_2e per year (13.7 billion gallons x 0.7 = 9.6 billion gallons of gasoline, and is 81% efficient at displacing fossil fuel emissions (though this figure can vary significantly by region and feedstock type). In the case of biodiesel, the energy equivalence conversion is referenced to diesel fuel instead of gasoline (and an EPA CO_2 emissions factor per gallon of diesel is used to calculated total displacement potential), and the net GHG efficiency is roughly 65% (see Table 11). These efficiency estimates fall well within the GHG displacement thresholds of 20%, 60%, and 50% for corn ethanol, cellulosic ethanol, and biodiesel, respectively, as stipulated by the RFS2. However, the estimates do not reflect emissions from indirect land use change or management intensity (EPA 2010a).

Table 9. Baseline fossil fuel emissions displacement from corn-based ethanol (excluding cultivation emissions)

	Item	Estimate	Calculation
A	RFS2 ethanol mandate	15 billion gallons	From RFS2
B	Energy equivalence of ethanol to gasoline	0.731	California Energy Commission 2007
C	Effective displacement of gasoline	10.5 billion gallons	A*B
D	CO_2 emissions per gallon of gasoline	8.91 kg/gallon	US-EPA, 2011
E	Displaced gasoline CO_2 emissions	93.5 million tons	C*D
F	Emissions from ethanol transport and processing	38.7 million tons	From FASOMGHG baseline simulation
G	Modeled net emissions displacement effect (from FASOMGHG)	54.8 million tons	From FASOMGHG baseline simulation
H	Net GHG efficiency	58.6%	F/E (in % terms)

Table 10. Baseline fossil fuel emissions displacement from cellulosic ethanol (excluding cultivation emissions)

	Item	Estimate	Calculation
A	RFS2 ethanol mandate	13.7 billion gallons	From RFS2
B	Energy equivalence of ethanol to gasoline	0.731	California Energy Commission 2007
C	Effective displacement of gasoline	9.6 billion gallons	A*B
D	CO_2 emissions per gallon of gasoline	8.91 kg/gallon	US-EPA 2011
E	Displaced gasoline CO_2 emissions	85.5 million tons	C*D
F	Emissions from ethanol transport and processing	16.4 million tons	From FASOMGHG baseline simulation
G	Modeled net emissions displacement effect (from FASOMGHG)	69.1 million tons	From FASOMGHG baseline simulation
H	Net GHG efficiency	80.8%	F/E (in % terms)

Table 11. Baseline fossil fuel emissions displacement from biodiesel (excluding cultivation emissions)

	Item	Estimate	Calculation
A	RFS2 ethanol mandate	1.67 billion gallons	From RFS2
B	Energy equivalence of biodiesel (B100) to diesel	0.95	National Renewable Energy Laboratory 1998
C	Effective displacement of diesel	1.59 billion gallons	A*B
D	CO_2 emissions per gallon of diesel	10.1 kg/gallon	US-EPA 2011
E	Displaced diesel CO_2 emissions	16.1 million tons	C*D
F	Emissions from biodiesel transport and processing	5.6 million tons	From FASOMGHG baseline simulation
G	Modeled net emissions displacement effect (from FASOMGHG)	10.43 million tons	From FASOMGHG baseline simulation
H	Net GHG efficiency	65.0%	F/E (in % terms)

Forestry sector emissions and implications of land use change

An important component of terrestrial-based emissions trajectories is emissions from the forestry sector, especially those sources of emissions and of sequestration directly related to land use competition with agriculture. In FASOMGHG, forestry sector "emissions" actually represent "net" emissions (emissions minus sequestration). Sequestration includes carbon stored in trees, soils, and understory on existing or afforested managed stands as well as carbon stored in final wood products. Emissions include the net carbon lost through deforestation (or harvesting), as well as fossil fuel emissions associated with forest product transport and processing. Because FASOMGHG is a fully dynamic model, investments made in the forest sector have an immediate or long-term impact on total emissions. Increased harvesting or land use change out of (or into) forestry in one simulation period can significantly alter total emissions, instantaneously or over the long run. Hence the simulation results presented in Figure 16 indicate large fluctuations in forest sector emissions.

The forestry sector accounts for a large source of emissions in early periods of the simulation horizon, in part due to land leaving forestry. The aggregate forestry GHG account includes carbon uptake from existing or reforested stands; emissions from deforestation, forest fuel use, timber harvesting, and transport/processing of final products; and carbon stored in afforested stands (transferred from agriculture) and final wood products. Emissions from forestry activities outweigh carbon sequestration and carbon stored in final wood products in early periods of the simulation horizon; they average 114 million t CO_2e per year between 2005 and 2025. The largest flux occurs in 2015, concurrent with high rates of agricultural deforestation. This flux decreases significantly by 2030 as sequestration on existing, reforested, or afforested stands outweighs emissions in the rest of the sector.

Carbon sequestered on afforested agricultural land is a significant component of the forestry GHG account. This land includes that converted to forestry, primarily from pasture use, which in part makes up for the large area of land leaving forestry in early simulation periods. Simulation results show that afforested land sequesters an average of 44 million t CO_2e per year until 2030, significantly reducing the large flux of emissions associated with other forestry activities. When the substantial sink in the forestry sector in 2030 is taken into account, emissions and sequestration from forestry and afforestation produce a net source of emissions averaging 54 million t CO_2e per year (2010 to 2030). In contrast, the EPA estimates that privately managed forestry operations currently produce a net carbon sink for the United States.

Policy Scenario Analysis

Land use, land management, and environmental outcomes under the current biofuels mandate are likely to change under alternative policy scenarios for the RFS. Land management implications of policy are the focus here.

Biofuel policy scenarios

The FASOMGHG pre-RFS2 scenario incorporates a combination of exogenous biofuel production targets consistent with mandates established in RFS1 and longer-term energy price projections from the Annual Energy Outlook (AEO 2009). Unlike the RFS2 scenarios, however, hard constraints are not imposed on total cellulosic ethanol or biodiesel production. Instead, minimum (lower-bound) constraints are imposed to ensure that total ethanol production is greater than or equal to the targeted rates and that excess ethanol can be produced when cost-effective. Essentially, this scenario depicts a baseline trajectory in the absence of the RFS2, wherein total biofuel production is a function of legislative targets (RFS1), exogenous energy market conditions, and endogenous agricultural-commodity market conditions. Table 12 displays minimum biofuel requirements under the pre-RFS2 scenario.

This report also evaluates alternative compositions of mandatory biofuel requirements. The RFS2 75% scenario reflects a case in which the total volume of mandated biofuels is reduced by 25%, holding the ratios of biodiesel, conventional ethanol, and cellulosic ethanol constant relative to the total. This scenario essentially models a moderate relaxation of the RFS2 legislation, whereby net expansion into each biofuel type is reduced by 25%. In this scenario, the total corn ethanol required actually falls below the pre-RFS2 market-projected rate of production. However, total (conventional plus cellulosic) ethanol remains well above market projections for the RFS2 75% scenario. This case was designed purely to examine key output variables after a volumetric shift in the mandate in both the positive and negative directions.

Volumetric requirements of the RFS2 are unlikely to be expanded at this time, given the relatively slow rate of cellulosic ethanol advancement. However, additional sensitivities wherein the RFS2 mandates for each fuel type are increased by 25% (RFS 125%) are evaluated to illustrate the scale patterns of land management responses to alternative biofuel volumes.

A final biofuel scenario is included to reflect the possibility that cellulosic ethanol does not expand as rapidly as called for in RFS2 (as has been observed to date) and that additional conventional ethanol is needed to fulfill the RFS2 volumetric requirements. This "RFS2 75% high corn" scenario assumes a 75%/25% split between conventional and cellulosic ethanol, a departure from the nearly 50%/50% split required by the RFS2. Table 12 summarizes biofuel production constraints implemented for this study.

Table 12. Biofuel production mandate constraints by scenario and time period

	Biofuel output (billion gallons)	2010	2015	2020	2025	Constraint type
RFS2 baseline	Conventional ethanol	12.82	14.99	15.00	15.00	Exact
	Cellulosic ethanol	0.46	4.74	13.70	13.70	Exact
	Biodiesel	0.86	1.44	1.47	1.47	Exact
Pre-RFS2	Conventional ethanol	10.80	11.31	12.30	13.12	Exact
	Cellulosic ethanol	0.00	0.25	0.25	0.25	Lower-bound
	Biodiesel	0.33	0.36	0.37	0.40	Lower-bound
RFS2 75%	Conventional ethanol	9.61	11.24	11.25	11.26	Exact
	Cellulosic ethanol	0.34	3.56	10.28	10.26	Exact
	Biodiesel	0.65	1.08	1.10	1.37	Exact
RFS2 125%	Conventional ethanol	16.02	18.73	18.75	18.75	Exact
	Cellulosic ethanol	0.57	5.93	17.13	17.13	Exact
	Biodiesel	1.08	1.81	1.84	1.84	Exact
RFS2 high corn	Conventional ethanol	7.21	14.77	21.55	21.55	Exact
	Cellulosic ethanol	0.26	4.74	7.17	7.17	Exact
	Biodiesel	0.48	1.44	1.47	1.47	Exact

Note: "Exact" indicates a hard constraint.

