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U.S. Agricultural and Forestry Impacts of the Energy Independence and Security Act: FASOM Results and Model Description

Final Report

Prepared for

U.S. Environmental Protection Agency
Office of Transportation and Air Quality
Ariel Rios Building
1200 Pennsylvania Avenue, N.W.
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CONTENTS

LIST OF FIGURES

LIST OF TABLES

SECTION 1
OVERVIEW OF FASOM

The Forest and Agricultural Sector Optimization Model (FASOM), developed by Professor Bruce McCarl of Texas A&M University and others, is a dynamic nonlinear programming model of the U.S. forest and agricultural sectors. The model solves a constrained dynamic optimization problem that maximizes the net present value of the sum of producer and consumer surplus across the two sectors over time. The model is constrained such that total production is equal to total consumption, technical input/output relationships hold, and total land use must remain constant. FASOM simulates the allocation of land over time to competing activities in both the forest and agricultural sectors and the associated impacts on commodity markets. In addition, the model simulates environmental impacts resulting from changing land allocation and production practices, including accounting for changes in net greenhouse gas (GHG) emissions for particular agricultural activities. The model was developed to evaluate the welfare and market impacts of policies that influence land allocation and alter production activities within these sectors. FASOM has been used in numerous studies to examine issues including GHG mitigation policy, potential impacts of climate change, timber harvest policy on public lands, federal farm programs, bioenergy production, and a variety of other policies affecting the forest and agricultural sectors.

The comprehensive sectoral coverage provided by FASOM is advantageous for analyzing the impacts of the Energy Independence and Security Act of 2007 (EISA) renewable fuel volume requirements for a number of reasons. Because the model accounts for land competition and landowner responses to changing relative prices, FASOM provides a more complete assessment of the net market impacts associated with increasing the demand for renewable fuel feedstocks than models that focus only on the feedstocks. Using FASOM enables determination of secondary impacts such as crop switching, movements between cropland and pasture, movements between agricultural land and forestland, and reductions in equilibrium quantities of agricultural and forest commodities due to higher prices. FASOM also captures changes in the livestock market due to higher feed costs as well as changes in U.S. exports and imports of major agricultural commodities. In addition, FASOM accounts for changes in the primary agricultural GHGs, which are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), from the majority of emitting agricultural activities and tracks carbon sequestration and carbon losses over time. The intertemporal dynamics of the economic and biophysical systems within FASOM allow for an accounting of environmental impacts over time and by region. This allows for a more complete quantification of net impacts than other models are generally able to produce, which provides insight into the multiple environmental and economic impacts in these sectors.

Section 1.1 provides a synopsis of the most recently updated version of FASOM used in analyses of the domestic agricultural, forestry, and environmental impacts of implementing the renewable fuel standard (RFS2) volumes consistent with EISA. Section 1.2 describes the application of FASOM to modeling the proposed renewable fuel volumes specified under EISA. In Section 1.3, we highlight modifications to the model that have been made since the analysis conducted for the RFS2 proposal to reflect comments received and availability of new data. In Section 2, we present key model results for this analysis. In addition, a set of four appendixes provides additional detail on the FASOM model, focusing on assumptions and parameters most directly relevant for the analysis of large-scale production of renewable fuels. Appendix A provides more detail on the FASOM model assumptions and GHG accounting. Appendix B presents additional information regarding the incorporation of starch- and sugar-based ethanol production in the model. Appendix C describes similar information for the production of biodiesel in FASOM. Finally, Appendix D summarizes assumptions underlying the modeling of ethanol production using cellulosic feedstocks. A fifth appendix, Appendix E, presents selected results from a sensitivity analysis examining the effects of assuming larger increases in corn and soybean yields over time.

1.1 Model Description

This section provides a brief history of the FASOM model and its predecessor models as well as an overview of model structure and a discussion of recent major updates, particularly those related to modeling renewable fuels markets.[1] Appendix A provides additional detail on FASOM model assumptions, modeling methodology, and GHG accounting.

1.1.1 Model Development

The current version of FASOM reflects numerous model enhancements that have been made over time, dating back to the first version of the Agricultural Sector Model (ASM).[2] Since the initial version of ASM, there have been many changes to the model, including

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[1]See http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf for additional detail on the FASOM model.

[2]Baumes, H. 1978. "A Partial Equilibrium Sector Model of U.S. Agriculture Open to Trade: A Domestic Agricultural and Agricultural Trade Policy Analysis." Ph.D. dissertation. W. Lafayette, IN: Purdue University.

improvements for pesticide analysis by Burton,[3] as reported in Burton and Martin,[4] and a number of model additions to enable more detailed environmental and resource analyses. ASM has been used for analyses of renewable fuel production dating back to the late 1970s and 1980s.[5,6,7] In addition, ASM was applied to study ozone impacts,[8,9] acid rain,[10] soil conservation policy,[11] global climate change impacts,[12,13,14,15,16,17,18] and GHG mitigation.[19,20]

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[3]Burton, R.O. 1982. "Reduced Herbicide Availability: An Analysis of the Economic Impacts on U.S. Agriculture." Ph.D. thesis. W. Lafayette, IN: Purdue University.

[4]Burton, R.O., and M.A. Martin. 1987. "Restrictions on Herbicide Use: An Analysis of Economic Impacts on U.S. Agriculture." *North Central Journal of Agricultural Economics* 9:181-194.

[5]Tyner, W., M. Abdallah, C. Bottum, O. Doering, B.A. McCarl, W.L. Miller, B. Liljedahl, R. Peart, C. Richey, S. Barber, and V. Lechtenberg. 1979. "The Potential of Producing Energy from Agriculture." Report to the Office of Technology Assessment. W. Lafayette, IN: Purdue University School of Agriculture.

[6]Chattin, B.L. 1982. *By-product Utilization from Biomass Conversion to Ethanol*. Ph.D. dissertation. W. Lafayette, IN: Purdue University.

[7]Hickenbotham, T.L. 1987. *Vegetable Oil as a Diesel Fuel Alternative: An Investigation of Selected Impacts on U.S. Agricultural Sector*. Ph.D. dissertation. St. Paul, MN: University of Minnesota.

[8]Hamilton, S.A. 1985. *The Economic Effects of Ozone on U.S. Agriculture: A Sector Modeling Approach*. PhD. Dissertation. Oregon State University.

[9]Adams, R.M., S.A. Hamilton, and B.A. McCarl. September 1984. "The Economic Effects of Ozone on Agriculture." Research Monograph. EPA/600-3-84-90. Corvallis, OR: USEPA, Office of Research and Development.

[10]Adams, R.M., J.M. Callaway, and B.A. McCarl. 1986. "Pollution, Agriculture and Social Welfare: The Case of Acid Deposition." *Canadian Journal of Agricultural Economics* 34:3-19.

[11]Chang, C.C., J.D. Atwood, K. Alt, and B.A. McCarl. 1994. "Economic Impacts of Erosion Management Measures in Coastal Drainage Basins." *Journal of Soil and Water Conservation* 49(6):606-611.

[12]Adams, R.M., J.D. Glyer, B.A. McCarl, and D.J. Dudek. 1988. "The Implications of Global Change for Western Agriculture." *Western Journal of Agricultural Economics* 13(December):348-356.

[13]Adams, R.M., C. Rosenzweig, R.M. Peart, J.T. Ritchie, B.A. McCarl, J.D. Glyer, R.B. Curry, J.W. Jones, K.J. Boote, and L.H. Allen Jr. 1990. *Global Change and U.S. Agriculture. Nature* 345:219-224.

[14]Adams, R.M., B.A. McCarl, K. Segerson, C. Rosenzweig, K.J. Bryant, B.L. Dixon, R. Connor, R.E. Evenson, and D. Ojima. 1999. "The Economic Effects of Climate Change on U.S. Agriculture. In *The Economics of Climate Change*, R. Mendelsohn and J. Neumann, eds., pp. 19-54. New York: Cambridge University Press.

[15]Adams, R.M., C.C. Chen, B.A. McCarl, and D.E. Schimmelpfenning. 2001. "Climate Variability and Climate Change." In *Advances in the Economics of Environmental Resources*, Vol. 3, D. Hall and R. Howarth, eds., pp. 115-148. London: JAI Press.

[16]McCarl, B.A. 1999. "Economic Assessments under National Climate Change Assessment." Presented at Meeting of National Climate Change Assessment Group, Washington, DC.

[17]Reilly, J., F. Tubiello, B. McCarl, and J. Melillo. 2000. "Climate Change and Agriculture in the United States." In *Climate Change Impacts on the United States: The Potential Consequences of Climate Variability and Change*, pp. 379-403. Report for the U.S. Global Change Research Program. New York: Cambridge University Press.

[18]Reilly, J.M., F. Tubiello, B.A. McCarl, D.G. Abler, R. Darwin, K. Fuglie, S.E. Hollinger, R.C. Izaurralde, S. Jagtap, J.W. Jones, L.O. Mearns, D.S. Ojima, E.A. Paul, K. Paustian, S.J. Riha, N.J. Rosenberg, and C. Rosenzweig. 2002. "U.S. Agriculture and Climate Change: New Results." *Climatic Change* 57:43-69.

[19]Adams, R.M., D.M. Adams, J.M. Callaway, C.C. Chang, and B.A. McCarl. 1993. "Sequestering Carbon on Agricultural Land: Social Cost and Impacts on Timber Markets." *Contemporary Policy Issues* 11:76-87.

[20]McCarl, B.A., and U.A. Schneider. 2001. "The Cost of Greenhouse Gas Mitigation in US Agriculture and Forestry." *Science* 294(Dec):2481-2482.

One of the drivers behind integrating ASM with forest-sector models to create FASOM was an ASM study examining issues regarding joint forestry and agricultural GHG mitigation.[21] Attempting to reconcile forestry production possibilities with the static single-year equilibrium representation in ASM led to the recognition that the model did not adequately reflect a number of dynamic issues associated with land allocation between forestry and agriculture. Thus, the initial FASOM model was constructed to address these limitations by linking a simple intertemporal model of the forest sector with a version of the ASM model in a dynamic framework, allowing some portion of the land base in each sector to be shifted to the alternative use. Land could transfer between sectors based on its marginal profitability in all alternative forest and agricultural uses over the time horizon of the model. Management investment decisions in both sectors, including harvest timing in forestry, were made endogenous, so they too would be based on the expected profitability of an additional dollar spent on expanding future output (both timber and carbon, if valued monetarily).

The basic structure of the forest sector was based on the family of models developed to support the timber assessment component of the U.S. Forest Service's decennial Forest and Rangeland Renewable Resources Planning Act (RPA) assessment process: TAMM (Timber Assessment Market Model),[22,23,24] NAPAP (North American Pulp and Paper model),[25,26,27] ATLAS (Aggregate Timberland Assessment System),[28] and AREACHANGE.[29,30] Timber inventory data

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[21] Adams, R.M., D.M. Adams, J.M. Callaway, C.C. Chang, and B.A. McCarl. 1993. "Sequestering Carbon on Agricultural Land: Social Cost and Impacts on Timber Markets." *Contemporary Policy Issues* 11:76-87.

[22] Adams, D.M. and R.W. Haynes. 1980. *The 1980 Softwood Timber Assessment Market Model: Structure, Projections, and Policy Simulations*. Forest Science Monograph 22, 64 p.

[23] Adams, D.M. and R.W. Haynes. 1996. *The 1993 Timber Assessment Market Model: Structure, Projections, and Policy Simulations*. General Technical Report PNW-GTR-368. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 58 p.

[24] Haynes, R.W. (Technical coordinator). 2003. *An Analysis of the Timber Situation in the United States: 1952 to 2050*. General Technical Report PNW-GTR-560. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 254 p.

[25] Ince, P.J. 1994. *Recycling and Long-Range Timber Outlook*. General Technical Report RM-242. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 23 p.

[26] Zhang, D., J. Buongiorno, and P. Ince. 1993. *PELPS III: A Microcomputer Price Endogenous linear Programming System for Economic Modeling: Version 1.0*. Research Paper FPL-526. Madison, WI: USDA, Forest Service, Forest Products Laboratory, 43 p.

[27] Zhang, D., J. Buongiorno, and P. Ince. 1996. "A Recursive Linear Programming Analysis of the Future of the Pulp and Paper Industry in the United States: Changes in Supplies and Demands, and the Effects of Recycling." *Annals of Operations Research* 68:109-139.

[28] Mills, J., and J. Kincaid. 1992. *The Aggregate Timberland Assessment System—ATLAS: A Comprehensive Timber Projection Model*. General Technical Report PNW-281. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 160 p.

[29] Alig, R.J., A. Plantinga, S. Ahn, and J. Kline. 2003. *Land Use Changes Involving Forestry for the United States: 1952 to 1997, with Projections to 2050*. U.S. Forest Service General Technical Report 587, Pacific Northwest Research Station. Portland, OR, 92 p.

and estimates of current and future timber yields were taken in large part from the ATLAS inputs used for the 2000 RPA Timber Assessment (these data have since been updated with information from the 2005 interim RPA assessment, as described below).[31] The AREACHANGE models provide timberland area and forest type allocations to the ATLAS model. TAMM and NAPAP are "myopic" market projection models (they project ahead one period at a time) of the solid wood and fiber products sectors in the United States and Canada. In ATLAS, harvested lands are regenerated (grown) according to exogenous assumptions regarding the intensity of management and associated yield volume changes. The timberland base is adjusted for gains and losses projected over time by the AREACHANGE models, including afforestation of the area moving from agriculture into forestry. Product demand relations were extracted directly from the latest versions of TAMM and NAPAP, as were product supply relations for the solid wood products (such as lumber) and all product conversion coefficients for both solid wood and fiber commodities. Trade between the United States and Canada in all major classes of wood products is endogenous and subject to the full array of potential trade barriers and exchange rates. Timber supply also uses nearly the full set of management intensity options available in ATLAS (e.g., for the South, seven planted pine management intensity classes directly from ATLAS), and the selection of management intensity is endogenous.

In addition, detailed GHG accounting for CO_2 and major non-CO_2 GHGs was added into a model denoted FASOMGHG.[32] The forest carbon accounting component of FASOM is largely derived from the Forestry Carbon (FORCARB) modeling system, which is an empirical model of forest carbon budgets simulated across regions, forest types, land classes, forest age classes, ownership groups, and carbon pools. The U.S. Forest Service uses FORCARB, in conjunction with their economic forest-sector models (e.g., TAMM, NAPAP, ATLAS, and AREACHANGE) to estimate the total amount of carbon stored in U.S. forests over time as part of the Forest Service's ongoing assessment of forest resources in general (i.e., pursuant to the RPA) and forest carbon sequestration potential in particular.[33,34] Deriving FASOMGHG's forest carbon accounting structure from FORCARB ensures that forest carbon estimates from FASOM can be

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[30] Alig, R.J., J.D. Kline, and M. Lichtenstein. 2004. "Urbanization on the U.S. Landscape: Looking Ahead in the 21st Century." *Landscape and Urban Planning* 69(2-3):219-234.

[31] Haynes, R.W. (Technical coordinator). 2003. *An Analysis of the Timber Situation in the United States: 1952 to 2050*. General Technical Report PNW-GTR-560. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

[32] Throughout the remainder of this report, references to FASOM refer to the most recent version of FASOMGHG used to conduct this analysis.

[33] Joyce, L.A., ed. 1995. *Productivity of America's Forests and Climate Change*. General Technical Report RM-271. Fort Collins, CO: U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station.

[34] Joyce, L.A., and R.A. Birdsey, eds. 2000. *The Impact of Climate Change on America's Forests*. RMRS-GTR-59. Fort Collins, CO: U.S. Forest Service, Rocky Mountain Research Station.

analyzed and compared with ongoing efforts by the U.S. Forest Service to estimate and project forest carbon estimates at the national level. It also enables FASOM to be updated over time as the FORCARB system evolves to incorporate improved science.

Following the inclusion of forest carbon accounting and some limited coverage of soil carbon changes associated with land use change, work began to widen the coverage of agricultural GHG sources and management possibilities for mitigating GHG. Schneider[35] and McCarl and Schneider[36] expanded the model to account for numerous categories of GHGs and to include a detailed set of agricultural-related GHG management possibilities. That work expanded ASM to include changes in tillage, land use exchange between pasture and crops, afforestation, nitrogen fertilization alternatives, enteric fermentation, manure management, renewable fuel offsets, fossil fuel use reduction, and changes in rice cultivation. The resulting model was labeled ASMGHG.

Given the dynamic modeling and forest carbon sequestration coverage included in FASOM and the agricultural coverage in ASMGHG, it was decided to merge the agricultural alternatives into the FASOMGHG structure. This was manifest in the first version of FASOMGHG that was built in the context of Lee.[37] In that work, the agricultural model was expanded to have all the GHG management alternatives in ASMGHG with the additional coverage of dynamics. More recently, additional model modifications have been made to enhance FASOM's ability to provide detailed analyses of the agricultural and environmental impacts of large-scale renewable fuel production under EISA. These modifications are discussed in Section 1.1.3.

1.1.2 Model Structure

Examining the dynamic effects of policies affecting the forestry and agricultural sectors requires an analytical framework that can simulate the time path of market and environmental impacts. FASOM simulates a dynamic baseline and changes from that baseline in response to changes in public policy or other factors affecting the sector. FASOM combines component models of agricultural crop and livestock production, renewable fuels production, livestock feeding, agricultural processing, log production, forest processing, carbon sequestration, GHG

[35]Schneider, U.A. December 2000. "Agricultural Sector Analysis on Greenhouse Gas Emission Mitigation in the U.S." PhD dissertation. College Station, TX: Department of Agricultural Economics, Texas A&M University.
[36]McCarl, B.A., and U.A. Schneider. 2001. "The Cost of Greenhouse Gas Mitigation in US Agriculture and Forestry." *Science* 294(Dec):2481-2482.
[37]Lee, H.C. 2002. "The Dynamic Role for Carbon Sequestration by the U.S. Agricultural and Forest Sectors in Greenhouse Gas Emission Mitigation." PhD thesis. College Station, TX: Department of Agricultural Economics, Texas A&M University.

emissions, wood product markets, agricultural markets, GHG payments, and land use to systematically capture the rich mix of biophysical and economic processes that will determine the technical, economic, and environmental implications of changes in policies. FASOM covers private timberlands and all agricultural activity across the conterminous (“lower 48”) United States, broken into 11 market regions. Finally, FASOM tracks five forest product categories and more than 2,000 production possibilities for field crops, livestock, and renewable fuel (see Appendix A for additional detail).

As noted above, FASOM assumes intertemporal optimizing behavior by economic agents. Landowners are assumed to have perfect foresight and base decisions in a given period on the net present value of the future returns to alternative activities.[38] For instance, the decision to continue growing a stand rather than harvesting it now is based on a comparison of the net present value of timber harvests from future periods versus the net present value of harvesting now and replanting (or not replanting and shifting the land to agricultural use). Similarly, landowners make a decision to keep their land in agriculture vs. afforestation based on a comparison of the net present value of returns in agriculture and forestry. Land can also move between cropland and pasture depending on relative returns. This process establishes an equilibrium price for land across the sectors (reflecting productivity in alternative uses and land conversion costs) and, given the land base interaction, a link between contemporaneous commodity prices in the two sectors as well.

Mathematically, FASOM solves an objective function to maximize net market surplus, represented by the area under the product demand function (an aggregate measure of consumer welfare) less the area under factor supply curves (an aggregate measure of producer costs). Such an approach involves solving a nonlinear programming model with endogenous product and factor prices. The resultant objective function value is consumer plus producer surplus.

Operationally, FASOM is a multiperiod, intertemporal, price-endogenous, mathematical programming model depicting land transfers and other resource allocations between and within the agricultural and forest sectors in the United States. The model solution portrays simultaneous market equilibrium over an extended time, typically 70 to 100 years on a 5-year time step basis when running the combined agriculture-forest version of the model. Results yield a dynamic simulation of prices, production, management, consumption, GHG effects, and other environmental and economic indicators within these sectors under each scenario defined in the model run.

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[38] FASOM calculates net present values using a 4% discount rate.

The key endogenous variables in FASOM include

- commodity and factor prices;
- production, consumption, export and import quantities;
- land use allocations between sectors;
- management strategy adoption;
- resource use;
- economic welfare measures;
  - producer and consumer surplus,
  - transfer payments,
  - net welfare effects; and
- environmental impact indicators:
  - GHG emission/absorption of CO_2, CH_4, and N_2O and
  - total nitrogen and phosphorous applications.

The subsections below provide an overview of the overall scope and structure of FASOM in terms of resources, production, processing, and commodity flows; land coverage; geographic scope; market modeling; land allocation; GHG accounting; renewable fuels; baseline; environmental indicators; dynamic scope; and dynamic yield, cost, and demand updating.

1.1.2.1 Resources, Production, Processing, and Commodity Flows

The basic conceptual framework of the agricultural sector in FASOM is presented in Figure 1-1. Land, water, labor, natural resources, and other resources (e.g., fertilizer, capital) are used to produce raw primary commodities, including renewable fuels feedstocks. These primary commodities may move directly to markets or they may be used as inputs to processing activities generating secondary commodities (e.g., renewable fuels), as direct livestock feed, or in the production of blended livestock feeds. The primary and secondary commodities, renewable fuels, blended feeds, and imports go to meeting household demand, other domestic demand, livestock feeding, and exports.

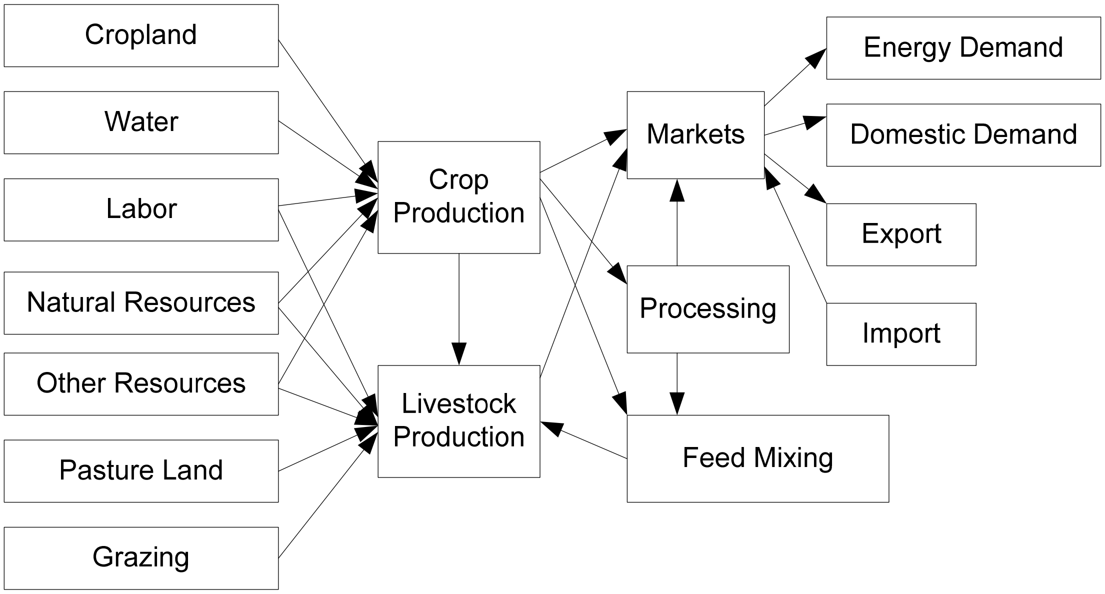

Figure 1-1. FASOM Agricultural Sector Modeling Structure

1.1.2.2 Commodities Modeled

FASOM includes several major groupings of agricultural and forest commodities, depending on the sector and whether they are raw, processed, used for bioenergy, or mixed for livestock feed. These commodity groups are

- raw crop, livestock, forestry, and renewable fuel feedstock primary commodities grown on the land;
- processed, secondary commodities made from the raw crop, livestock, and wood products;
- energy products made from renewable fuel feedstocks; and
- blended feeds for livestock consumption.

Agricultural commodities are quite frequently substitutable in demand. For example, sorghum is a close substitute for corn on a calorie-for-calorie basis in many uses, and beet sugar is a perfect substitute for sugar derived from sugarcane. In addition, a number of feed grains are substitutes in terms of livestock feeding. Similarly, many forestry products are substitutes for one another, such as sawtimber or pulpwood derived from alternative hardwood and softwood species groups. In addition, bioenergy feedstocks derived from agricultural and forestry commodities are substitutes for one another (e.g., ethanol can be produced using either crop residues or logging residues, among other potential feedstocks).

FASOM contains a set of processing activities that make secondary commodities. Secondary commodities are generally included in the model either to represent substitution or to depict demand for components of products. For example, processing possibilities for soybeans are included depicting soybeans being crushed into soybean meal and soybean oil because these secondary commodities frequently flow into different markets. Similar possibilities exist in the forest sector. For instance, paper could be made from pulp logs or from logging residues. Thus, the model reflects a large degree of demand substitution.

1.1.2.3 Geographic Coverage

FASOM includes all states in the conterminous United States, broken into 63 subregions for agricultural production and 11 market regions (see Table 1-1). The 11-region breakdown reflects the existence of regions for which there is agricultural activity but no forestry, and vice versa. Forestry production is included in 9 of the market regions (all but Great Plains and Southwest), whereas agricultural production is included in 10 of the market regions (all but Pacific Northwest—West side). The Great Plains and Southwest regions are kept separate because they reflect important differences in agricultural characteristics. Likewise, there are important differences in the two Pacific Northwest regions (PNWW, PNWE) for forestry, so they are maintained separately, although only the PNWE region is considered a significant producer of agricultural commodities tracked in the model.

1.1.2.4 Land Base Coverage

FASOM includes all cropland, pastureland, rangeland, and private timberland[39] throughout the conterminous United States. 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. Land categories included in the model are based on USDA Economic Research Service land use data[40] and are specified as follows:

- **Cropland** is land suitable for crop production that is being used to produce either traditional crops (e.g., corn, soybeans) or dedicated energy crops (e.g., switchgrass). The 1997 U.S. Department of Agriculture (USDA) National Resource Inventory (NRI) data (most recent NRI dataset that is publicly available at a spatially disaggregated level) coupled with USDA National Agricultural Statistics Service (NASS) data on county-level harvested acreage were used to specify land availability. Cropland is tracked by crop tillage system and irrigated/dryland status as well as the amount of time it has been in such a system to allow tracking of sequestered soil

[39] Although public timberland is not explicitly modeled because the focus of the model is on private decision-maker responses to changing incentives, FASOM includes an exogenous timber supply from public forestlands.
[40] USDA Economic Research Service. *Major Land Uses*. Dataset available at: http://www.ers.usda.gov/Data/MajorLandUses/.

Table 1-1. Definitions of 11 Market Regions in FASOM

Key	Region	States/Subregions
NE	Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia
LS	Lake States	Michigan, Minnesota, Wisconsin
CB	Corn Belt	All regions in Illinois, Indiana, Iowa, Missouri, Ohio (IllinoisN, IllinoisS, IndianaN, IndianaS, IowaW, IowaCent, IowaNE, IowaS, OhioNW, OhioS, OhioNE)
GP	Great Plains	Kansas, Nebraska, North Dakota, South Dakota
SE	Southeast	Virginia, North Carolina, South Carolina, Georgia, Florida
SC	South Central	Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Tennessee, Eastern Texas
SW	Southwest (agriculture only)	Oklahoma, All of Texas but the Eastern Part (Texas High Plains, Texas Rolling Plains, Texas Central Blacklands, Texas Edwards Plateau, Texas Coastal Bend, Texas South, Texas Trans Pecos)
RM	Rocky Mountains	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming
PSW	Pacific Southwest	All regions in California (CaliforniaN, CaliforniaS)
PNWE	Pacific Northwest—East side (agriculture only)	Oregon and Washington, east of the Cascade mountain range (agriculture only)
PNWW	Pacific Northwest—West side (forestry only)	Oregon and Washington, west of the Cascade mountain range (forestry only)

carbon and the transition to a new soil carbon equilibrium after a change in tillage. Cropland can be converted to cropland pasture or forestland.

- **Cropland pasture** is managed land suitable for crop production (i.e., relatively high productivity) that is being used as pasture, but it can potentially be converted to crop production or forestland.
- **Forest pasture** is pasture on land with varying amounts of tree cover that can also be used for livestock production, although forage productivity of these lands tends to be relatively low. This land category is further subdivided into forest pasture in forest (pasture on private timberland), forest pasture in agriculture (woodland pasture on farmland), and forest pasture in public (pasture on forested public lands that can be grazed).[41,42] Forest pasture in agriculture can be converted to private timberland, but the other two categories of forest pasture cannot be converted to any other uses.

[41] USDA Economic Research Service. *Major Land Uses*. Dataset available at: http://www.ers.usda.gov/Data/MajorLandUses/.
[42] Mitchell, J.E. 2000. *Rangeland resource trends in the United States: A technical document supporting the 2000 USDA Forest Service RPA Assessment*. General Technical Report RMRS-GTR-68. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

- **Rangeland** comprises both public and private rangeland, which is typically unimproved land where a significant portion of the natural vegetation is native grasses and shrubs. Rangeland generally has low forage productivity and is unsuitable for cultivation. In addition, much of the rangeland in the U.S. is publicly owned. It is assumed that rangeland cannot be used for crop production or forestland.

- **Forestland** in FASOM refers to private timberland, with a number of subcategories (e.g., different levels of productivity, management practices, age classes) tracked (see below for additional details). The model also reports the number of acres of private forestland existing at the starting point of the model that remains in standing forests (i.e., have not yet been harvested), the number of acres harvested, the number of harvested acres that have been reforested, and the area converted from other land uses (afforested). Public forestland area is not explicitly tracked because it is assumed to remain constant over time. Forestland can be converted to cropland, cropland pasture, or forest pasture in agriculture.

- **Developed** (urban) land is assumed to increase over time at an exogenous rate for each region based on projected changes in population and economic growth. It is assumed that the land value for use in development is sufficiently high that the movement of forest and agricultural land into developed land will not vary between the policy cases analyzed. Each of the four land categories described above moves into the developed land category at an exogenous rate (with the exception of forest pasture in forest and forest pasture in public), decreasing the total land base available for forestry and agriculture over time.

- **Conservation Reserve Program (CRP) land** is specified as land that is voluntarily taken out of crop production and enrolled in the USDA's CRP. Land in the CRP is generally marginal cropland retired from production and converted to vegetative cover, such as grass, trees, or woody vegetation to conserve soil, improve water quality, enhance wildlife habitat, or produce other environmental benefits. However, it is possible for this land to move back into cropland as landowner commitments to maintain land in CRP expire.