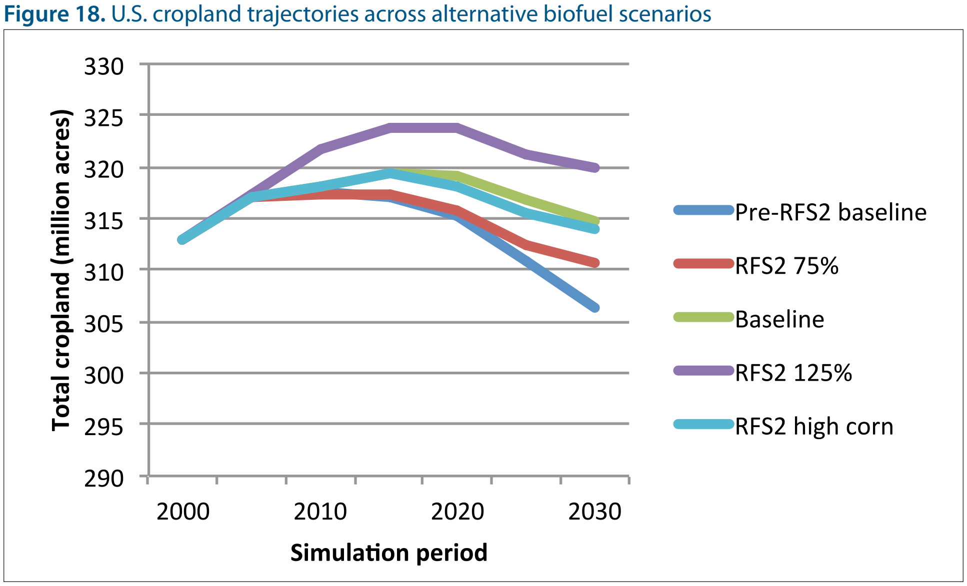
Land use

Figure 18 illustrates trajectories of cropland over time across the biofuel scenarios. The RFS2 baseline is represented by the green bar and reflects the second-highest land use total. As Figure 18 indicates, land use trends do not change substantially among scenarios; the total acreage does vary under the different biofuel requirements.

The amount of cropland varies directly with the stringency of the biofuel mandate. Scenarios less stringent than RFS2 generally decrease cropland. Total cropland decreases an average of 1.35% (or roughly 4.3 million acres) for the pre-RFS2 scenario relative to the baseline. When the total volume of the mandate is relaxed by one-fourth for the RFS2 75% case, total cropland decreases an average of 0.95% from baseline levels, or approximately 3 million acres.

This total shift is relatively small for a significant decrease in total mandated biofuels. Total cropland is also somewhat responsive to increases in the RFS2 volumes. Estimated trajectories for the RFS2 125% biofuel scenario exceed baseline cropland levels at an average rate of 1.4% (or 4.43 million acres) from 2010 to 2030. This shift is similar in magnitude (but opposite in direction) to the shift in the RFS2 75% case. The implied long-run cropland elasticities for a percentage change in the mandate ([% change in biofuels]/[% change in cropland]) are 0.185 and 0.175, respectively, for the RFS2 75% and RFS2 125% cases.

Figure 18. U.S. cropland trajectories across alternative biofuel scenarios



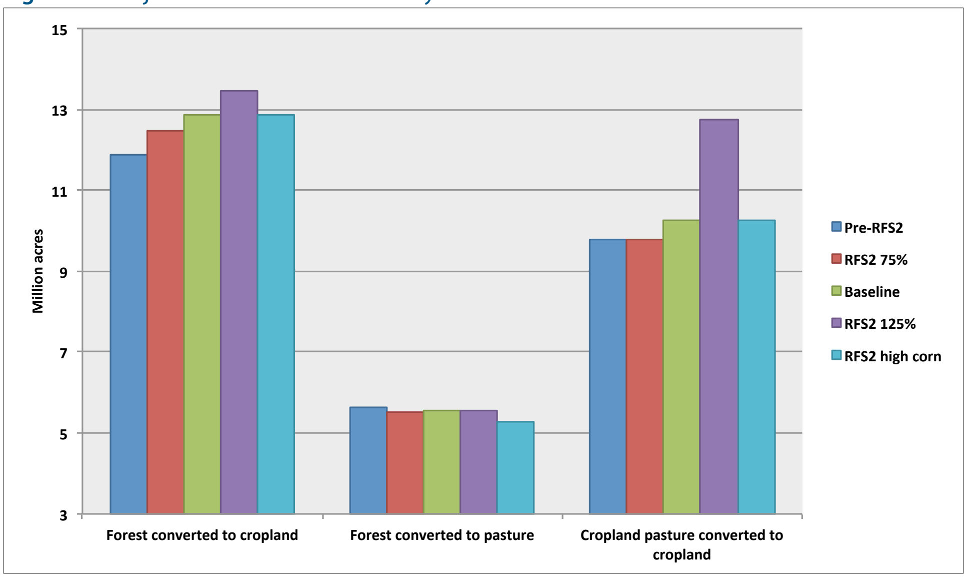
Regionally, the greatest cropland response to the RFS2 policy occurs in the Great Plains, Midwest, and Southeast regions. The largest proportionate gains occur in the Southeast and Great Plains (including Texas and Oklahoma). Cropland shifts in the Great Plains are driven by pasture cultivation or reversion of CRP lands in response to higher biofuel feedstock demand and commodity prices. Crop expansion in the Southeast is partially driven by agricultural deforestation. Cropped acreage expands in the Corn Belt as well, but at a much lower rate than elsewhere.

As noted above, much of the acreage expansion in the Southeast involves dedicated energy crops and conventional commodities. The increase in acreage dedicated to conventional commodities is in response to a reduction in the supply of some these commodities in some of the most productive regions such as the Corn Belt. This increase represents an indirect land expansion effect of the mandates.

Estimated shifts among major land use types also offer insight into potential policy impacts on the domestic agricultural land base. Figure 19 displays cumulative land use transitions by 2030 (totals include initial shifts in the 2000 and 2005 base periods, plus all subsequent land movement through the 2030 simulation period). Shifts from pasture and forestry into crop production are responses to the alternative biofuel mandates. Deforestation whereby land shifts to cropland (cropland deforestation) is 7.5% lower under the pre-RFS2 scenarios than under the RFS2 baseline, suggesting that expanded mandates can induce forest clearing for agriculture. When the mandates are relaxed by 25%, cropland deforestation is 2.9% lower than under the RFS2. Inversely, raising the mandate by 25% boosts deforestation rates by approximately 4.7% (or 0.61 million acres). Shifting the mandate to a higher proportion of conventional ethanol also boosts deforestation, though only slightly (less than 1%). However, pasture deforestation (or forestland cleared for grazing purposes) decreases with the volume of biofuels produced. As cropland rents expand with the volume of biofuels produced, additional land that would have been transferred to pasture is cultivated for crop production instead.

Shifts of land from grazing use to crop production also grow with the mandate. Cropland pasture to cropland movement (pasture cultivation) is lowered by approximately 4.8% when the mandate is reduced 25%. However, when the mandates are increased, pasture cultivation expands greatly (24.2%, or roughly 2.5 million acres, cumulative). This result suggests that pasture cultivation rates in the United States are likely more sensitive to alternative biofuel targets than deforestation rates; this result is consistent with previous studies.

Figure 19. Projected land use transitions by 2030

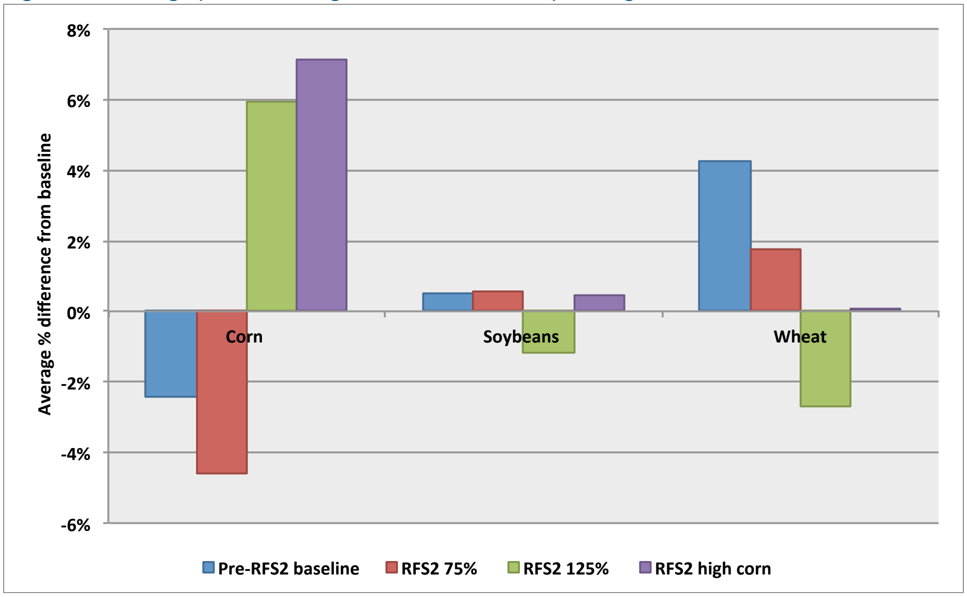


U.S. biofuel expansion can lead to shifts in crop mix (or rotation) decisions. Figures 20 and 21 illustrate how acreage of some conventional and dedicated crops could shift under various biofuel targets.