Land is allowed to move between categories subject to the restrictions discussed under each category above. The conversion costs of moving between land categories are set at the present value of the difference in the land rental rates between the alternative uses based on the assumed equilibration of land markets.

Timberland refers to productive forestlands able to generate at least 20 cubic feet of live growing stock per acre per year and that are not reserved for uses other than timber production (e.g., wilderness use). Lands under forest cover that do not produce at least 20 cubic feet per year, called unproductive forestland, and timberland that is reserved for other uses are not considered part of the U.S. timber base and are therefore not tracked by the model. In FASOM, endogenous land use modeling is only done for privately held parcels, not publicly owned or managed timberlands. The reason is that management of public lands is significantly influenced by government decisions on management, harvesting, and other issues that account for multiple public uses of these lands rather than private responses to market conditions. However, an exogenous quantity of timber harvested on U.S. public lands is accounted for within the model. Regional public harvest levels are set at exogenous levels based on past harvesting within the region and timber inventory levels for public timberlands are simulated based on the exogenous timber harvest levels that are assumed to be set by government administrative decree. The public land managers could change allowable harvest levels at any time, but those changes are not predictable, so harvest is assumed to remain fixed over time.

Private timberland is tracked by its quality and its transferability between forestry and agricultural use. FASOM includes three different site classes to reflect differences in forestland productivity (these site groups were defined based on ATLAS inputs[43]), where yields vary substantially between groups:

- HIGH—high site productivity group (as defined in ATLAS);
- MEDIUM—medium site productivity group; and
- LOW—low site productivity group.

FASOM also tracks land ownership including two private forest owner groups: forest industry (FI) and nonindustrial private forests (NIPF). The traditional definitions are used for these ownership groups: industrial timberland owners possess processing capacity for the timber, and NIPF owners do not.

In addition, FASOM tracks land in terms of the type of timber management, the species on the land, and the stand age. There are 18 different possible management intensity classes depending on whether thinning, partial cutting, passive management, or other management methods are used. There are also 25 different forest species types, which vary by region (e.g., Douglas fir and other species types in the West and planted pine, natural pine, and various hardwood types in the South). Stand age is explicitly accounted for in 5-year cohorts ranging from 0 to 4 years up to 100+ years.

[43]Haynes, R.W., D.M. Adams, and J. Mills. 1995. *The 1993 RPA Timber Assessment Update*. General Technical Report RM-259. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 66 p.

1.1.2.5 Production Modeling

The production component includes agricultural crop and livestock operations, as well as FI and NIPF forestry operations. Harvests from public forest lands are included in the model but are treated as exogenously determined by the government. FASOM contains an agricultural production model for each of the primary crop, livestock, and renewable fuels feedstock commodities. Production of agricultural crops, renewable fuel feedstocks, and livestock compete for land, labor, and irrigation water at the 63 or 11-region level, depending on the regional level selected for a given model run.[44] The costs of these and other inputs are included in the budgets for regional production variables.

Budgets are included for all primary crop and renewable fuel feedstocks included in the model. For each crop, production budgets are differentiated by region, tillage choice (three choices: conventional tillage, conservation tillage, or no-till), and irrigated or dryland and cropland type (four as discussed in land use section above). The differentiation included results in thousands of cropping production possibilities (budgets) representing agricultural production in each 5-year period. Energy crop production possibilities are similar, except that irrigation is not an available option in the current FASOM production possibilities; all energy crops are assumed to be produced under nonirrigated conditions and do not compete for irrigation water.

For livestock production, budgets are included that are defined by region, animal type, enteric fermentation management alternative, manure management alternative, and feeding alternative. Hundreds of livestock production possibilities (budgets) represent agricultural production in each 5-year period.

Supply curves for agricultural products are generated implicitly within the system as the outcome of competitive market forces and market adjustments. This is in contrast to supply curves that are estimated from observed, historical data. This approach is useful here in part because FASOM is often used to simulate conditions that fall well outside the range of historical observation (such as large-scale tree-planting programs or implementation of mandatory GHG mitigation policies).

The forest production component of FASOM depicts the use of existing private timberland as well as the reforestation decision on harvested land. Timberland is differentiated

[44] Because of model size and run time considerations, FASOM is often run with 63 regions in initial years (e.g., first 20 years of an analysis) and then switched to using only the 11 market regions in later years.

by region, the age cohort of trees,[45] ownership class, cover type, site condition, management regime, and suitability of the land for agricultural use. Decisions pertaining to timber management investment are endogenous. Actions on the inventory are depicted in a framework that allows timberland owners to institute management activities that alter the inventory consistent with maximizing the net present value of the returns from the activities. The key decision for existing timber stands involves selecting the harvest age. Lands that are harvested and subsequently reforested or lands that are converted from agriculture to forestry (afforested) introduce decisions involving the choice of species type, management type, and future harvest age.

1.1.2.6 Land Allocation

Underlying the commodity production described above and the associated environmental impacts is the decision by landowners on how much, where, and when to allocate land across the two sectors. The inclusion of endogenous land allocation across sectors sets FASOM apart from the majority of other forest and agricultural sector models of the United States. The conceptual foundation for land allocation is described below.

In terms of transferability between agriculture and forestry, FASOM includes five land suitability classes:

- FORONLY—includes timberland acres that cannot be converted to agricultural uses
- FORCROP—includes acres that begin in timberland but can potentially be converted to cropland
- FORPAST—includes acres that begin in timberland but can potentially be converted to pastureland
- CROPFOR—includes acres that begin in cropland but can potentially be converted to timberland
- PASTFOR—includes acres that begin in pasture but can potentially be converted to timberland

Land can flow between the agricultural and forestry sectors or vice versa in the FORCROP, FORPAST, CROPFOR, and PASTFOR land suitability categories. Movements between forestry and cropland are only permitted within the high-quality forest site productivity class. Changes in land allocation involving pastureland occur within the medium-quality forest

[45]Timberlands are grouped in 21 5-year cohorts, 0 to 4 years, 5 to 9, up to 100+ years. Harvesting is assumed to occur at the midyear of the cohort.

site productivity class. In addition, land movements in forestry are only allowed in the NIPF owner category, reflecting an assumption that land held by the FI ownership group will not be converted out of timberland.

As mentioned above, the decision to move land between uses depends on the net present value of returns to alternative uses, including the costs of land conversion. Land transfers from forestry to agriculture take place only upon timber harvest and require an investment to clear stumps, level, and otherwise prepare the land for planting agricultural crops. Agricultural land can move to other uses during any of the 5-year model periods, but when afforested it begins in the youngest age cohort of timberland.

In addition to the endogenous land allocation decision, land also moves out of agricultural and forestry uses into developed uses (e.g., shopping centers, housing, and other developed and infrastructural uses) at an exogenous rate. Thus, although land can move between forest, cropland, and pasture, the total land area devoted to agricultural and forestry production is trending downward over time as more land is developed. FASOM generally holds CRP land area fixed at initial levels, but for the EISA analysis, CRP land is permitted to convert back to cropland under the constraint that a minimum of 32 million acres of land remains in the CRP to be consistent with the 2008 Farm Bill and USDA assumptions.[46]

1.1.2.7 Nonland Factor Modeling

In addition to land, FASOM depicts factor supply of other resources, including water, labor, and other agricultural inputs in agriculture, as well as nonwood inputs in the forest sector.

In agricultural production, water and labor availability are specified on a regional basis. Supply curves for both items have a fixed price component and an upward-sloping component, representing rising marginal costs of higher supply quantities. For water, the fixed price is available to a maximum quantity of federally provided agricultural water, while pumped water has an upward-sloping supply curve and is subject to maximum availability. Other inputs are assumed to be infinitely available at a fixed price (i.e., the agricultural sector is a price taker in these markets).

On the forestry side, nonwood inputs are available on an upward-sloping basis and include hauling, harvesting, and product processing costs. Other forest inputs are assumed to be infinitely available at a fixed price.

[46]In addition, we explore a sensitivity analysis where the land area remaining in the CRP is allowed to fall to about half of the baseline CRP area in FASOM (which is just over 37 million acres).

1.1.2.8 Product Processing Modeling

Raw agricultural and forestry products are converted into processed products in FASOM using processing budgets. These budgets are generally reflective of a somewhat simplified view of the resources used in processing, where the primary factors in the budgets are the use of primary commodities as inputs, the yield of secondary products, and processing costs to convert primary products into processed products. Processing costs for the production of processed agricultural products are usually assumed to equal the observed price differential between the value of the outputs and the value of the inputs based on USDA Agricultural Statistics.[47] On the forestry side, the nonwood input supply curve provides the cost of processing wood.

The processing budgets for wood products are regionalized for all forest products with different data in the nine domestic forest production regions and the Canadian regions. Agricultural processing is regionalized for renewable fuels production, soybean crushing, wet milling, and bioelectricity generation. Processing budgets for other agricultural products are defined at a national level.

1.1.2.9 Market Modeling

FASOM uses commodity supply and demand curves for the U.S. market that are calibrated to historic price and production data with constant price differentials between regions and the nation for some crops. In addition, the model includes supply and demand data for major commodities traded on world markets such as corn, wheat, soybeans, rice, and sorghum across 37 foreign regions.[48] FASOM includes information on transportation costs to all regions, which affect equilibrium exports.

The model solution requires that all markets are in equilibrium (i.e., quantity supplied is equal to the quantity demanded in every market modeled at the set of market prices in the model solution). The demand and supply curves included within the model and that need to be in equilibrium in each 5-year period include

- regional product supply,
- national raw product demand,

[47] U.S. Department of Agriculture, National Agricultural Statistics Service. Various years. USDA Agricultural Statistics (1990–2002). Available at http://www.nass.usda.gov/Publications/Ag_Statistics/.

[48] FASOM foreign regions include the European Economic Community, North Central Europe, Southwest Europe, Eastern Europe, Adriatic, Eastern Mediterranean, Former Soviet Union, North Africa, East Africa, West Africa, South Africa, Red Sea, Iran, India, Taiwan, Japan, South Korea, North Korea, China, Bangladesh, Indonesia, Myanmar, Pakistan, Philippines, Thailand, Vietnam, West Asia, Southeast Asia, Australia, Caribbean, Eastern Mexico, Eastern South America, Western South America, Argentina, Brazil, Canada, and Other.

- regional or national processed commodity demand,
- regional or national supply of processed commodities,
- regional or national (depending on commodity) export demand,
- regional or national (depending on commodity) import supply,
- regional feed supply and demand,
- regional direct livestock demand,
- interregional transport perfectly elastic supply,
- international transport perfectly elastic supply, and
- country-specific excess demand and supply of rice, sorghum, corn, soybeans, and the individual types of wheat modeled.

In the case of forestry products, commodities are typically produced regionally and are then transported to meet a national demand at a fixed regional transport cost. For agricultural products, processed commodities such as soybean meal, gluten feed, starch, and all livestock feeds are manufactured and used on the 11-market region basis but are supplied into a single national domestic market as well to meet export demand.

1.1.2.10 GHG Accounting

FASOM quantifies the stocks of CO_2 and non-CO_2 GHGs emitted from and sequestered by agriculture and forestry, plus the stock on lands in the model that are converted to developed use. In addition, the model tracks GHG emission reductions in selected other sectors that result from mitigation actions in the forest and agricultural sectors. For instance, FASOM accounts for reduced GHG emissions from fossil fuel use in the energy sector due to the supply of renewable fuel feedstocks from agriculture. GHG accounting in FASOM covers both the agricultural and forest sectors as well as production of renewable fuels. Additional detail on GHG accounting in FASOM is provided in Appendix A.

1.1.2.11 Temporal Scope and Dynamics

FASOM is typically run for periods up to 100 years to depict land use, land transfers, and other resource allocations between and within the U.S. agricultural and forest sectors. The model solution portrays a multiperiod equilibrium on a 5-year time step basis. As noted earlier, FASOM incorporates deterministic expectations of future prices, or perfect foresight, where expected future prices are identical to the prices that are realized in the future. Thus, landowners are able to foresee and account for the consequences of their land use, management, and production decisions on future commodity prices and incorporate that information into their decisions. It is assumed that producers maximize the net present value of future returns. The results from FASOM yield a dynamic simulation of prices, production, management, consumption, and GHG effects within these two sectors under the scenarios defined for a particular model run.

Given the long rotation lengths in forestry, an important consideration for modeling the dynamics of landowner decision making is the possibility that trees could be planted with a rotation length that exceeds the amount of time remaining in a model simulation. Producers would need to anticipate net returns that justify keeping land in forestry (or moving land from agriculture to forestry) and incurring stand establishment costs in order to plant trees. To account for cases where the anticipated harvest date of a stand that could potentially be planted in a given period is past the end date being modeled,[49] "terminal conditions" must be defined. Terminal conditions represent the projected net present value of an asset for all time periods after the end of the explicit model projection. Several types of terminal assets are valued in FASOM, including initial timber stands that are not harvested during the simulation period, reforested stands remaining at the end of the simulation period, and agricultural land retained in agriculture.

1.1.2.12 Dynamic Yield, Cost, and Demand Updating

FASOM also incorporates a number of assumptions regarding changes in yields, production costs, and demand over time. Assumed rates of technological progress that vary by commodity are included based on historical yield growth and projections of future yields. In addition, certain processing activities, particularly those that rely on relatively new technologies, are expected to experience increases in production efficiency and corresponding reductions in processing costs in the future. For these activities (e.g., cellulosic ethanol production), processing yields (quantity of secondary product output per unit of primary commodity input) and production costs are assumed to change over time at rates that vary by process. Finally, domestic and export demand are assumed to change over time at growth rates that vary across commodities based on historical experience and USDA projections.

Simultaneous changes assumed for each of these variables over time are reflected in the baseline simulation. Changes in yield, production and processing costs, and demand over time

[49]For instance, if a stand with a 30-year rotation were being considered in year 90 of a 100-year simulation, the anticipated harvest date would fall outside the time period modeled, and the producer would not receive revenue from harvesting (and would therefore not be expected to plant trees in this period in the absence of terminal conditions assigning a value to future harvests).

will alter the relative returns to production of different commodities and will affect producer decisions. Other things being equal, for commodities where demand is growing faster than productivity, real prices will tend to increase over time. For commodities where demand growth is slower than productivity improvements, real prices will generally trend downward. Of course, these changes in relative returns will lead to shifts in land allocation and production practices until the point where a new equilibrium is reached.

1.1.3 Model Updates for Renewable Fuels Analyses

The recently updated version of the FASOM model applied in this analysis has been improved over previous versions in several ways, including the addition of a more detailed representation of GHG sources and sinks and inclusion of updated baseline data on land use and agricultural policies, input costs, and output prices. In addition, the forest sector component of the model has been modified to include updates from the most recent 2005 interim RPA data.[50] Important changes to the forest sector in the latest version of FASOM include reflection of large transfers of forest land from traditional industrial owners to timber investment management organizations (TIMOs) and real estate investment trusts (REITs), domestic production costs that are high relative to prices in some regions, changing trade patterns, increasing reliance on nonfederal timber and expanded use of plantations on private timberlands, and a change in outlook for Canadian timber harvests associated with pest outbreaks[51]. In addition, assumptions about growth in demand for developed land have been updated to reflect recent projections of income and population growth.

There have also been significant improvements in the representation of the renewable fuels sector in FASOM. The model now includes multiple feedstocks that can meet the demand for producing liquid renewable fuels, including starch- and sugar-based ethanol production, biodiesel, and cellulosic ethanol production. Some of the key inputs for this sector that have been reviewed and updated recently, where possible, include production and delivery costs, energy crop and crop residue yields, ethanol conversion rates, and the rates of technological change. There is also an updated secondary market for renewable fuel production, namely the use of distillers grains (DG) for livestock feed. Many of these improvements are explained in more detail in Appendixes B, C, and D.