Figure 20 displays the percentage change in conventional crop acreage, by crop, from the baseline (averaged from 2010 to 2030). Some conventional crop acreage totals, including wheat cotton and sorghum, increase as the mandates are relaxed, but they decrease as the mandates are made more stringent. For example, wheat acreage is 4% to 5% greater for the pre-RFS2 scenario, and approximately 2% greater for the RFS2 75% scenario (relative to the baseline). However, an expansion in the mandate drops wheat acreage by approximately 3%. Because some regions can often substitute corn or perennial energy crops for wheat, the cropping patterns shift to a lower proportion of wheat under higher biofuel targets. Meanwhile, the opposite is true for corn acreage: corn acreage expands with the volume of the conventional ethanol mandate (approximately 6% or more for the RFS2 125% and RFS high corn scenarios, respectively).

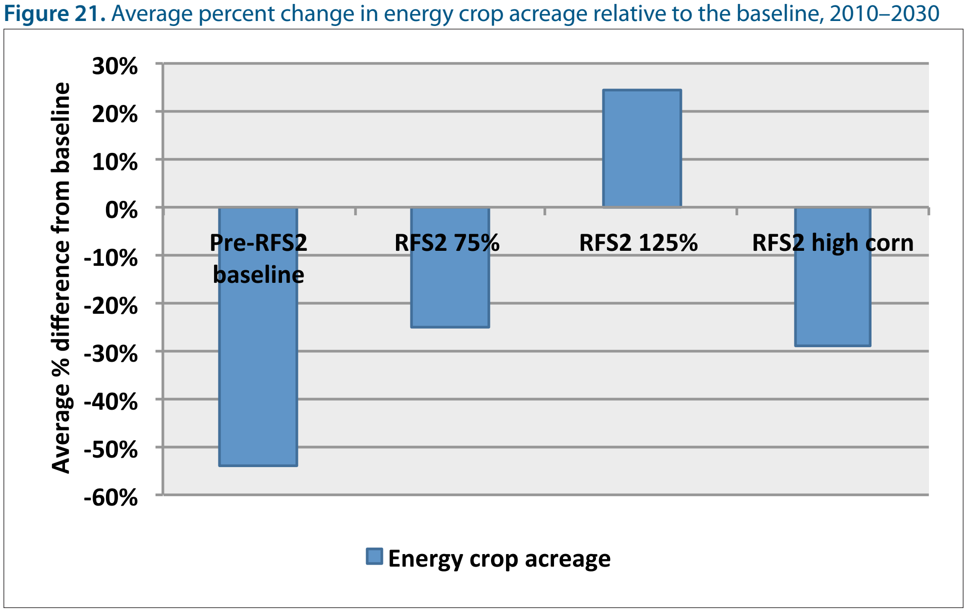
This result indicates a strong land substitution effect among crops. As more land is needed in corn, soybean, or energy feedstock production, acreage for conventional commodities like wheat that do not play a major role in the biofuel feedstock portfolio is reduced. Thus, biofuel mandates lead to movement on the extensive margin by bringing new land into production and by shifting land resources out of non-biofuel crops.

Figure 20. Average percent change in conventional crop acreage relative to the baseline, 2010–2030



Energy crop acres shift by the greatest amount proportionally across biofuel scenarios (Figure 21), because cellulosic ethanol mandates are the primary driver of dedicated energy crop area. Varying either the total volume mandated or the proportion of cellulosic to conventional ethanol has a dramatic impact on planted acreage. The average percent change in dedicated energy-crop acreage across the RFS2 75% and RFS2 125% scenarios is approximately -25% and 25%, respectively.

Figure 21. Average percent change in energy crop acreage relative to the baseline, 2010–2030



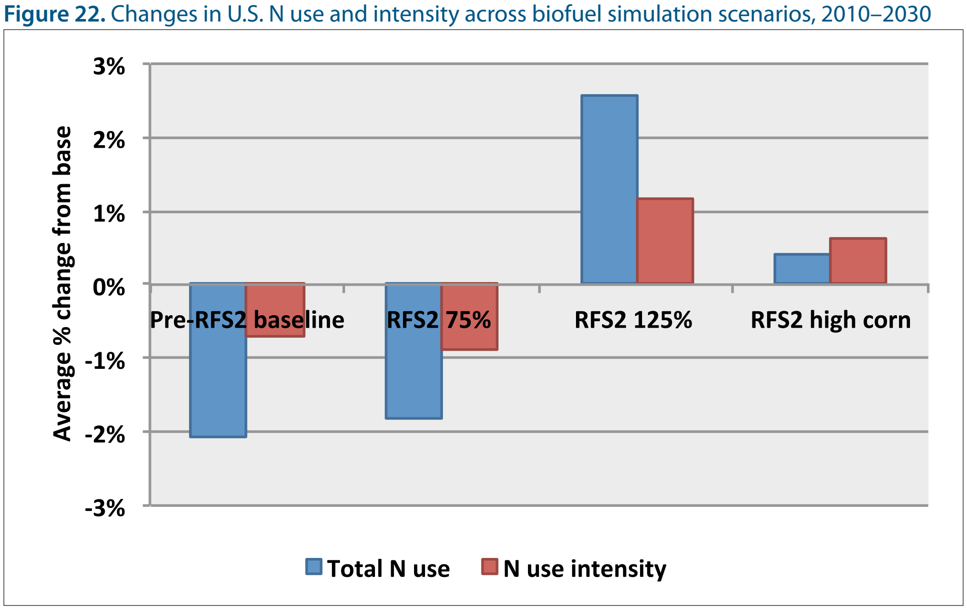
Nitrogen use and intensity

Nutrient management, both in total nutrients applied and intensity per unit area, is responsive to alternative biofuel policy scenarios. Simulation results on nutrient application serve as a proxy for potential water quality effects of emerging policy drivers.[16]

On a national basis, N use expands slightly with the level of required biofuels. Figure 22 displays changes in total N use and intensity across the biofuel sensitivity scenarios (expressed as the average percent difference from the baseline, 2010–2030). In the RFS2 75% scenario, total N use decreases by roughly 1.8% relative to the baseline, which is higher than the percentage drop in total cropland during the same time span, implying that N use intensity also falls (0.9%). In the pre-RFS2 scenario, total N application decreases 2% relative to the baseline, and N use intensity per acre falls by 0.7%. When the mandates are increased by 25%, total N use and intensity expand by 2.6% and 1.2%, respectively. The RFS2 high corn scenario also raises total N use and intensity, by 0.4% and 0.6%, respectively. The intensification effect is higher than the N use expansion effect, because this scenario implies a greater proportion of acreage in corn, which is the most N-intensive crop in most regions.

Higher total nutrient use levels are primarily a result of cropland use expansion, but shifting regional crop-mix patterns and increased application rates also play an important role in the higher per-acre N use intensity estimates. The effect of expansion and intensification in nutrient use as a result of biofuel mandates confirms analytical modeling results from previous studies (Feng and Babcock 2010).

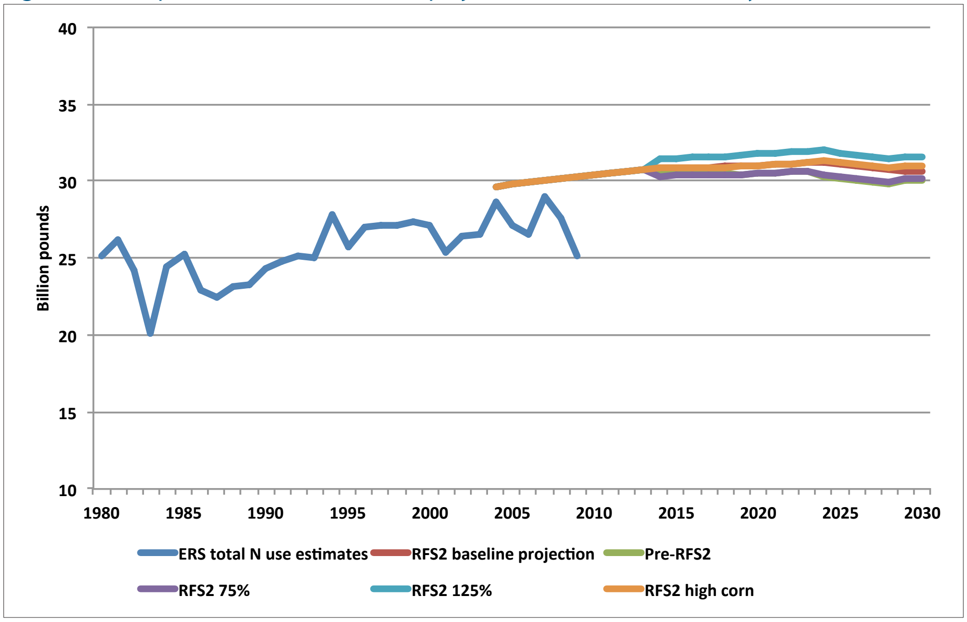
Figure 22. Changes in U.S. N use and intensity across biofuel simulation scenarios, 2010–2030



Over time, N use increases modestly across all biofuel scenarios (Figure 23). This modest upward trend is consistent with the observed increase in total N use since 1980. The difference among scenarios is not extreme and remains relatively constant throughout the simulation horizon. As expected, lower biofuel requirements decrease total N use (pre-RFS2 and RFS2 75% totals are lower than the RFS2 baseline N levels), whereas increasing the mandate raises total N use throughout the horizon. Virtually no difference between the RFS2 baseline and RFS2 high corn scenarios is projected. Finally, the total difference in N use as simulated by alternative biofuel policy scenarios is quite small in comparison to the historic fluctuations in total N use observed from year to year.

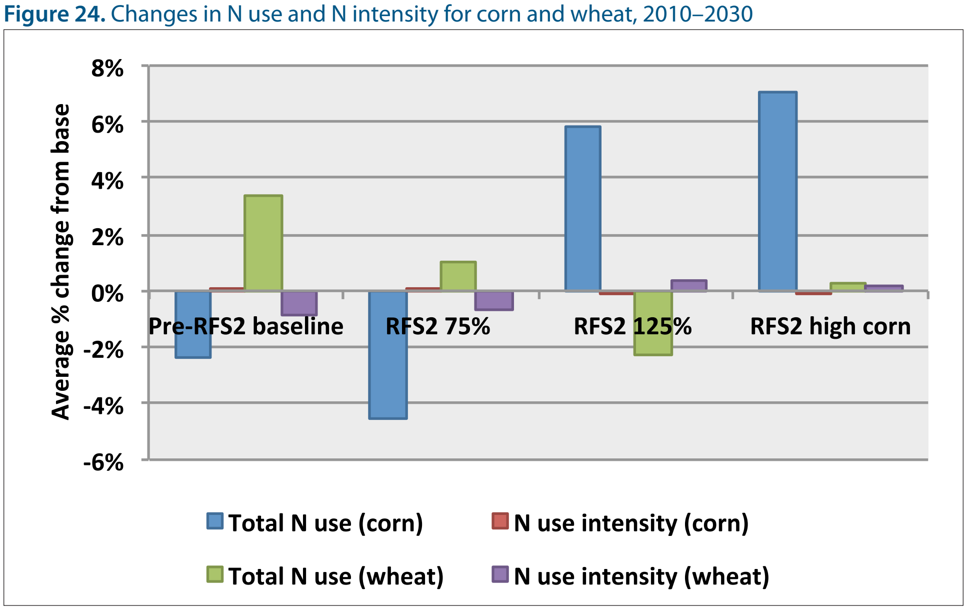
16. For research linking N application rates from U.S. agriculture to national and regional water quality outcomes, see Pattanayak et al. 2005.

Figure 23. Comparison of historic N use to projected N use over time and by biofuel scenario



Nitrogen use and intensity also vary by crop across biofuel scenarios. Figure 24 shows the results of this effect on corn and wheat. For wheat, total N use decreases with the volume of the mandate, because more (less) wheat acreage is found as the mandate is reduced (increased). N use intensity for wheat decreases as acreage expands, but intensifies as total wheat acreage decreases. This result reflects an extensive/intensive margin tradeoff, whereby reducing total wheat area leads to higher average production intensity. Total N use for corn expands with the mandate, because acreage shifts to accommodate more or less corn for conventional ethanol, but N use intensity does not change substantially.

Figure 24. Changes in N use and N intensity for corn and wheat, 2010–2030



In most regions, N use and intensity trends are similar in sign to national results but vary in magnitude. Table 13 summarizes average percent deviations in regional N use and intensity shifts from the baseline. N use and intensity are quite sensitive to biofuels policy shifts in some regions but change little in others. In the Northeast, for instance, total N use and intensity change substantially in percentage terms, but this region is a relatively small production region, meaning that absolute N use shifts are not as severe as with a smaller percentage change in a larger production region. However, increased nutrient use presents legitimate water quality concerns in the Northeast, because production in much of the region could produce constituents that flow to the ecologically and economically critical Chesapeake Bay watershed.

In the Midwest, total N use and intensity increase with the amount of biofuels produced, and under the high corn scenario, as corn acreage expands in the Midwest. N use and intensive margin shifts are less than 1% in the Great Plains for all but the RFS2 125% scenario. In that scenario, N use and intensity increase sharply as total cropped acres expand in response to rising biofuel feedstock demand (Great Plains cropland increases 3.75% over the same time horizon). N use and intensity shift as would be expected in the South Central and Southeast regions (similar to national trends). However, in the RFS2 high corn scenario, N use and intensity decrease slightly in the region, indicating that the cellulosic ethanol requirements and feedstock demand are a primary driver of changes in N use in the Southeast across scenarios.

Table 13. Average percent difference from baseline in regional N use and intensity, 2010–2030

		Pre-RFS2	RFS2 75%	RFS2 125%	RFS2 high corn
Midwest	Total N use	-2.41%	-2.36%	0.18%	1.06%
	Intensity	*-0.66%*	*-0.58%*	*0.43%*	*1.65%*
Northeast	Total N use	-7.46%	-1.50%	7.86%	0.27%
	Intensity	*0.59%*	*1.30%*	*1.32%*	*0.16%*
Great Plains	Total N use	-0.96%	-0.84%	6.84%	0.20%
	Intensity	*-0.37%*	*-0.82%*	*2.98%*	*0.23%*
South Central/Southeast	Total N use	-2.10%	-2.71%	0.59%	-0.27%
	Intensity	*-1.76%*	*-2.56%*	*0.33%*	*-0.27%*
West Coast and Rocky Mts.	Total N use	-1.59%	-1.44%	0.76%	-0.10%
	Intensity	*-0.55%*	*-0.41%*	*0.56%*	*-0.16%*

GHG emissions in alternative biofuel scenarios

To isolate the net emissions effect of varying the volume of the biofuel mandate, the mix of the mandate, or both, the various sources of AF emissions under each policy scenario must be compared with the baseline emissions trajectory. Net emissions changes that result from varying the mandates are a combination of the change in fossil fuel emissions displacement (which increases or decreases with the mandate) and all other sources of direct or indirect AF emissions that respond to the different policy stimuli.

Emissions effect of alternative biofuel scenarios =

Fossil fuel emissions displaced –

Net emissions (direct and indirect) to produce biofuels

Figure 25 illustrates net emissions for major GHG accounts by scenario. Emissions fluxes are represented as annuities, which convert annual emissions streams over the entire simulation period (2010–2070) into a single present-value measure using time discounting (at a 4% real discount rate) and expressed in annualized equivalents. A measure annualized in this way allows for a relatively direct side-by-side comparison of emissions by biofuel scenario, while recognizing the importance of timing in emissions. Notice that across all scenarios, total AF emissions do not vary widely; the most noticeable difference shows up in the biofuel emissions-displacement account. The net emissions effect is not substantial; relative to the baseline, annualized emissions changes range from 3% to 11%, depending on the scenario. However, net emissions from the AF sectors do rise relative to the baseline when the biofuel mandates are relaxed, or when cellulosic ethanol comprises a smaller share of the total. In other words, more biofuels do lower net AF emissions on balance.

Figure 25. GHG emissions by aggregate GHG account

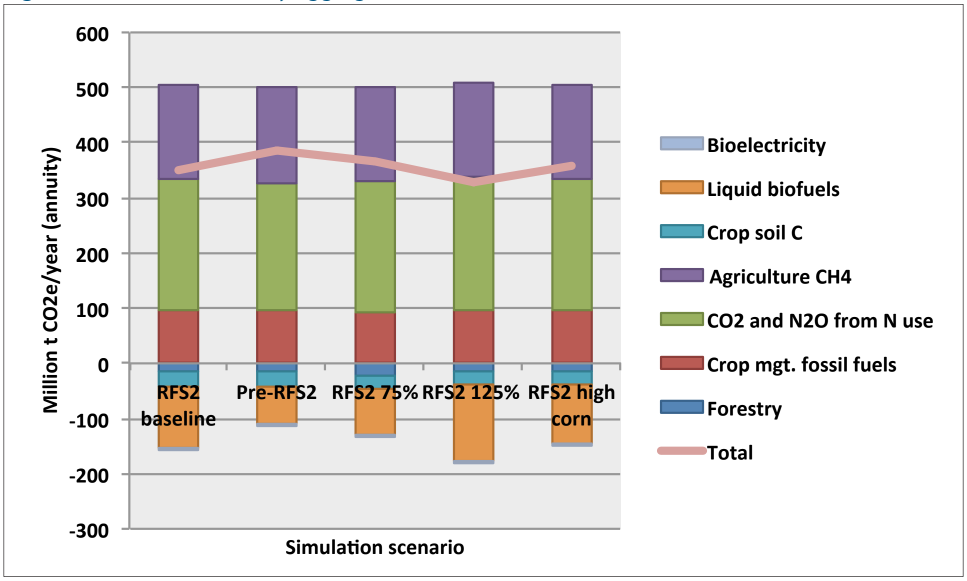


Figure 26 compares annualized differences in mitigation over an extended time period. Figures 26 and 27 display net GHG emissions from agricultural activities over time and across scenarios. For simplicity, forestry sinks are not included in these figures.

Figure 26 includes fossil fuel emissions displacement from biofuel use as part of the agricultural sectoral emission effects. Consequently, total emissions are lower over time for the scenarios with the highest levels of biofuel production. The largest emissions fluxes occur under the pre-RFS2 and RFS2 75% scenarios, because these scenarios have the lowest fossil fuel emissions-displacement effect. The RFS2 125% case produces the lowest net emissions due to the stricter mandate. Because of the net emission differences between corn and cellulosic processes, the high corn scenario initially produces higher net emissions than the RFS2 baseline, while producing the same biofuel volume. But the emissions differences eventually converge to the baseline. The implication is that although the RFS2 as currently constructed might produce greater initial emissions displacement relative to a scenario with a higher proportion of corn ethanol, the long-term difference in GHG benefits between these two scenarios might not be substantial (in part due to the additional acreage needed for energy crops).