[50] USDA Forest Service. 2007. Interim Update of the 2000 Renewable Resource Planning Act Assessment. FS-874. Washington, DC.

[51] Canadian timber harvests are incorporated into FASOM in more detail than other foreign trade because Canadian timber has a major impact on U.S. markets (large quantities are imported and processed into wood products in the United States).

1.2 Modeling the Energy Independence and Security Act (EISA) Using FASOM

For this analysis, FASOM was applied to assess the domestic agricultural and environmental impacts associated with implementing EISA. EISA calls for 36 billion gallons per year (BGY) of renewable fuels by 2022, but not all of this production is expected to be derived from agricultural and forestry feedstocks modeled in FASOM. Thus, the volume of renewable fuels modeled in FASOM is less than the full 36 BGY (about 30.2 BGY or 30.9 BGY in ethanol equivalents), with the remainder distributed across municipal solid waste, yellow grease, and imported renewable fuels exogenous to FASOM.

Below we discuss the proposed volumes of agricultural feedstocks modeled in FASOM. For this analysis, we refer to baseline conditions without EISA requirements, which are based on projected volumes of ethanol and biodiesel in Annual Energy Outlook 2007 (AEO2007),[52] as the "Reference Case" and the case where EISA volume requirements are binding and set at their primary expected volumes under base CRP acreage, energy price, and corn yield assumptions as the "Control Case." Results for the Reference and Control Cases are presented in Section 2.

1.2.1 Proposed Renewable Fuel Volumes

For the domestic agricultural sector analysis of the RFS2 renewable fuels volumes, we assumed that 15 BGY of transportation fuels would come from domestically produced starch- and sugar-based ethanol by 2022. Although the overwhelming majority comes from corn ethanol, FASOM includes production possibilities for using other feedstocks as well, and feedstocks other than corn enter the model solution in some years in small volumes. Given projected increases in ethanol production under baseline conditions (Reference Case) in FASOM, a requirement of 15 BGY by 2022 under the Control Case is an increase of only 2.7 BGY relative to the Reference Case. We also modeled a volume of 13.7 BGY of cellulosic ethanol from agricultural sources in 2022, with another 2.3 BGY of cellulosic ethanol derived from municipal solid waste, which is being modeled outside of FASOM. Because there is very little cellulosic ethanol being produced in the Reference Case (only 0.25 BGY of cellulosic ethanol produced from bagasse and sweet sorghum pulp in 2022), the volume of cellulosic ethanol is increased to a much larger degree than starch-based ethanol (increase of 13.45 BGY). Although some of the projected increases in cellulosic renewable fuels are expected to be in the form of a diesel substitute, FASOM does not currently include this renewable diesel or biomass to liquids as potential processing pathways. Therefore, for the FASOM analysis all of the cellulosic volumes are assumed to be cellulosic ethanol. In addition to ethanol production, we

[52] Energy Information Administration, U.S. Department of Energy. 2006. Annual Energy Outlook 2007. DOE/EIA-0383(2007). Available at: http://tonto.eia.doe.gov/ftproot/forecasting/0383(2007).pdf.

modeled the use of 1.47 BGY of biodiesel (2.2 BGY in ethanol equivalents) in 2022, which is an increase of 1.25 BGY (1.88 BGY in ethanol equivalents) above the Reference Case volume.

A number of potential feedstocks can be used in FASOM to produce ethanol or biodiesel. The proposed renewable fuel volumes are implemented in the model as constraints on national production of each of the three categories of renewable fuels modeled, with the model solution reflecting the mix of feedstocks in each region and year that maximizes welfare based on model assumptions and the constraints on renewable fuels production by category. Generally, the model solution in such a case will include production in regions where feedstocks to produce the required volumes of starch-based ethanol, cellulosic ethanol, or biodiesel are available at the lowest delivered cost per gallon of renewable fuel produced.

1.3 Model Modifications Since the RFS2 Proposal

A number of modifications have been made to FASOM since the analysis conducted for the proposed revisions to the National RFS2 program rule published in the *Federal Register* on May 16, 2009. These changes were made to reflect comments received and the availability of new data, including the availability of an updated version of the combined forest-agriculture version of the model. At the time of the previous analysis, the combined forest-agriculture version was undergoing revisions and was not available for use, but those revisions have since been completed. Other major changes to the modeling framework used include using updated values for cellulosic ethanol yields, switchgrass yields, and distillers grains replacement rates of corn and soybean meal in animal feed; adding corn oil from extraction as a biodiesel fuel pathway; and adding additional land categories, including the replacement of rangeland measured in animal unit months (AUMs) with rangeland measured in acres, consistent with the other land categories included in the model. Each of these significant modifications is described in more detail below.

1.3.1 Use of Combined Forest-Agriculture Model

FASOM can be run for the forest sector only, the agriculture sector only, or for both sectors combined. Running the model with both sectors simultaneously allows for analyzing of interactions between the two sectors, which compete for land. However, because the forestry component of the model was undergoing a substantial update at the time of the analyses conducted for the RFS2 proposal and was not ready for use in the renewable fuels analyses conducted, we used the agriculture-only version of the model for the proposal. Since that time, the updates to the forestry component that were underway have been completed. Thus, we used combined model runs to generate the results presented in this report to enable better assessment of the impacts on land use as well as other interactions between the forest and agricultural sectors. In addition, this modeling change allowed market modeling of potential use of forest-derived feedstocks for cellulosic ethanol production rather than the exogenous assumption applied for the proposal.

1.3.2 Updated Yields for Cellulosic Ethanol Production

Based on new research conducted by the National Renewable Energy Laboratory (NREL),[53] we updated the assumed cellulosic ethanol yields derived from alternative cellulosic feedstocks. Rather than having several different yields across types of feedstocks, all feedstocks included in FASOM were assumed to reach one of two yields by 2022. The yield for all crop residues, switchgrass, bagasse, sweet sorghum pulp, and softwood residues was assumed to be 92.3 gallons of ethanol per dry ton of feedstock in 2022. The yield for hybrid poplar, willow, and hardwood residues was assumed to be 101.5 gallons of ethanol per dry ton of feedstock in 2022. These updates resulted in higher ethanol yields per ton of feedstock for all crop residues other than corn and sorghum residues, sweet sorghum pulp, hybrid poplar, willow, and hardwood logging and milling residues, but lower yields for corn residue, sorghum residue, bagasse, and softwood logging and milling residues than those used in the analysis for the proposal.[54]

1.3.3 Updated Switchgrass Yields

Switchgrass yields per acre were updated based on new work conducted by the Pacific Northwest National Laboratory,[55] which increased average switchgrass yields at the national level. In the analysis for the RFS2 proposal, national average switchgrass yields in 2022 were 6.3 wet tons per acre in the Control Case. In the current analysis for the final rulemaking, national average switchgrass yields in 2022 are now 7.8 wet tons per acre in the Control Case.

1.3.4 Addition of Corn Oil Extraction as a Biodiesel Pathway

FASOM did not explicitly include corn oil extracted from DG as a potential source for making biodiesel in the analysis for the proposal. The model has been modified to add this pathway as part of the dry milling process, with the potential for corn oil to be derived from either extraction from DG or fractionation prior to the creation of DG. Corn oil from

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[53] Tao, L. and A. Aden, *Technoeconomic Modeling to Support the EPA Notice of Proposed Rulemaking (NOPR),* November 2008.

[54] Beach, R.H., B.A. McCarl, and A.W. Lentz. *Agricultural Impacts of the Energy Independence and Security Act: FASOM Results and Model Description,* October 2008.

[55] Thomson, A.M., R.C. Izarrualde, T.O. West, D.J. Parrish, D.D. Tyler, and J.R. Williams. 2009. Simulating Potential Switchgrass Production in the United States. PNNL-19072. College Park, MD: Pacific Northwest National Laboratory.

fractionation is assumed to be food grade and a perfect substitute for corn oil produced from the wet milling process. Corn oil from extraction, however, is nonfood grade and can only be used in biodiesel production in the model. Based on EPA research on expected technological adoption, it was assumed that the share of plants employing extraction or fractionation in their production processes would increase over time. Based on Chapter 1.4 of the Regulatory Impact Analysis (RIA), it was assumed that by 2022, 70% of dry mill ethanol plants will withdraw corn oil via extraction, 20% will withdraw corn oil via fractionation, and 10% will do neither.

1.3.5 Modifications to Feed Replacement Rates for Dried Distillers Grains

As mentioned above, one of the by-products of the dry mill ethanol production process is DG. This by-product can be used as feed for beef cattle, dairy cattle, swine, and poultry in place of traditional feed sources such as corn and soybean meal, and its use has been growing substantially in recent years as ethanol production has expanded. In the previous analyses conducted for the RFS2 proposal, it was assumed that one pound of DG would replace one pound of a combination of corn and soybean meal, consistent with current livestock production practices. However, based on research conducted by Argonne National Laboratory,[56] one pound of DG can potentially substitute for 1.196 pounds of total corn and soybean meal for cattle because the DG has higher nutritional content per pound. Thus, we have updated the replacement rates used in the model such that they increase over time from a 1:1 replacement rate of DG for corn and soybean meal initially to the maximum technological replacement rate estimated by Argonne of 1:1.196 in 2017 for beef and dairy cattle. We continue to use a replacement rate of 1:1 throughout the entire modeling time frame for swine and poultry. We also implemented maximum DG inclusion rates in livestock feed as a percentage of total feed based on the Argonne study. These limits vary by species and are assumed to increase between 2007 and 2017, reaching maximum levels of 50% for beef cattle, 30% for dairy cattle, and 25% for both swine and poultry by 2017.

In addition, DG produced as a by-product of a dry milling process with corn oil fractionation/extraction has different nutritional characteristics than traditional DG, which contain higher levels of oil.[57] Based on this research, the proportion of soybean meal vs. corn replaced by fractionated/extracted DG is higher than for traditional DG when used for swine or poultry feed, although the total replacement rate of DG for a combination of corn and soybean meal remains 1:1. Therefore, we have modified the model to apply different replacement rates

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[56] Salil, A., M. Wu, and M. Wang. 2008. "Update of Distillers Grains Replacement Ratios for Corn Ethanol Life-Cycle Analysis." Available at http://www.transportation.anl.gov/pdfs/AF/527.pdf.

[57] Shurson, G.C. 2006. "The Value of High-Protein Distillers Compounds in Swine Feeds." *Distillers Grains Quarterly*, First Quarter 2006:22-25.

for fractionated/extracted DG and traditional DG when used in swine and poultry feed. Because there was no comparable research identified for cattle diets, we assumed that replacement rates for cattle remain the same for fractionated/extracted DG as for traditional DG.

1.3.6 Added Export Market for DG

In the version of the model used for the proposal, it was assumed that all DG produced in the United States would go into the domestic livestock feed market. In addition to the changes to replacement rates described above, the model was modified to account for potential exports of DG. This provides a larger market for the DG produced and is more consistent with recent experience, where DG is being shipped overseas to be used in livestock feed.

1.3.7 Modifications to Land Use Categories

The land use categories defined and modeled within FASOM have been updated since the proposal to add more detail and to match up total forest and agricultural land tracked within the model more closely with national land use data.[58] One major change was to split the former pasture category into separate categories of cropland pasture and forest pasture, with three separate subcategories of forest pasture, as described in Section 1.1.2.4. Along with this change, the ability of pasture to move into cropland and vice versa was respecified such that exchanges between cropland and pasture are now only permitted for the higher productivity cropland pasture category. In addition, rangeland was formerly tracked and reported in terms of animal unit months (AUMs) rather than acres.[59] The model has been modified to specify all livestock budgets in terms of animal unit grazing requirements, with estimates of acres per animal unit developed for each pasture type present in each region. Thus, rangeland is now specified in terms of acres (with productivity of rangeland depending on the AUM data that had been used in the past, similar to each of the pasture categories). Whereas rangeland and pasture were incorporated independently in FASOM livestock budgets previously, producers can now substitute directly between them to provide sufficient forage for their livestock. The area included in each of the new categories was also updated to track additional idle lands and match more closely with total rural land available for forests and agriculture in other land use assessments.

[58] USDA Economic Research Service. *Major Land Uses*. Dataset available at: http://www.ers.usda.gov/Data/MajorLandUses/.

[59] An AUM is defined as the amount of forage required for one month to sustain 1 animal unit or its equivalent, where an “animal unit” is defined as one mature 1,000-pound cow and her calf.

1.3.8 Updated Data for Nitrous Oxide Emissions from Soil Management

Another change that has been incorporated since the proposal is the use of updated estimates of N_2O emissions from soil management. The Natural Resource Ecology Laboratory at Colorado State University generated new estimates of direct N_2O emissions from fertilizer application, as well as indirect N_2O emissions from leaching and volatilization that were incorporated into FASOM. The emissions estimates were generated using the DAYCENT model[60] and reflect recent updates to the data and model. Emissions estimates vary by region, crop, fertilizer application rate, tillage, irrigation status, and residue removal rate and better capture the heterogeneity of emissions than previously available estimates of N_2O emissions from soil management. Because these updated values from DAYCENT simulations reflect emissions from the complete N cycling process, there is no longer a need for separate calculations of N_2O emissions from crop residues or nitrogen fixing by legumes.

[60] The DAYCENT model was developed by Colorado State University. This model simulates soil dynamics and trace gas fluxes at a daily time step. See Appendix A for additional information on the model.

SECTION 2
SUMMARY OF DOMESTIC AGRICULTURE AND FORESTRY IMPACTS

In this section, we summarize the key impacts of the Renewable Fuel Standards required by the EISA on the U.S. agricultural sector. The impacts presented in this section are based on FASOM simulations of agricultural and forestry market outcomes under a Reference Case without EISA as well as under a Control Case with EISA renewable fuel requirements. The differences in market outcomes between these two scenarios provide an estimate of the net impacts of EISA.

2.1 Agricultural Commodity Impacts

Because the agricultural sector is a primary source of feedstocks for the production of ethanol and biodiesel, required increases in production of these fuels will increase the demand for agricultural feedstocks and will affect agricultural market outcomes. Not only will prices and quantities of directly affected feedstock markets be affected, but also effects will be transmitted throughout the agricultural sector. Changing returns to production of alternative commodities will lead landowners to alter their choice of commodities to produce as well as the management practices used (e.g., irrigation, tillage). Sectors that use products derived from crops as inputs, such as the livestock sector, will be affected by changes in the absolute and relative prices of those inputs. Changes in practices may also result in different quantities of by-products and coproducts being produced, which will affect those markets as well.

In addition to market effects, the changes in agricultural production associated with EISA have implications for environmental outcomes by affecting fertilizer use, use of agricultural chemicals, and GHG emissions. Estimated impacts of EISA on key commodity prices and quantities, land use, renewable fuel by-products, livestock and related industries, international agricultural commodity trade, and environmental measures based on the Control Case are presented below. Results presented focus on estimated impacts in 2017 and 2022.

2.1.1 Commodity Prices and Quantities

Because of increases in demand for certain agricultural products as feedstocks for renewable fuels production under EISA, prices for those products are generally expected to increase relative to baseline conditions. Table 2-1 presents the distribution of ethanol and biodiesel production across feedstocks under both the Reference and Control Cases based on FASOM model results, which provides an indication of the commodity markets expected to be most directly affected by increasing renewable fuels production.

Table 2-1. Renewable Fuel Production by Feedstock Used under the Reference Case and Control Case (millions of gallons per year)

	2017		2022	
Feedstock	**Reference Case**	**Control Case**	**Reference Case**	**Control Case**
Biodiesel				
Corn oil (nonfood grade)	0	542	0	681
Edible tallow	23	23	24	24
Lard	16	53	23	55
Nonedible tallow	46	47	48	48
Soybean oil	104	659	120	659
Cellulosic ethanol				
Bagasse	185	581	229	614
Corn residue	0	0	0	4,871
Hardwood logging residue	0	75	0	73
Softwood logging residue	0	33	0	36
Sweet sorghum pulp	65	107	22	110
Switchgrass	0	3,879	0	7,912
Wheat residue	0	42	0	77
Starch-based ethanol				
Sorghum	3	0	16	0
Corn (wet milling process)	1,281	1,391	1,311	1,391
Corn (dry milling process)	10,009	13,594	10,969	13,594
Sweet sorghum	18	30	6	30
Total ethanol	11,562	19,729	12,553	28,728
Total biodiesel	189	1,324	214	1,467
Total renewable fuels from agricultural feedstocks in FASOM	11,750	21,053	12,766	30,195

In 2017, the majority of the incremental ethanol production is starch-based ethanol derived from corn, although there is a substantial increase in cellulosic ethanol production as well, primarily from switchgrass with smaller increases in bagasse, sweet sorghum pulp, wheat residue, and forestry residues. By 2022, almost half of the total increased ethanol production associated with the Control Case is cellulosic ethanol derived from switchgrass. Corn residue also enters as a major feedstock, while the use of other ethanol feedstocks changes little between 2017 and 2022. For biodiesel, the majority of the increase between the Reference and Control Cases is derived from soybean oil and corn oil (nonfood grade), with very little change in the use of the other feedstocks included in FASOM relative to the Reference Case. Table 2-2 summarizes acreage, production, and price for corn and soybeans under the Reference and Control Cases, as well as the changes between cases.

Table 2-2. Acreage, Production, and Price of Corn and Soybeans under the Reference Case and Control Case

Crop	2017			2022		
	Reference Case	Control Case	Change	Reference Case	Control Case	Change
Corn						
Acreage (million acres)	78.7	83.6	4.9	77.9	81.5	3.6
Price ($2007/bushel)	$3.45	$3.74	$0.29	$3.32	$3.60	$0.27
Production (million bushels)	13,812.1	14,586.1	774.0	14,511.7	15,079.2	567.5
Soybeans						
Acreage (million acres)	67.3	67.2	-0.1	68.1	66.6	-1.4
Price ($2007/bushel)	$10.02	$10.97	$0.95	$9.85	$10.87	$1.02
Production (million bushels)	2,988.7	2,966.2	-22.5	3,080.5	3,028.1	-52.4

Over time, changes in relative prices will induce increased production of these products that may at least partially offset price increases due to higher demand, but changes in relative prices will also have implications for prices and quantities in other agricultural markets. Using FASOM to quantify these impacts over time enables us to account for supply and demand conditions in the markets for all major agricultural commodities produced in the United States simultaneously. In the subsections below, we summarize impacts in the markets for corn, soybeans, cellulosic feedstocks, and other agricultural commodities.

2.1.1.1 Corn

As the principal feedstock for starch-based ethanol production in the United States, corn is the commodity most likely to be affected by proposed increases in starch-based ethanol production. However, EISA's focus on increasing production of advanced renewable fuels such as cellulosic ethanol rather than starch-based ethanol mitigates these impacts. The rapid growth in starch-based ethanol production in recent years and continued increases anticipated under baseline conditions will result in a relatively small increment in production necessary to reach the 15 billion gallons per year (BGY) of starch-based ethanol specified by the EISA (about 3.7 BGY increase in 2017 and 2.7 BGY increase in 2022 relative to the Reference Case). Nonetheless, the increased demand for corn ethanol, as well as the demand for corn oil as a biodiesel feedstock, will affect U.S. corn markets and utilization patterns.

This increase in demand results in higher equilibrium corn prices relative to the Reference Case, as shown in Figure 2-1, and induces greater corn production (see Figure 2-2).[61] Under the Control Case, corn prices increase by 8.3% in 2017 (from $3.45/bushel to $3.74/bushel) and by 8.2% in 2022 (from $3.32/bushel to $3.60/bushel). Corn production increases by 5.6% in 2017 and 3.9% in 2022 relative to the Reference Case.

Within FASOM, U.S. corn consumption is broken down into four major categories: livestock feed; ethanol production; corn exports; and other food, seed, and industrial uses. Under the Control Case, the percentage of corn feedstock used for renewable fuels increases substantially. Although total corn production and consumption increase under the Control Case, this increase in allocation of corn to renewable fuels production results in decreases in corn use for both livestock feed and exports. Corn used for livestock feed falls 5.7% (261 million bushels) in 2017 relative to the Reference Case. In 2022, corn used for feed is expected to fall by 2.5% (118 million bushels), relative to the Reference Case. However, some of the decline in corn used for feed is replaced by DG, gluten feed, and gluten meal, which are all coproducts of ethanol production. In the Control Case, model results show that the use of ethanol coproducts to replace corn as livestock feed increases by 261 million bushels of corn replaced relative to the Reference Case, to a total of 1,076 million bushels. For 2022, model results indicate that the Control Case results in an increase of 148 million bushels of corn replaced by ethanol coproducts, with a total of 1,175 million bushels of corn replaced. In addition, corn exports decline by 184 million bushels in 2017 (8.4%) and by 188 million bushels in 2022 (8.2%). Figures 2-3 and 2-4 display the allocation of corn use in 2017 and 2022, respectively.

[61] Note that projected prices are declining slightly over time, reflecting future model equilibrium values accounting for supply adjustments, both increased land allocation to corn production and increasing corn yields over time due to improvements in technology. Falling real (inflation-adjusted) prices indicate that supply is growing more rapidly than demand between 2017 and 2022 in both the Reference Case and Control Case.

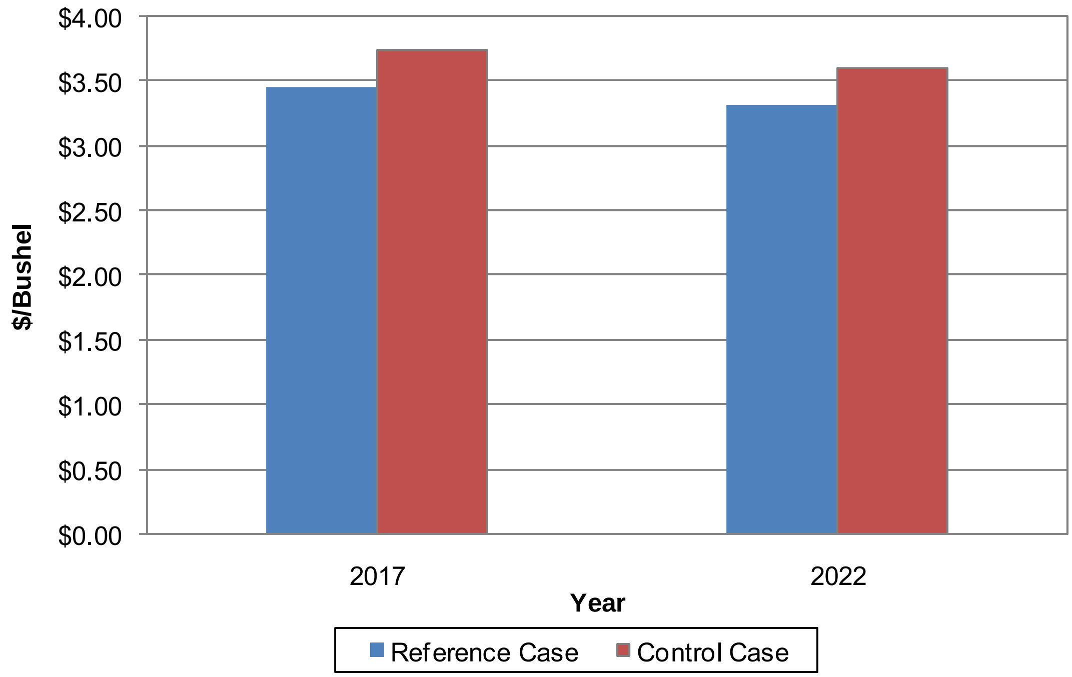

Figure 2-1. Corn Prices under the Reference Case and Control Case (2007$)

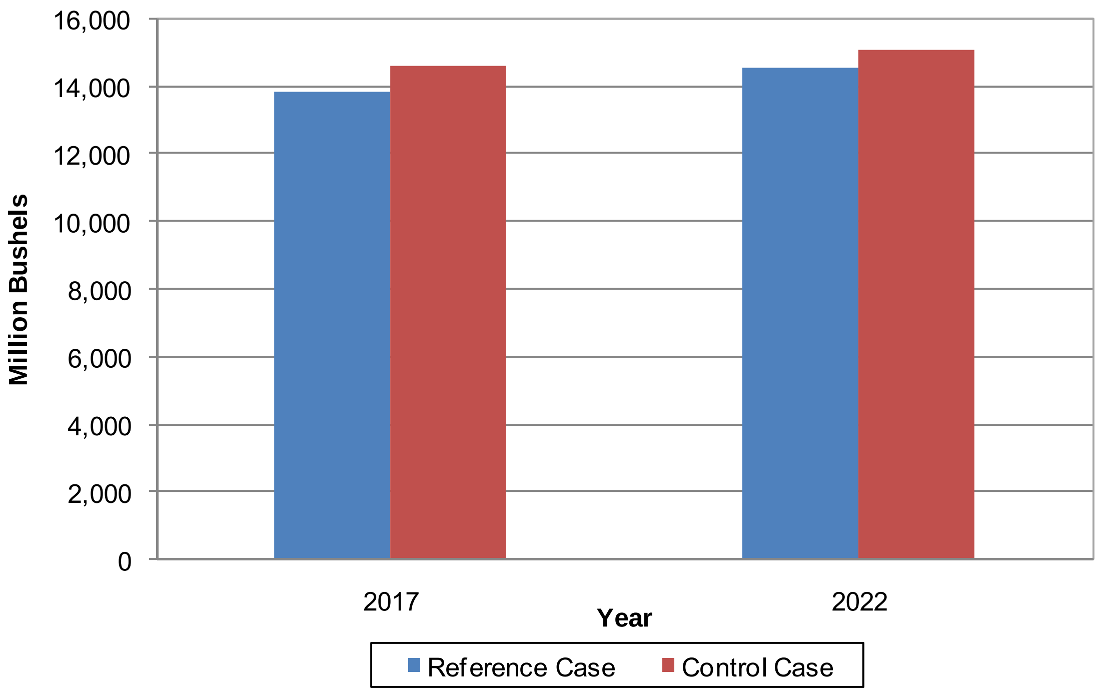

Figure 2-2. Corn Production under the Reference Case and Control Case

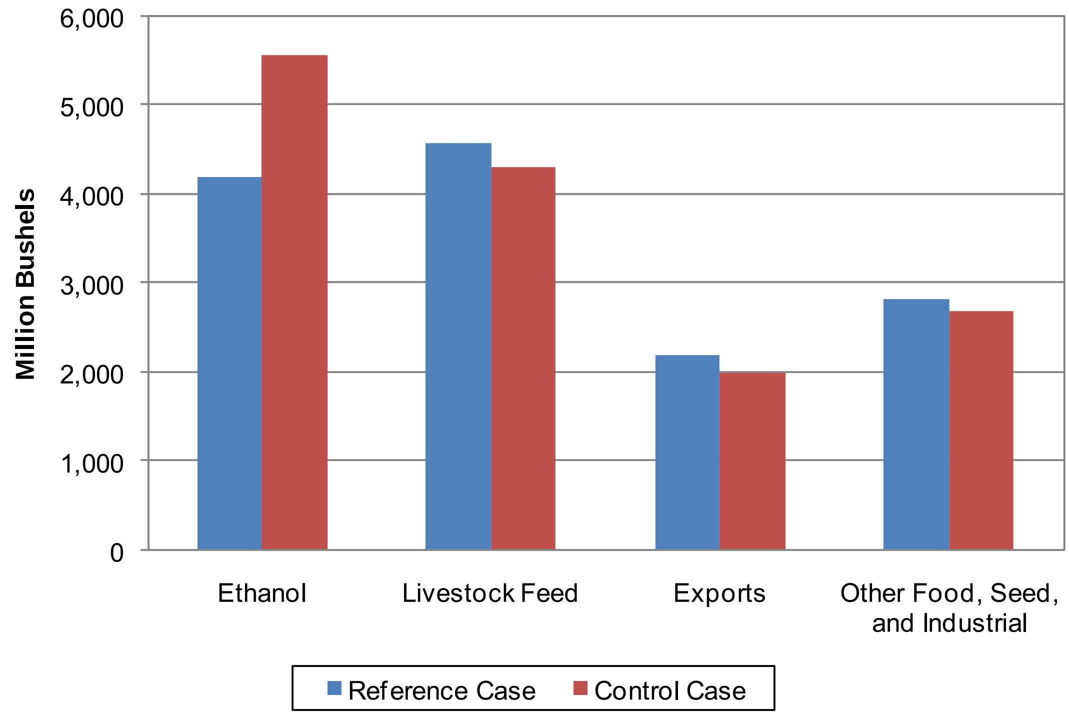

Figure 2-3. Distribution of Corn Usage across Consumption Categories, 2017

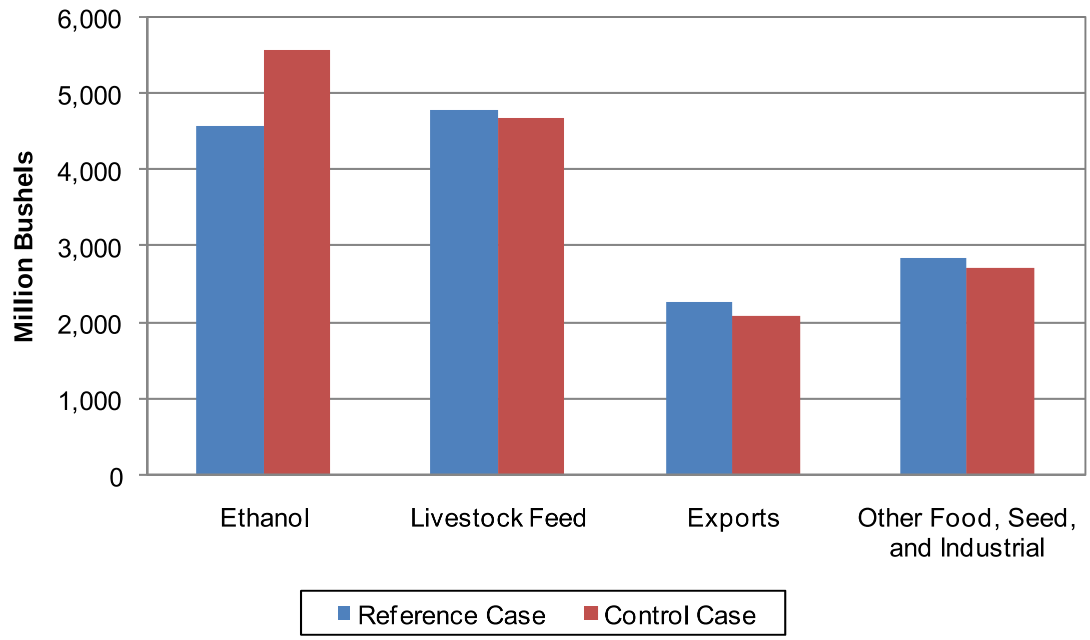

Figure 2-4. Distribution of Corn Usage across Consumption Categories, 2022

Increased demand for corn oil use in biodiesel results in large increases in non-food grade corn oil prices as well, as shown in Figure 2-5. Non-food grade corn oil prices increase by 304% in 2017 (from $0.28 per gallon to $1.14 per gallon) and by 271% in 2022 (from $0.34 per gallon to $1.26 per gallon) under the Control Case.