Total emissions decrease from 2010 to 2020 across all scenarios as biofuel production (and emissions displacement) increases. Beyond 2020, emissions begin to climb as biofuels are locked in at mandated levels. As in the baseline, emissions increase as production continues to intensify and soil carbon stocks, particularly those associated with switchgrass and other energy crops, begin to saturate and their rate of carbon absorption slows.

Figure 26. Net agricultural GHG emissions over time and by scenario (with biofuel emissions displacement)

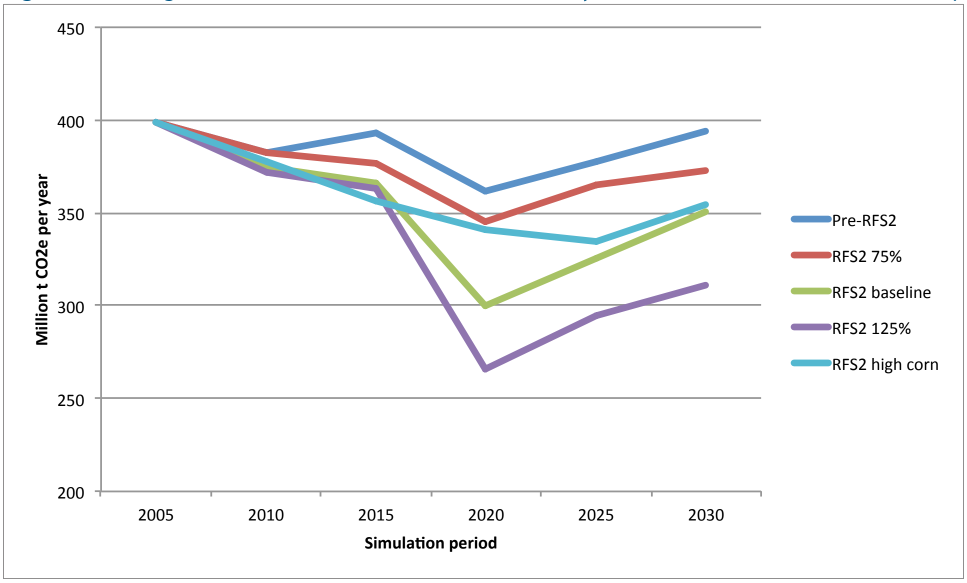
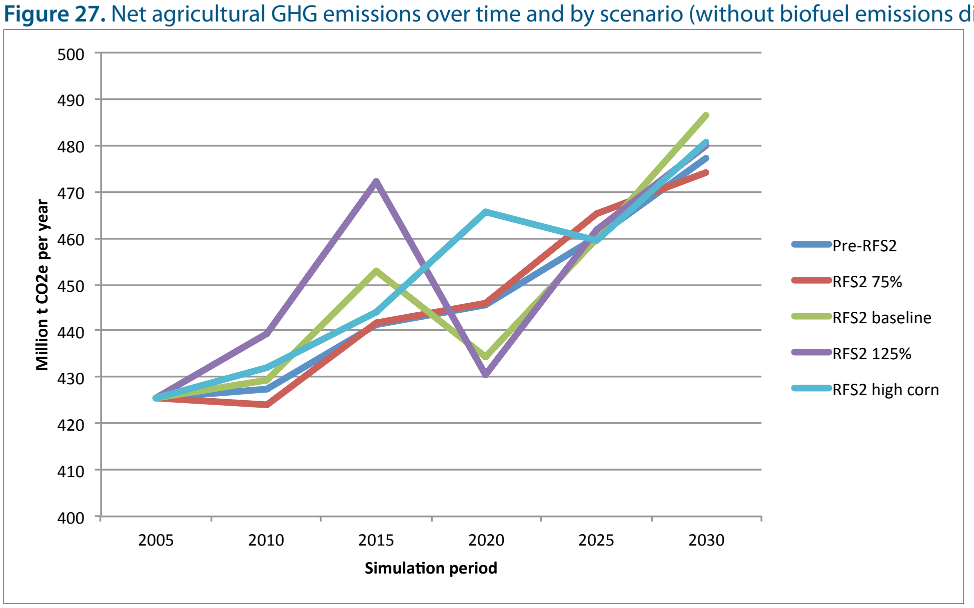


Figure 27. Net agricultural GHG emissions over time and by scenario (without biofuel emissions displacement)



Net GHG implications of varying the RFS2 mandates

Figure 28 shows the annualized change in emissions, by aggregated GHG account, relative to the RFS2 baseline. First, consider the fossil fuel emissions displacement effect. In the pre-RFS2 scenario, emissions displacement is approximately 41.5 million t CO_2e per year lower than it is under the RFS2 (baseline). In Figure 25, this displacement is represented as a positive flux, because it captures emissions from fossil fuel consumption in the general economy that would otherwise be displaced by biofuels under RFS2 conditions (not accounting, yet, for ILUC emissions). The implication is an increase in total emissions from the AF sectors, because liquid fossil fuel displacement is reduced. When the full mandates are relaxed by 25%, gasoline and diesel emissions displacement drops by 27.3 million t CO_2e per year relative to the RFS2 scenario. Satisfying the mandate with a higher proportion of corn ethanol also lessens the displacement effect, because cellulosic ethanol is a more GHG-efficient renewable fuel alternative due to the relatively high energy output of dedicated energy crops and forest biomass on a per unit area basis. When the mandate is made 25% more stringent, emissions displacement increases by 27.6 million t CO_2e per year.

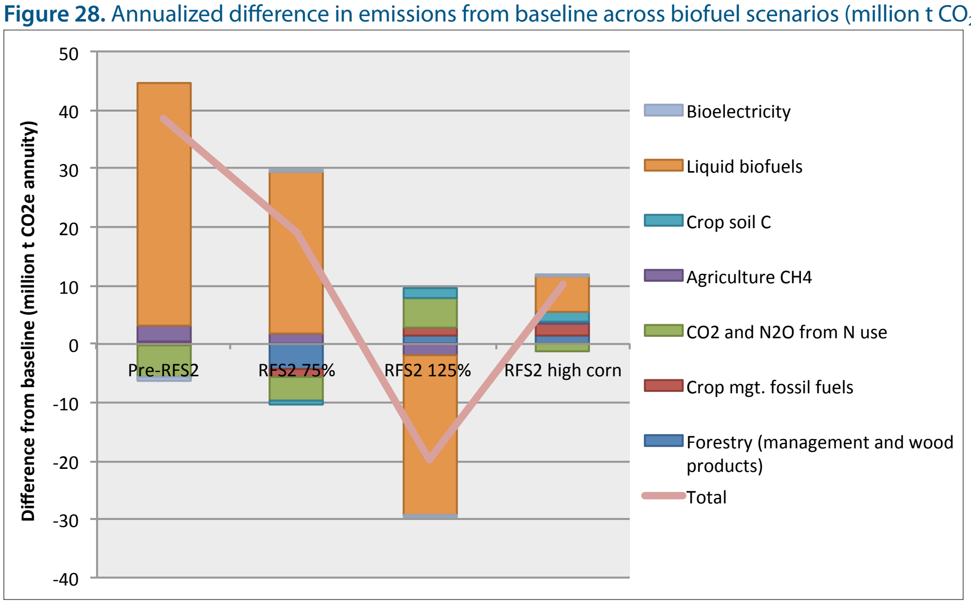
Emissions reductions vary across other sources, including those emissions associated with nitrogen and fossil fuel use for crop management. In the pre-RFS2 scenario, the sector forgoes the fossil fuel replacement emissions reduction from an increase in mandated biofuels, but total emissions from crop cultivation decrease 5.6 million t CO_2e per year. However, this result is countered to an extent by an increase in methane emissions from livestock cultivation—less stringent biofuel mandates boost feed-grain production and, hence, livestock operations. In total, emissions from agriculture decline by approximately 2.9 million t CO_2e per year (less than 1% of total AF emissions) relative to the RFS2 baseline. Forestry sector emissions also do not change significantly for the pre-RFS2 scenario.

A similar effect occurs if the mandates are relaxed by 25%. In this scenario, crop cultivation emissions decrease by roughly 5.4 million t CO_2e per year, but the increased flux from livestock operations is less than it would be the under the pre-RFS2 scenario (because higher cellulosic ethanol requirements under the RFS2 75% scenario reduce feed grain availability relative to the pre-RFS2 scenario). This outcome leads to a larger net reduction in total GHG emissions (4.2 million t CO_2e per year). Forestry sector emissions decrease under the RFS2 75% scenario, because deforestation for agriculture would be lower than that under the baseline. Although this land use trend is also found in the pre-RFS2 scenario, no significant reduction in forestry sector emissions was found, because cellulosic ethanol mandates under the RFS2 scenarios drive demand for lignocellulosic biomass from forestry. This demand shifts forest management trends and leads to greater levels of afforestation (particularly from pasture) under the RFS2 scenarios relative to pre-RFS2 conditions, thus reducing the net emissions flux from forestry.

Increasing the mandate by 25% has the opposite effect. Under the RFS2 125% scenario, total agricultural emissions increase by 7.9 million t CO_2e per year relative to the baseline, but CH_4 emissions from livestock operations drop by 2 million t CO_2e per year. Net AF sector emissions increase by roughly 5.9 million t CO_2e per year under the RFS2 125% scenario. Forestry sector emissions are slightly higher as well (1.5 million t CO_2e per year) due to greater rates of cropland expansion through deforestation.