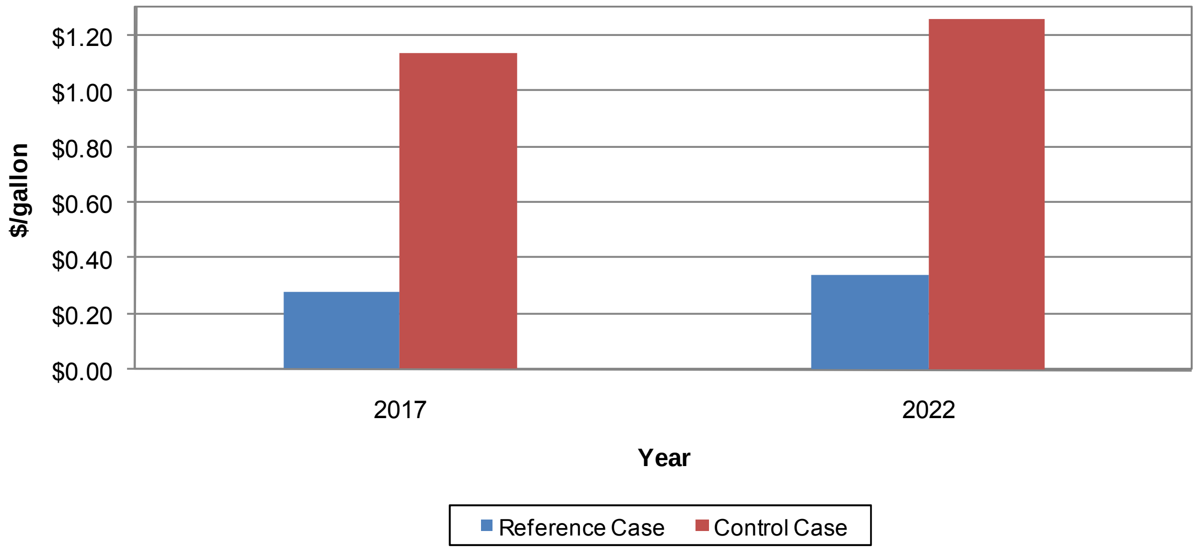

Figure 2-5. Corn Oil (Non-food Grade) Prices under the Reference Case and Control Case (2007$)

2.1.1.2 Soybeans

In the markets for soybeans and soybean oil, prices increase because of greater demand for soybean oil in biodiesel production under the Control Case and increases in corn production that shift land away from soybeans, reducing the supply. Soybean meal prices, on the other hand, decline under the Control Case. This is consistent with soybean oil being the product that is in increased demand due to EISA, whereas soybean crushing to produce oil also generates large quantities of soybean meal as a coproduct. Thus, the price of soybeans depends on both the price of soybean oil and soybean meal, and a bushel of soybeans produces more meal than oil, about 11.16 pounds of soybean oil and 45.57 pounds of soybean meal. Large increases in soybean meal associated with increased soybean oil production for use in making biodiesel lead to a reduction in soybean meal prices of about 1.8% in 2017 and 0.1% in 2022, which contributes to holding down soybean price increases. Although there is an increased demand for soybean meal as a feed source due to increasing prices of corn, soybeans, and other feed sources, the increase in supply is larger than the increase in demand, leading to a reduction in equilibrium meal prices.

Changes in soybean and soybean oil prices are shown in Figures 2-6 and 2-7, respectively. Prices for soybeans increase by 9.4% in 2017 (from $10.02/bushel to $10.97/bushel) and by 10.3% in 2022 (from $9.85/bushel to $10.87/bushel) relative to the Reference Case. Soybean oil prices increase by far larger percentages of 37.0% in 2017 (from $249.89/1,000 lbs to $342.35/1,000 lbs) and by 37.9% in 2022 (from $241.55/1,000 lbs to $333.21/1,000 lbs).

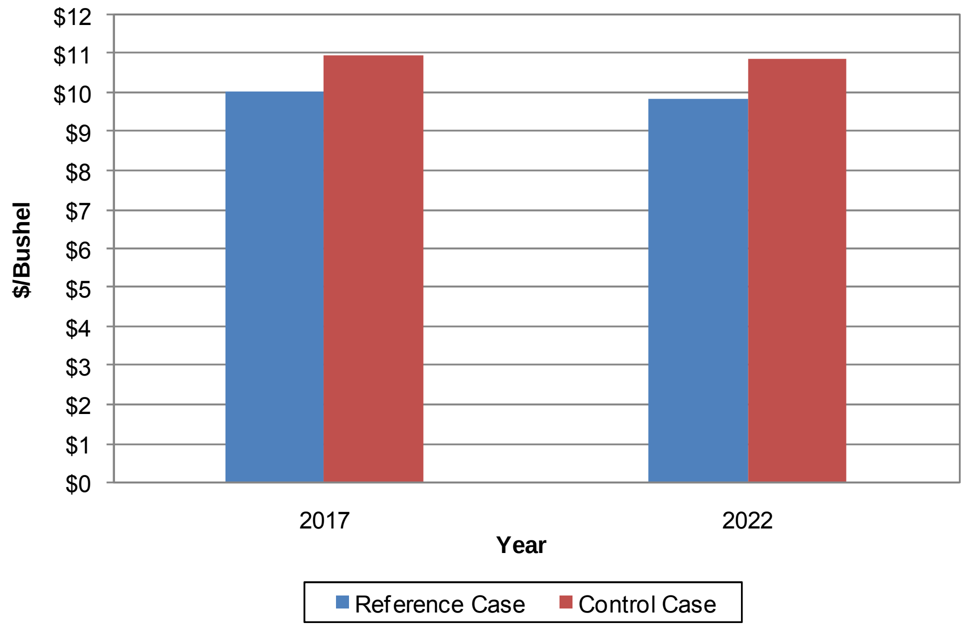

Figure 2-6. Soybean Prices under the Reference Case and Control Case (2007$)

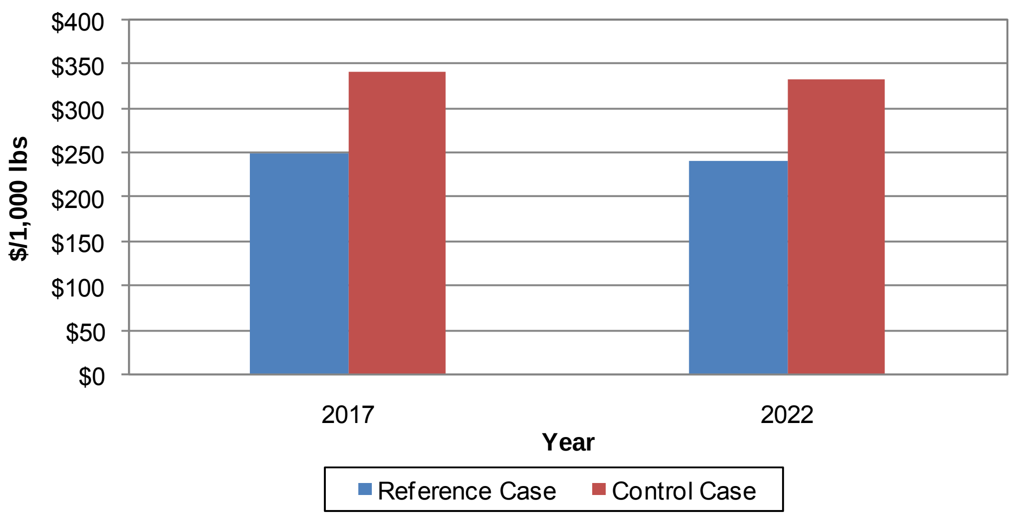

Figure 2-7. Soybean Oil Prices under the Reference Case and Control Case (2007$)

As shown in Figure 2-8, U.S. soybean production declines slightly under the Control Case as more cropland is allocated to corn production, contributing to a decrease in soybean acreage. Soybean oil production, on the other hand, increases under the Control Case. The demand for soybean oil for biodiesel production results in more soybeans being used to produce soybean oil domestically with a sizable reduction in exports, as shown in Figures 2-9 and 2-10. Figure 2-11 summarizes the modeled change in soybean oil production between the Reference and Control Cases.

FASOM allows for the production of biodiesel from a variety of sources (e.g., soybean oil, corn oil (food grade or non-food grade), edible tallow from beef slaughter, nonedible tallow from beef slaughter, lard). To the extent that collection processes improve, lower cost tallow and waste oil feedstocks might constitute a larger share of biodiesel at some point in the future, but based on current modeling assumptions, most of the incremental biodiesel associated with EISA is expected to be produced from oils that have competing uses in food production (corn and soybean oils). In addition, FASOM does not currently model biodiesel from algae or poultry waste, which have historically been a small portion of the biodiesel market. If these technologies become widespread and more cost-effective, the impact of higher biodiesel volumes on soybean and corn oil prices would be reduced.

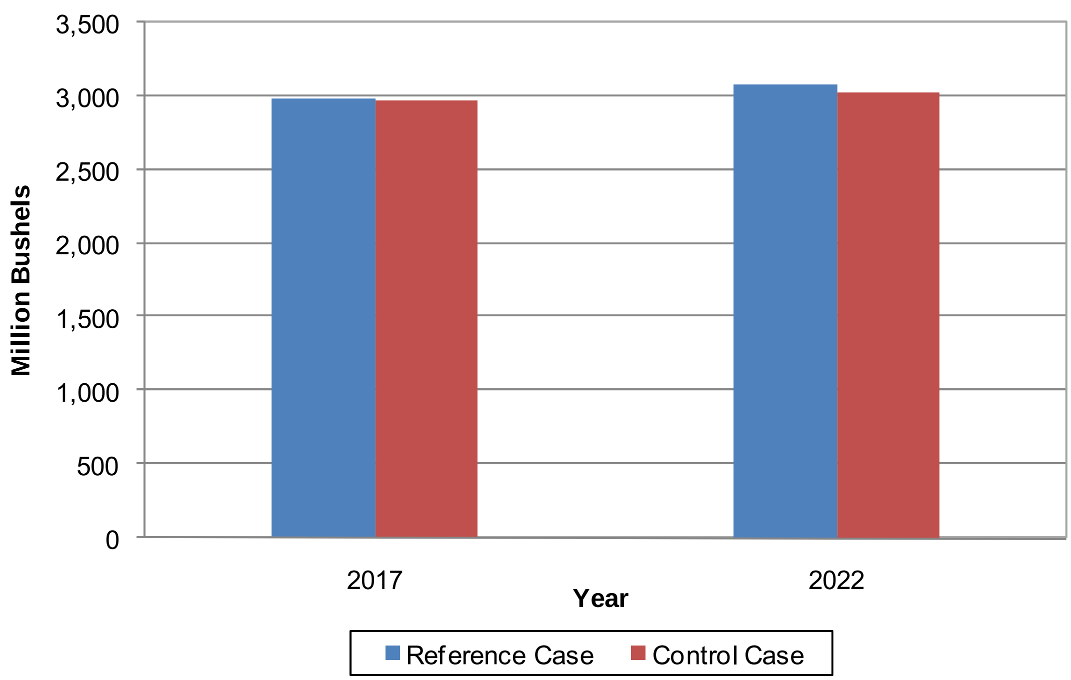

Figure 2-8. Soybean Production under the Reference Case and Control Case

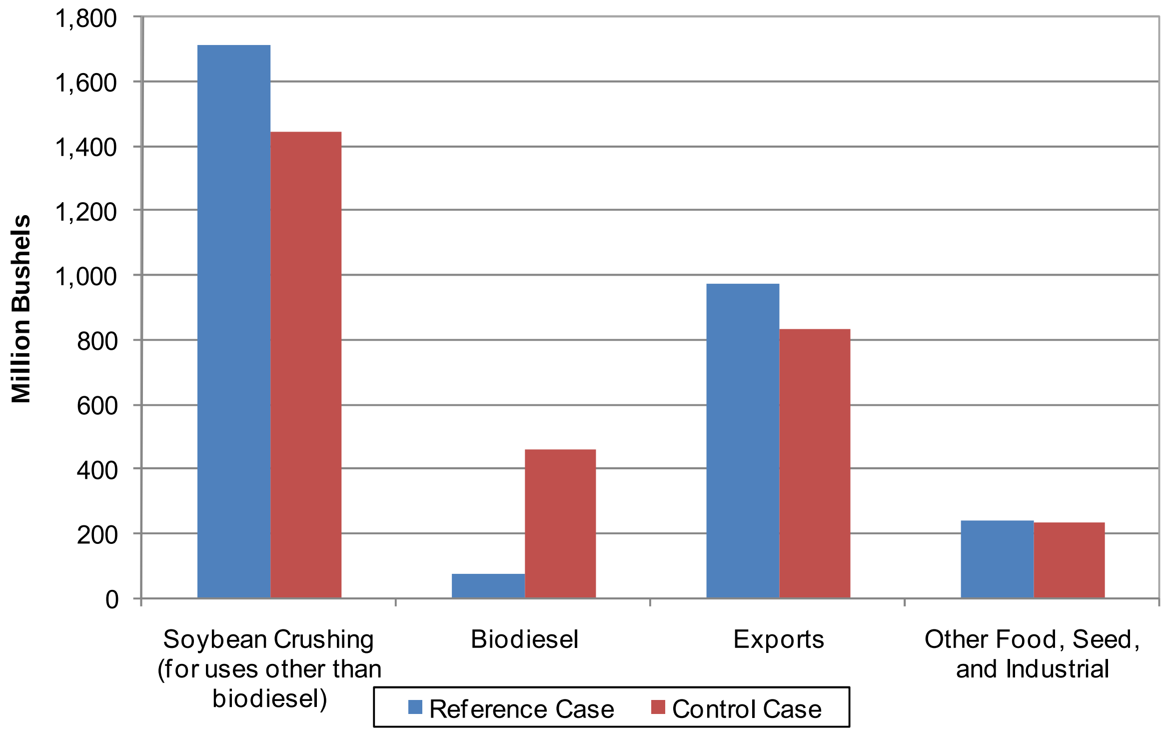

Figure 2-9. Soybean Usage, 2017

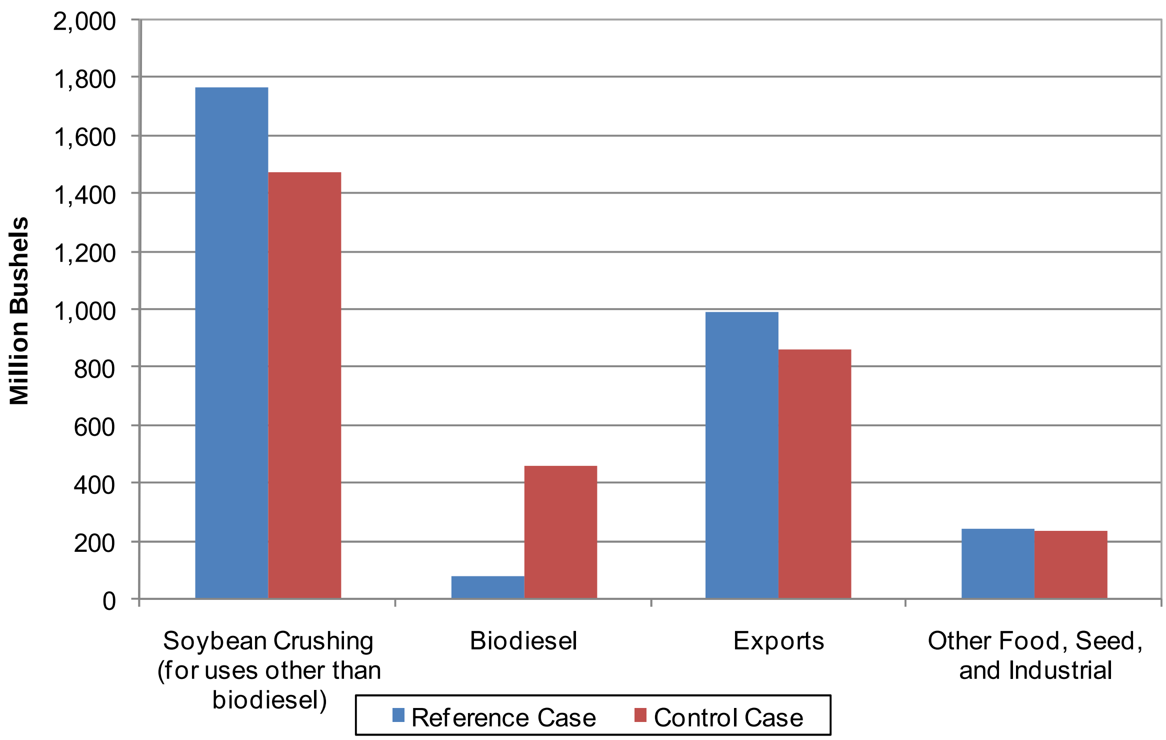

Figure 2-10. Soybean Usage, 2022

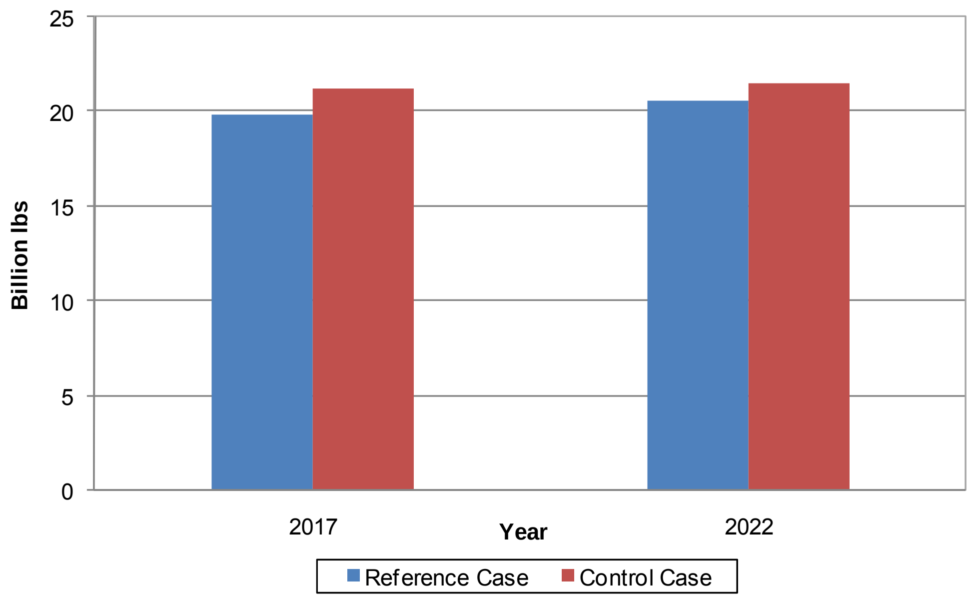

Figure 2-11. Soybean Oil Production under the Reference Case and Control Case

2.1.1.3 Cellulosic Feedstocks

FASOM model results show cellulosic ethanol production from agricultural feedstocks reaching 4.7 BGY by 2017 and 13.7 BGY by 2022. To achieve these production levels, large quantities of feedstocks must be available for processing. In our model simulations, switchgrass is the largest source of cellulosic feedstock (see Table 2-3). FASOM model results indicate that 3.9 BGY of ethanol are produced from switchgrass in 2017, with production doubling to 7.9 BGY in 2022. Switchgrass and other energy crops are attractive cellulosic feedstocks because they have the potential to produce high yields per acre compared to residue crops. However, in general, a lower price is required to induce farmers to collect residues from grain production to sell as a cellulosic ethanol feedstock than to replace other production with dedicated energy crops. As a result, a large share of feedstock in major crop-producing regions is expected to come from crop residues, particularly corn residue. Because corn produces the most residue per acre among the crops considered and is the highest density crop in major agricultural production regions of the United States, corn residues are a particularly attractive feedstock to meet cellulosic ethanol production requirements.

Because moisture content and ethanol yields vary across feedstocks and these yields are assumed to improve over time for cellulosic ethanol production, the actual quantity of feedstock required for a given level of ethanol production varies across feedstocks and time. Table 2-3 summarizes the quantities of residues estimated to be used for cellulosic ethanol production under the Control Case.

Table 2-3. Cellulosic Feedstock Use (millions of dry tons per year)

Feedstock	2017	2022
Bagasse	6.465	6.647
Corn residue	0	52.693
Hardwood logging residue	0.756	0.724
Softwood logging residue	0.372	0.391
Sweet sorghum pulp	1.192	1.192
Switchgrass	43.166	86.012
Wheat residue	0.466	0.837
Total across all	52.418	148.496

Because there is very little commercial market for cellulosic ethanol under the Reference Case, market prices estimated in FASOM for residue feedstocks and energy crops are very low or zero in the Reference Case. Under the Control Case, however, a significant market for these feedstocks develops. Although there is no market for switchgrass or corn residues in the Reference Case (i.e., market equilibrium quantities are zero), the average national farm-level price of switchgrass in the model results is $43.22 per dry ton in 2017 and $46.42 per dry ton in 2022.[62] Similarly, equilibrium farm-level corn residue prices are $19.24 per dry ton in 2017 and $39.19 per dry ton in 2022 as a market for these residues develops. Table 2-4 summarizes prices reported by FASOM for all cellulosic feedstocks that are used in the market equilibrium. As shown in Table 2-4, only seven cellulosic feedstocks (corn residue, wheat residue, switchgrass, bagasse, hardwood logging residue, softwood logging residue, and sweet sorghum pulp) are used in ethanol production in the model solution for the Control Case.

Note that although the delivered cost of acquiring alternative cellulosic feedstocks sufficient to generate a given quantity of ethanol within a region should be very close in equilibrium, there may be differences in the farm-level price paid for alternative feedstocks for a number of reasons. First, a dry ton of different feedstocks will provide differing quantities of ethanol because of the variance in energy density and ethanol conversion rates. Because ethanol processors consider the amount they are paying for feedstock in terms of the amount per gallon of ethanol produced, farm-level prices will vary to reflect the difference in energy content. In addition, feedstocks vary in handling and hauling costs per dry ton (and similarly per gallon of ethanol produced after adjusting for energy content) and those differences will contribute to differences in equilibrium prices that would be paid for cellulosic feedstocks at the farm level.

[62] These prices represent the feedstock price at the farm level, not including storage, transportation, and processing at the ethanol plant.

Table 2-4. National Average Farm-Level Cellulosic Feedstock Prices ($2007/dry ton)

Feedstock	2017 Reference Case	2017 Control Case	2022 Reference Case	2022 Control Case
Crop residues				
Corn residue	$0	$19.24	$0	$39.19
Wheat residue	$0	$34.15	$0	$36.25
Energy crops				
Switchgrass	$0	$43.22	$0	$46.42
Processing residues				
Bagasse	$7.81	$39.93	$9.32	$43.06
Hardwood logging residue	$0	$30.27	$0	$34.83
Softwood logging residue	$0	$23.41	$0	$27.55
Sweet sorghum pulp	$81.05	$119.46	$79.26	$115.45

Note: Prices are presented only for those feedstocks that enter the market solution in the Control Case.

2.1.1.4 Other Commodities

In addition to the most directly affected commodity markets discussed above, all markets for agricultural commodities are affected to some extent because of competing uses for land and other resources that result in land use change and production shifts in response to changes in relative prices. Figures 2-13 and 2-14 show estimated percentage changes in production and prices, respectively, for other key commodities under the Control Case. Production of most other crops declines because land has moved out of these commodities into corn production. These reductions in production result in price increases for the majority of commodities tracked, with some of the largest price increases taking place in markets for grains such as oats, barley, and rye. The sugar market also experiences substantial effects on price and production, where the increased value of sugarcane bagasse results in a large shift in refined sugar production away from using sugarbeets and toward using sugarcane. In addition to the value of the sugar produced using sugarcane, there is also the additional value associated with the bagasse used in ethanol production. Production of livestock products experiences relatively small percentage changes with both increases and decreases across products modeled. Livestock prices are generally increased, but the prices of some meats are declining.

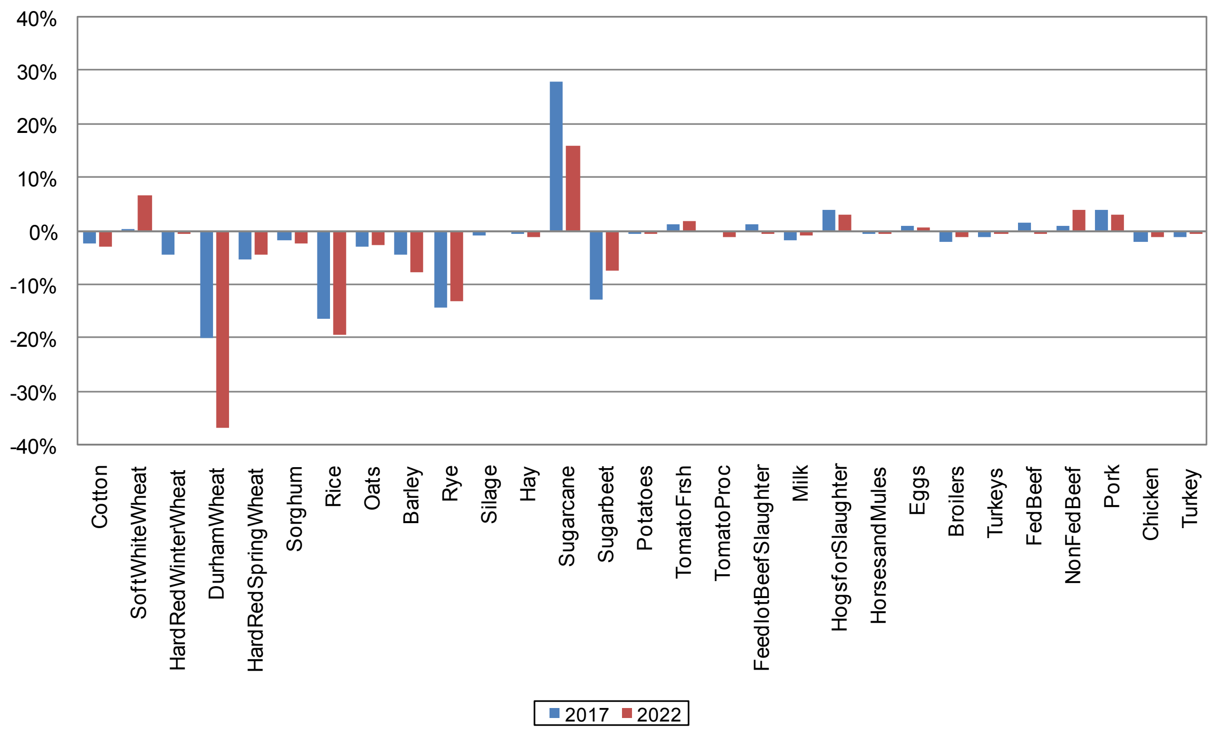

Figure 2-13. Percentage Change in Commodity Production under the Control Case Relative to the Reference Case

2.1.2 Land Use

Increases in demand for agricultural commodities used to produce large quantities of renewable fuels, such as corn and soybeans, are expected to affect U.S. land usage substantially. Total U.S. cropland and pasture acreage are both declining over time in the Reference Case because of assumed exogenous rates of conversion of agricultural land for development, although land in production is increasing in both categories. Land can move back and forth between cropland and pasture subject to constraints, but based on FASOM assumptions regarding baseline demand growth for crop and livestock commodities and changes in yields over time, the use of pasture in production is increasing faster than the use of cropland in the Reference Case. Some lands in the CRP move back into cropland over time. FASOM allows up to 5.3 million acres of CRP lands to revert to cropland by 2022 under both scenarios (such that CRP land will reach 32 million acres, as authorized in the 2008 Farm Bill).

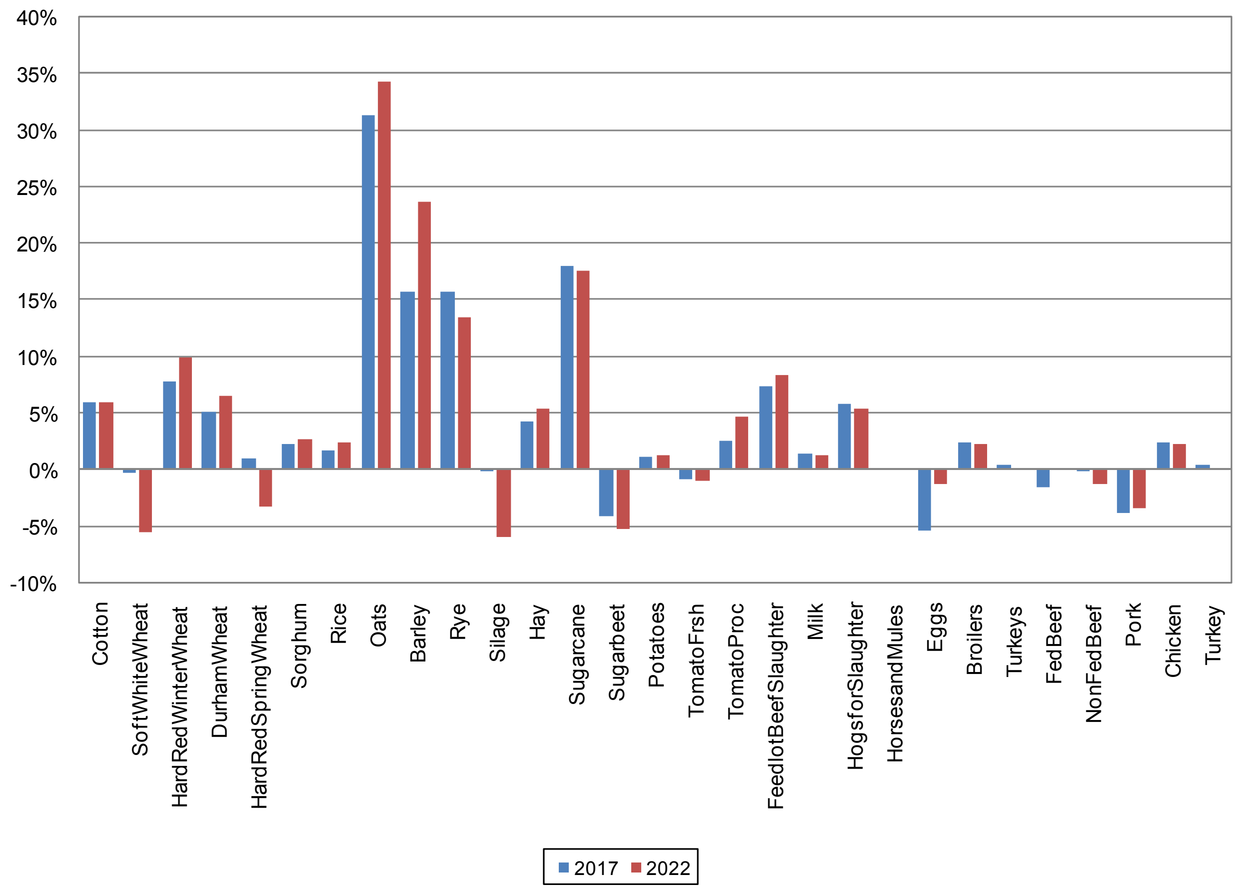

Figure 2-14. Percentage Change in Commodity Prices under the Control Case Relative to the Reference Case

By increasing the demand for cropland to produce ethanol feedstocks, the Control Case increases the use of cropland and pasture in production, while contributing to a decrease in land allocation to private forestland relative to the Reference Case. Much of the increase in land in agricultural production is drawn from previously idle pastureland. As shown in Figure 2-15, total U.S. cropland in production increases by about 0.6 million acres between 2017 and 2022 under the Reference Case. The Control Case both increases land allocation to cropland and reduces the area of idle cropland relative to the Reference Case. Cropland area in production is increased by 4.6 million acres in 2017 and 8.1 million acres in 2022 relative to the Reference Case. Pasture in use increases by 11.0 million acres in 2017 and 3.1 million acres in 2022 relative to the Reference Case.