When the volume of the mandates is held constant and the fuel mix is altered (RFS2 high corn), both emissions from crop cultivation and livestock increase, leading to a net flux from agriculture of 2.8 million t CO_2e per year. Agricultural expansion into forestry also increases, leading to higher forestry sector emissions (1.6 million t CO_2e per year).

Figure 28. Annualized difference in emissions from baseline across biofuel scenarios (million t CO_2e)



Net change in emissions displacement efficiency from RFS2 baseline (including cultivation and ILUC emissions)
Table 14 summarizes the net GHG implications of moving from one RFS2 scenario to another.[17] It includes net land use change emissions within the United States. It does not include international land use change emissions, which cannot be directly estimated through FASOMGHG simulations.

The first column of Table 14 represents the difference in net ethanol (conventional and cellulosic) output when moving from the RFS2 baseline to an alternative biofuel policy scenario (in billion gallons per year, annualized over the length of the simulation horizon). Thus, as total mandated biofuels are reduced, the difference in total ethanol output (in annual average) is negative (for the pre-RFS2 and RFS2 75% scenarios). The second column similarly reports biodiesel output.

The third column reports the ethanol and biodiesel outputs (summed) in terms of their gasoline equivalence. Because of differences in conversion efficiency, the correspondence between a gallon of biofuel used and a gallon of gasoline displaced is less than 1:1. This value can be interpreted as the difference in potential fossil fuel displacement, assuming no change in transportation fuel markets results from the biofuel mandate. However, previous studies have shown that biofuel policies can indirectly stimulate fossil energy consumption by lowering energy costs in general (de Gorter and Just 2009). Such market feedback would diminish some of the fossil fuel displacement of biofuels. However, this report ignores energy market feedback effects, because they are likely quite small relative to the factors on which it focuses.

The fourth column converts the difference in energy output to total CO_2 emissions from fossil energy displacement. Again, this metric represents total emissions reductions achievable through full energy displacement if biofuels were to yield carbon-neutral renewable energy. In the pre-RF2 and RFS2 75% scenarios, this value is negative, meaning that moving from the RFS2 baseline to a policy scenario defined by less biofuel output achieves *less GHG abatement* (or conversely, *greater total emissions*). The opposite is true for the 125% scenario. Moving to a scenario with greater biofuel output increases potential emissions displacement.

Biofuels are not purely carbon-neutral; they require energy consumption for biomass cultivation, transport, storage, and processing. The fifth column represents the emissions change attributable to feedstock transport, storage, and processing when the policy changes to require more or less biofuel. In the pre-RFS2 scenario, this difference is roughly 26.8 million t CO_2e per year, meaning that lower biofuel mandates substantially reduce supply chain emissions. Conversely, when RFS2 mandates are increased, an additional 20 million t CO_2e per year of production-related emissions are generated. The estimated direct GHG emissions abatement effect attributed to biofuels (column 6) nets out the biofuel production emissions from the fossil fuel emissions displacement. Net mitigation from biofuels decreases substantially in the pre-RFS2 scenario relative to the baseline (approximately 40 million t CO_2e per year). The GHG displacement difference from the baseline for the RFS2 75% and RFS2 125% scenarios is similar in magnitude (approximately 27 million t CO_2e per year) but opposite in sign.

The seventh column reports the GHG efficiency of biofuels relative to the baseline scenario; that efficiency is defined as the ratio of estimated emissions displacement (column 6) to the implied emissions displacement (column 4). For the pre-RFS2 scenario, the ratio is 61.4%. This number implies that, on average, the additional biofuel output made available by a shift from the pre-RFS2 to the RFS2 baseline is slightly more than 60% efficient at displacing fossil fuel emissions. This efficiency ratio of approximately 60% is consistent with GHG reduction targets imposed by the RFS2 on a per unit energy-equivalent basis (U.S. EPA 2010). Estimated efficiency is 58% for the RFS2 75% and 125% scenarios.

However, the efficiency estimate in column 7 ignores AF emissions induced by variations of the baseline biofuel policy. To assess this indirect land use effect, total shifts in these emissions must be examined relative to the RFS2 baseline, which aggregates all direct and indirect changes in emissions from agricultural cultivation, livestock operations, and land use changes. This process offers a full (U.S.) systematic estimate of expected emissions changes due to deviation from the RFS2 baseline. As discussed above, total emissions from agricultural production (including livestock) are lower under the pre-RFS2 and RFS2 75% scenarios than under the baseline. Additionally, forestry sector emissions are lower for the RFS2 75% scenario. When the mandate is expanded by 25%, total AF emissions grow by an additional 7.4 million t CO_2e per year.

17. To directly assess emissions resulting from different volumetric targets, only those scenarios that vary the total volume of the mandates are included here.

To obtain the net emissions effect of the policy change (column 10), the net change in AF emissions is added to the estimated difference in biofuels emissions displacement. This total is divided by the direct emissions displacement (column 4) to calculate the total emissions efficiency of biofuels when shifting from policy scenario to the baseline. Results imply that incorporating these indirect land use effects reduces efficiency by nearly a third, especially under the RFS2 75% and RFS2 125% scenarios.

Under the pre-RFS2 scenario, forestry sector emissions change little. However, even a relatively small decrease in agricultural sector emissions causes efficiency to drop by more than 3% relative to the previous estimate (61.4% to 57.7%). Thus, inclusion of the indirectly induced emissions within AF sectors does not substantially change efficiency in the pre-RFS2 scenario, as it does in the RFS2 75% and 125% scenarios.

Under the RFS2 75% scenario, the reduction in AF emissions is more substantial than the reductions resulting from a shift to pre-RFS2 conditions (which is not surprising given that corn ethanol production is lower under the RFS2 75% scenario than under the pre-RFS2 standard). When the change in national AF emissions is added to the efficiency metric, total biofuel efficiency is reduced by approximately one-third (58.4% to 40.3%), signaling the impact that domestic indirect emissions effects have on total system efficiency. Conversely, moving to the RFS2 125% scenario increases emissions flux from the AF sector. When this change is added to the efficiency metric, total abatement efficiency decreases by nearly one-third, thereby undermining the benefits of biofuel mandate expansion.

In summary, increasing the mandates will boost cultivation emissions, slightly reduce livestock emissions, and lead to an overall increase in domestic ILUC emissions. When fully accounted for, biofuels can produce a net source of GHG mitigation, but total GHG efficiency resulting from changes in the biofuels mandate is roughly 40% of implied emissions reduction once all domestic emissions sources from biofuels production (direct and indirect) are accounted for. If international ILUC emissions from global agricultural expansion resulting from higher mandated biofuels were added to this metric, the net efficiency of biofuel expansion would likely be further reduced. Emissions from international production shifts caused by U.S. biofuel policies are being addressed in a separate report by this research team.

Table 14. Net GHG consequences of varying the volume of the RFS2 mandates (comparing annuity values)

	1. Difference in ethanol output (billion gallons/year)[a]	2. Difference in biodiesel output (billion gallons/year)[a]	3. Total difference in gasoline equivalence (bgy)[b]	4. Direct fossil fuel emissions displacement (million t CO_2e)[c]	5. Difference in emissions to produce biofuels (million t CO_2e)[d,e]	6. Direct GHG emissions abatement (million t CO_2e)	7. Direct GHG emissions abatement/direct displacement	8. Induced agricultural cultivation emissions (million t CO_2e)[d]	9. Induced forestry sector emissions (million t CO_2e)[d]	10. Net emissions abatement effect (direct abatement effect less induced AF emissions)	11. Net GHG displacement efficiency of baseline biofuels relative to alternative scenarios
Pre-RFS2	-9.44	-0.58	-7.51	-67.55	-26.08	-41.47	**61.4%**	-2.93	0.46	-39.00	**57.7%**
RFS2 75%	-6.66	-0.37	-5.26	-47.35	-19.67	-27.67	**58.4%**	-4.16	-4.42	-19.10	**40.3%**
RFS2 125%	6.61	0.37	5.23	47.03	19.75	27.28	**58.0%**	5.87	1.54	19.87	**42.2%**

a. From FASOMGHG simulation output based on total grain and cellulosic ethanol (or biodiesel), less total ethanol (biodiesel) in the baseline (annualized average).
b. One gallon of ethanol (E85) yields approximately 0.731 gallons of gasoline-equivalent energy. Biodiesel (B100) yields 1.047 gallons of gasoline equivalent. Ethanol and biodiesel gasoline gallon equivalents are summed together. The gasoline equivalence conversion factor can be found at http://www.energy.ca.gov/2007publications/CEC-600-2007-002/CEC-600-2007-002-D.PDF.
c. Assumes 0.00891 t CO_2e emissions factor per gallon of gasoline. See http://www.epa.gov/cleanenergy/energy-resources/calculator.html.
d. FASOMGHG estimates (million t CO_2e annuity).
e. Excludes emissions from feedstock cultivation.

Comparison of emissions displacement estimates

In 2010, the U.S. EPA conducted a regulatory impact analysis (RIA) of the RFS2 (U.S. EPA 2010). It evaluated the full life-cycle GHG abatement potential of various biofuels using a variety of modeling frameworks. These frameworks included FASOMGHG for domestic cultivation, livestock, and land use emissions, and other sources for indirect international land use change emissions and technology-specific processing emissions. EPA performed an individual life-cycle analysis for each biofuel, including corn ethanol, soybean biodiesel, and cellulosic ethanol from switchgrass and corn stover.[18]

Table 15 compares EPA's fuel-specific emissions displacement efficiency estimates with this report's displacement efficiency estimates. The first column in Table 15 highlights the difference in net biofuel output from EPA's reference case scenario with the RFS2 control case. Moving from EPA's reference case to the control (RFS2) case increases corn ethanol output by roughly 2.7 billion gallons per year in 2022. In other words, without the RFS2, EPA estimates that corn ethanol production would be about 12.3 billion gallons, only 2.7 billion gallons less than the mandated 15 billion gallons. The greatest total shifts in biofuel are output are for cellulosic ethanol from switchgrass (7.9 billion gallons higher under RFS2) and corn stover (4.9 billion gallons higher).

To make a direct comparison between this report's full-portfolio estimates of emissions displacement efficiency and EPA's fuel-specific estimates, a portfolio displacement efficiency metric implied by EPA's fuel-specific factors must be computed. This task is accomplished by computing a weighted average of the individual displacement efficiencies by multiplying the proportion of each particular biofuel to the new fuel mix (Column 2) by the EPA estimated (or mandated) GHG displacement factors (Column 3). Then, summing over each weighted average (for every biofuel type) generates the net displacement efficiency factor for the resulting fuel mix. Column 3 displays the EPA-estimated net displacement efficiency factors for each biofuel type. Assuming that additional biofuels result in GHG abatement rates that *exactly match EPA-estimated displacement factors* for each fuel type, the resulting weighted average emissions-displacement rate from such a fuel mix is approximately 84%. In other words, on average, additional biofuel production associated with a movement from EPA's reference case to the RFS2 would displace approximately 84% of energy-equivalent fossil fuel emissions. This incredibly efficient fossil fuel emissions displacement rate is due to high displacement efficiency estimates for cellulosic ethanol, which forms the bulk of the additional biofuel portfolio (approximately 80% of the additional fuels produced come from switchgrass and crop residue-derived fuels).

Displacement efficiencies calculated in this study are much lower (approximately 40% to 60%, as indicated by Table 14) than those calculated by EPA. Consider this study's estimated displacement efficiency when moving from the pre-RFS2 to the RFS2 baseline scenarios, the scenarios that most closely match the EPA baseline versus RFS2 calculation (column 4). Table 15 shows that this efficiency is approximately 57.7%, implying that biofuels are roughly one-third less efficient at mitigating GHG emissions than the weighted EPA displacement measures. This finding is striking, given that *the EPA study includes induced international land use change emissions, and this one does not.*

This study's net displacement efficiency estimates differ from the EPA study's estimates for several reasons. First, this study uses an updated and enhanced version of FASOMGHG. This version reflects modeling assumptions that differ from those in the EPA analysis.

Second, this study shifts the entire biofuel portfolio, instead of examining individual biofuels one at a time. Although this approach cannot isolate the relative emissions impacts of adjusting a particular fuel volume, it captures the combined effects of requiring additional simultaneous production of multiple fuels, which is, in fact, what the U.S. biofuels policy mandates. This requirement pressures agricultural production to the intensive and extensive margins, leading to greater domestic GHG impacts. The interactions entailed by simultaneous varying of multiple biofuel volumes can result in net emissions estimates higher than estimates arrived at by examination of each fuel in isolation. For example, the EPA displacement efficiency estimates for cellulosic ethanol relied in part on increased carbon storage from domestic land use change. In other words, more cellulosic ethanol was considered to induce higher (than baseline) carbon storage rates elsewhere on the landscape. With such positive or "good" leakage, the direct GHG benefits of biofuel use are augmented by net emissions reductions elsewhere, rather than net emissions increases (negative or "bad" leakage). This positive leakage is the reason that the resulting emissions displacement effect is greater than 100%.

18. Corn stover is the residue (stalk, leaves, husks, and cobs) remaining in the field after harvest. It can be collected and processed into cellulosic ethanol.

The third reason for the difference in estimates is associated with the treatment of corn stover. The EPA analysis relied heavily on corn stover for cellulosic ethanol, whereas this study relies on a cellulosic mix almost entirely comprised of dedicated energy crops (primarily switchgrass) and some forestry products (such as residues and pulpwood). This analysis includes adjusted cost specifications for cellulosic ethanol feedstocks (Rose et al. 2011). According to these specifications, transportation and storage costs are higher than those contained in previous versions of FASOMGHG, which the EPA analysis used, rendering ethanol from corn stover less cost-effective in this study than in the EPA study. Dedicated energy crops can produce a GHG-efficient biofuel source, but they require significant land areas, whereas corn stover does not compete directly with food crops and thus does not push emissions elsewhere.

In summary, although this analysis does not estimate indirect LUC emissions in international regions, it finds the net GHG displacement potential of moving from pre-RFS2 conditions to the RFS2 (57.7%) to be much lower than the implied displacement efficiency estimated by the EPA (83.9%). When the RFS2 75% and 125% scenarios (40.3% and 42.2%, respectively) are examined, the differences in the findings of the two studies are even more striking, because emissions from domestic deforestation reduce the net efficiency of biofuels even further. The implication of the differences in these findings is that policy makers should be mindful that the combined effects of simultaneously adjusting multiple biofuel volumes could reduce the overall displacement efficiency of individual biofuels.

Table 15. Comparison of this study's net displacement efficiency estimates with EPA estimates

	1. Difference in fuel volume from reference case to the RFS2, 2022 (billion gallons)	2. Share of additional biofuel output	3. EPA-estimated displacement efficiency by biofuel type[a]	4. Displacement efficiency for this study (pre-RFS2 to RFS2 baseline)[b]
Corn ethanol	2.7	16.9%	21.0%	--
Cellulosic ethanol (switchgrass)	7.9	49.4%	91.0%	--
Cellulosic ethanol (corn stover)	4.9	30.6%	110.0%	--
Soybean biodiesel	0.5	3.1%	57.0%	--
Displacement efficiency for the full biofuel portfolio			**83.9%**	**57.7%**

a. Includes international LUC emissions. EPA examined individual biofuel types one at a time and assumed use of specific conversion technologies and fuel use.
b. Does not include international LUC emissions.

Conclusions and Policy Implications

The 2007 U.S. Renewable Fuels Standard (RFS2), requires the use of at least 36 billion gallons per year of biofuels, most of which would be produced using feedstock from domestic agriculture, by 2022. This policy created a substantial change in the sector, mandating a five-fold increase from 2007 biofuel production levels. The policy is intended to promote energy security, reduce anthropogenic GHG emissions from fossil fuel consumption, and enhance rural incomes. But the policy also has important implications for commodity production and land use, which in turn affect the environment and economy in many ways.

This report examines long-term trends in GHG emissions and N use in U.S. agriculture and how these trends are affected—directly and indirectly—by U.S. biofuel policies. It draws on results from a comprehensive model of U.S. agriculture, forestry, and land use to project a future baseline and simulate departures from that baseline due to variations in biofuel policy. The baseline departures focus on land use change, commodity production, GHG emissions, and N use in the U.S. AF sectors. These results are compared with historical and current trends in an effort to assess whether biofuel policies, and possible changes to them, are likely to have a large impact on sectoral economics, environmentally sensitive input use, and GHG emissions. The approach to this study is based on the following principles:

A system-wide view is necessary to accurately gauge the net GHG displacement effects of biofuels. Agricultural feedstock cultivation emissions are an important component of "well-to-wheel" life-cycle emissions for biofuels, but agricultural emissions under business-as-usual trajectories are important to consider when gauging the incremental effect of biofuel policy. Biofuel expansion will raise the demand for feedstock commodities such as corn. Some of this demand may stem from new cultivation, and thus increase emissions. In other cases, corn production is simply shifted from other end uses, such as animal feed and processed goods, and thus the net impact on emissions is more ambiguous. Indirect effects of increasing biofuel production are reflected in commodity prices, output substitution, land use change, and livestock populations, among other factors. Thus, evaluating all sources of emissions (from land transformation to cultivation to livestock to processing to use) within the entire system (the land base, commodity markets, and production and transportation infrastructure) is critical. These baseline emissions must be compared to emissions under alternative policy scenarios to fully capture the net change in full-system emissions resulting from a change in biofuels production.

Time dynamics in the production system should be explicitly captured. Other studies have recognized the importance of capturing full-system emissions fluxes, but the modeling efforts often rely on static (one-period) modeling techniques in which a baseline is compared to an alternative biofuel expansion scenario that shocks the system with a one-time increase in biofuel requirements (Hertel et al. 2010). The resulting difference in land use change (or cultivation) emissions is factored into the net GHG displacement calculation. Although this modeling approach is valid for addressing some problems, it ultimately ignores system dynamics and agricultural and forestry land use competition over the long term. Moreover, applying a large one-time shock to the system can overstate the marginal indirect impact of an additional unit of biofuels.

The FASOMGHG model used for this analysis is designed to meet these analytical objectives by capturing a systematic view of the U.S. AF sectors dynamically over multiple decades. To provide context for these projections, they are linked to historic observations of key variables, as described below.

Historic and current trends

Agricultural GHGs steadily account for about 7% of U.S. GHG emissions. According to recent U.S. EPA analysis, net GHG emissions from U.S. agricultural production have been relatively flat over the past decade, averaging approximately 400 million t CO_2e per year (excluding emissions from crop management fossil fuel use). These emissions accounted for roughly 7% of total anthropogenic emissions in the United States over the same period.

Cropland area has remained fairly steady. Agricultural land use has continued to ebb and flow, with no discernible upward or downward trend between 1960 and 2009. Cultivated cropland has been relatively stable since 1990 (averaging approximately 310–320 million acres).

Nitrogen use surged in the 1960s and began to taper off in the late 1990s. Nitrogen application began to increase dramatically during the Green Revolution of the 1960s but has increased only marginally since 2000 (the one exception was the 2008–2009 period, during which fertilizer prices soared and N use dropped substantially). The flattening of N use implies that U.S. agriculture has been able to meet rising demands over the last decade without significantly altering its resource base or intensifying input use. Efficiency in N use has also improved due to scientific advances in crop breeding and application techniques and technologies. For corn, total N use has remained about constant, use per bushel produced has fallen, and N use intensity per acre has grown since 1960, which indicates that additional corn ethanol might increase U.S. nitrogen consumption and pollution.

Despite the relative stability of resource use in the last decade, the RFS2 could put considerable pressure on the system by requiring large volumes of AF feedstocks to meet biofuel-processing requirements, thereby inducing increases in the area of land under cultivation and input intensification. This report analyzes how land use patterns and traditional crop mixes might shift with changes in biofuel policy and how such shifts might alter crop management choices, nitrogen use and runoff, and GHG emissions.

Baseline simulation results

Commodity price projections initially rise and then decrease, consistent with long-term trends in agricultural markets. Under baseline conditions (with the RFS2 intact), historical trends in U.S. agriculture continue; real commodity prices decline over time after an initial rise due to RFS2 and other demand factors. These simulated prices must be put into context—FASOMGHG is a deterministic model that simulates a projected baseline in five-year time steps consistent with recently published government mid-term projections of crop and energy demands. These government demand projections, and thus the FASOMGHG projections, do not reflect various exogenous factors that have contributed to recent price spikes (weather, biofuel expansion policies, rising demand/changing preferences, and other factors as discussed in Trostle et al. 2008), but they do reflect more defined long-term trends. This study does not alter foreign agricultural production and land use to reflect the possible effects of U.S. biofuel initiatives. Commodity prices, although generally projected to decrease in absolute terms, are expected to be higher than they would be in the absence of biofuel mandates.

Price projections are heavily affected by productivity and technical change. Over the long term, steady to falling prices are attributable to productivity improvements, which in our projections outpace demand growth. Although not the focus of this study, price trajectories (and hence land use decisions) are quite sensitive to baseline assumptions regarding productivity improvement and demand growth. For example, if export demand were to grow more than the current assumptions, prices would increase considerably. Alternatively, realizing lower productivity gains (or shifting the expected supply curve inward) could also boost market prices considerably, because the global demand for food calories is highly inelastic (Roberts and Schlenker 2009).

Cropland area initially expands to meet the demands of RFS2, then decreases. Initially, baseline cropland area is projected to increase, because additional land is needed for energy feedstock production; it starts to decrease once the mandates are met. The majority of this expansion occurs in the Midwest and Great Plains, which realize greater levels of corn production and devote large areas to dedicated energy crops. Expansion also occurs in the Southeast, which increases conventional production to help meet supply shortages left by changing crop-mix patterns in the Midwest and Great Plains. Energy crop production also expands in the Southeast, but not until after the 2020 simulation period.

Because biofuel mandates are held constant beyond 2022, continued productivity improvements reduce the demand for land as the primary input. Thus, after initially requiring a greater land base for higher levels of corn and soybean production, and approximately 20 million acres for energy crop production, the system is able to meet biofuel feedstock demands on less land by producing more per unit area.

Nitrogen use rises. Projected total N use and intensity per acre are projected to increase slightly under baseline conditions, consistent with recently observed trends. But unlike prices and cropped acreage, total N use and intensity do not taper off in later periods, due to required intensification in N use associated with higher future yields.

Net GHG emissions from agriculture fall and then rise. Projected baseline GHG emissions initially fall due to the fossil fuel emissions-displacement effect of biofuels and increased agricultural soil carbon stocks (partly attributable to increases in belowground carbon storage associated with energy crop production). However, emissions begin to rise after full implementation of the RFS2 (in the 2020 period) as technological progress continues but emissions displacement of biofuels remains nearly constant. When forestry sector emissions are included in the total, the AF sectors are initially projected to be a net source of emissions (emissions are greater than sequestration), because land use initially shifts out of forestry, creating carbon emissions that outweigh carbon sequestered on new and existing forest stands. Over time, however, the forest carbon sink recovers, and net AF sector emissions decrease.

GHG emissions are projected to rise once the RFS2 is fully implemented, because no further policy incentives for their reduction are assumed. If, however, the United States adopted a comprehensive GHG reduction policy that included the AF sectors, either through direct regulation or through positive incentives (such as offset credits or carbon prices for the rest of the economy), future emissions could potentially decrease.

Policy scenario simulation results

To understand the impact of biofuel mandates and variations thereof, this analysis developed a set of sensitivity scenarios that varied the amount and mix of biofuels required to meet the mandates. The scenarios include a pre-RFS2 baseline that mimics minimum biofuel constraints consistent with the previous lower biofuel mandate (RFS1), along with the effect of energy prices that might drive demand beyond the mandate. Other policy scenarios vary the total mandated volume up and down by 25% (holding proportions constant by biofuel type). Another scenario holds the mandated volume constant and raises the proportion of conventional ethanol allowed to meet the mandate.

Cropland use varies directly with the mandate levels, but the effect is relatively modest. Total cropland increases when the volume of the biofuels produced is increased, but only by a modest amount (1%–2% for a 25% change in the mandate). Some additional crop production comes from extensive margin expansion, as agricultural deforestation and pasture cultivation grow with the mandate. As additional land is cultivated under higher biofuel production targets, much of the newly cropped acreage is used to produce dedicated energy crops such as switchgrass and hybrid poplar. Although corn and soybean production increases with the mandates, land use for other conventional commodities, such as wheat and cotton, shrinks.

Higher mandates and certain feedstocks require more nitrogen use. More cropland implies greater levels of other agricultural inputs, especially nitrogen. Indeed, total N use expands with increases in the biofuel mandate and whenever a higher proportion of corn ethanol is required. N use per-unit area also expands with increases in the mandate and in the high corn scenario, indicating a substitution of higher N-using crops and a degree of an intensive margin shift. N use shifts are relatively modest; average changes from the baseline range from -2% to 2.5%. N use intensity shifts are even less dramatic, ranging from -1% to 1%. If more ethanol could be produced with cellulosic feedstocks rather than corn, the relative demand for N use would decrease.

How effective are biofuels as a GHG reduction strategy?

Several recent studies suggest that the net GHG benefits of biofuels can be quite small, even negative, once the energy required to produce biofuels and the emissions consequences of the land use change induced by biofuel feedstock expansion are considered. This study directly addresses these issues by estimating various forms of GHG displacement from biofuel expansion.

Biofuels have positive GHG displacement effects, but they vary by type and by scope of emissions accounting. Shifts in land management patterns in response to different biofuel targets alter AF emissions trajectories and can affect the net GHG displacement potential of biofuels.

The net GHG reduction efficiency of biofuels drops as the scope of the accounting system is expanded to include direct and indirect cultivation and LUC emissions (in the United States only). Including these direct and indirect land use emissions decreases the GHG reduction efficiency of biofuel policy. Consequently, GHG efficiency is cut by about one-third from initial estimates that ignore land use emissions, because the spillover effects on other land uses is more pronounced. However, under the pre-RFS2 scenario, the induced GHG effects (and reduction in efficiency) are not as pronounced, because much of the biofuel production is driven by actual demand in the energy market, rather than by mandate levels. The change in cultivation emissions when moving from RFS2 to pre-RFS2 drops the net displacement efficiency by approximately 4% (or one-fifteenth).

The net GHG displacement efficiency of biofuels is lower than comparable EPA estimates. Implied GHG displacement efficiency in this study is lower than the implied displacement efficiency of moving to the RFS2 following EPA's analysis of the RFS2 at the time of implementation. This finding is noteworthy because the same model (FASOMGHG) was used for both studies. There are two main reasons for the difference. The first is that this study has used a more recent version of the model that reflects new data and parameters to determine the most cost-effective feedstock options. The second reason is that the approach to calculating the net displacement efficiency was different. The EPA study examined the displacement efficiency of various fuel types one at a time. This study examines them simultaneously as a group, capturing substitution among the fuel sources as they collectively meet the broad mandate. The latter approach, which better captures the applicable policy conditions, results in a less GHG-efficient biofuel portfolio than suggested by the EPA analysis.

Ultimately, this study shows that biofuels can contribute to GHG reduction goals, but that indirect emissions fluxes reflecting changes in land use and livestock herds must be considered in evaluating those fuels' net GHG abatement potential. This study examines emissions across the AF sectors, but within the United States alone. A national perspective is quite useful for assessing domestic policy success, but a more comprehensive assessment—one that factors in international LUC emissions using a similar modeling approach—is needed. The net global consequence of U.S. biofuel policy on global GHG emissions and N use is the subject of a forthcoming study co-produced by this research team.

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