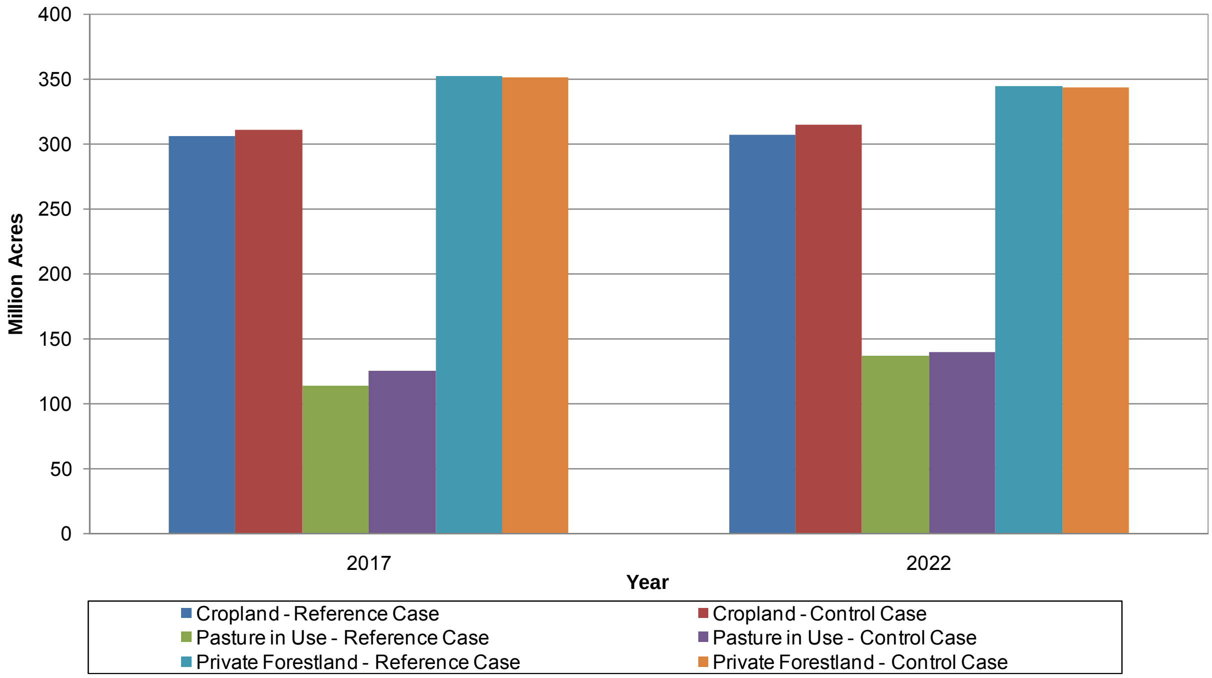

Figure 2-15. Total U.S. Cropland and Pasture in Use under the Reference Case and Control Case

FASOM assumes a constant annual yield increase in cropland productivity (for instance, FASOM assumes that corn yields increase at just over 1.6% per year). Under this assumption, as long as productivity increases outpace assumed annual demand growth, total cropland acreage tends to fall while relative land use values increase. As cropland competes with development and other uses of land, continued increases in cropland productivity are very important for reducing the costs of large-scale expansion of renewable fuels production.

Figures 2-16 and 2-17 show changes in land allocation between cropland, pasture, CRP, and developed uses under the Reference Case and Control Case, respectively.[63] The Control Case results in more pastureland converted to cropland and less conversion of cropland to developed use than in the Reference Case. Overall, as a cumulative result of changes in land allocation over time, total cropland sent to pasture is 16.6% lower (0.78 million acres) in 2017 and 16.4% lower (0.77 million acres) in 2022 under the Control Case.

[63] Developed use includes land converted to use for homes, businesses, roads, parking lots, etc. FASOM assumes that this land is no longer available for any forestry or agricultural production in the future after conversion to developed use.

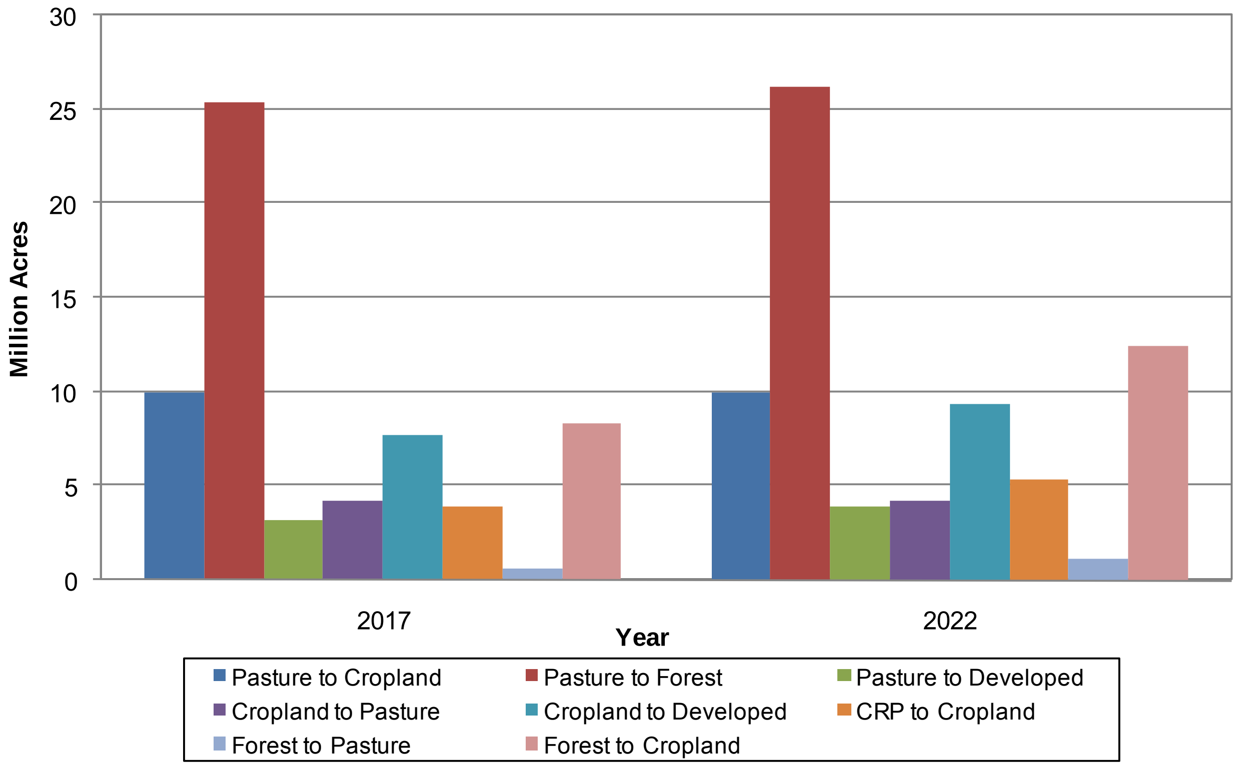

Figure 2-16. Changes in Land Allocation over Time, Reference Case

The higher prices of agricultural commodities associated with increasing demand for use in renewable fuels production will have a direct impact on the value of U.S. agricultural land. As demand increases for corn and soybeans and feed inputs for livestock increase in price, the value of agricultural land is expected to increase, as shown in Figure 2-18. In 2017, the Control Case results in an increase in cropland value of 37.9% relative to the Reference Case (from $4,571 per acre to $6,305 per acre). In 2022, the Control Case increases cropland value by 39.5% (from $4,526 per acre to $6,315 per acre). The value of cropland pasture increases as well, though by a much smaller percentage. The average cropland pasture value increases from $1,801 per acre to $1,900 per acre in 2017 (5.5% increase) and from $1,846 per acre to $2,091 per acre in 2022 (13.3% increase).

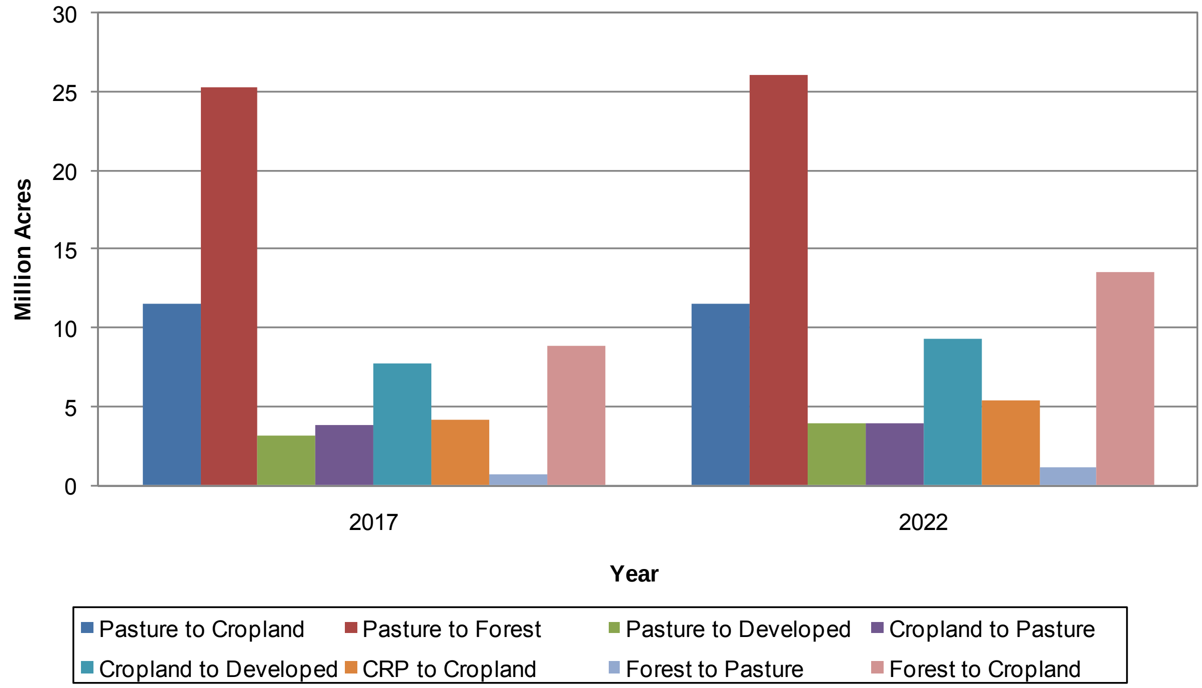

Figure 2-17. Changes in Land Allocation over Time, Control Case

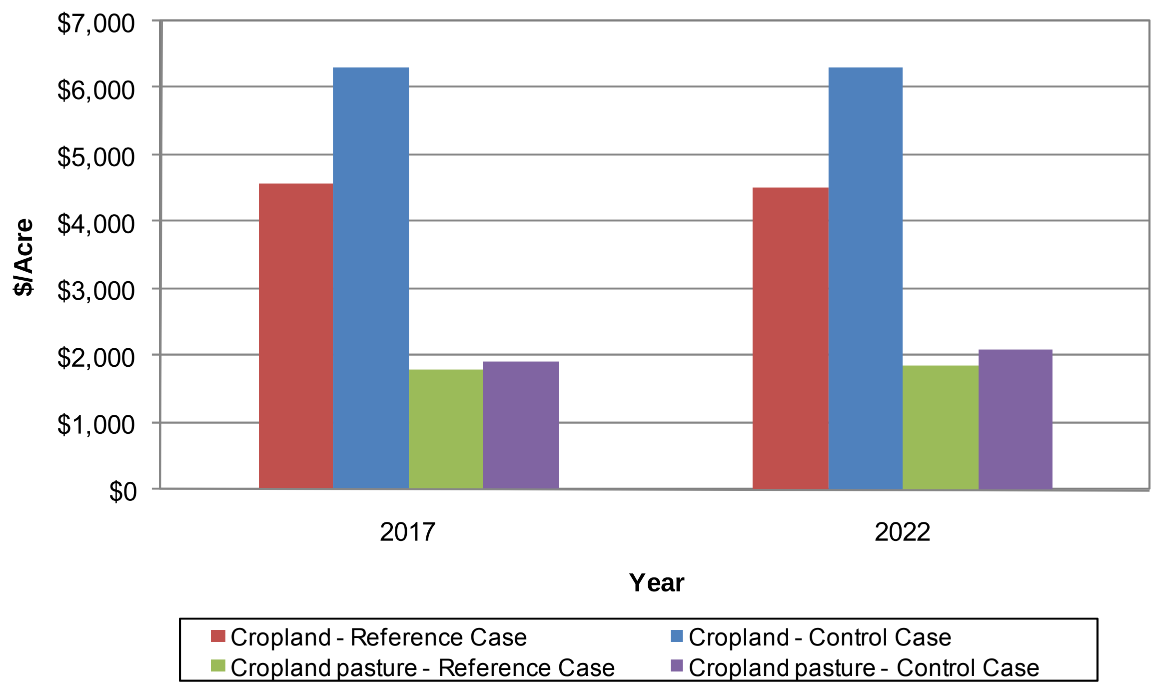

Figure 2-18. U.S. Land Values for Cropland under the Reference Case and Control Case (2007$)

As demand for corn and corn stover (corn residue) increases, more acres of cropland are expected to be used in the production of corn, as shown in Figure 2-19. FASOM results indicate that acreage devoted to corn production will increase by 6.2% (4.9 million acres) in 2017 under the Control Case. By 2022, cropland devoted to corn production is expected to increase 4.6% (3.6 million acres), relative to the Reference Case.[64] As noted earlier, although there is an increase in the demand for soybeans as a renewable fuel feedstock as well, there is still a reduction in acreage as land shifts into corn production, although the percentage change is relatively small. Although there is an increase in demand for soybeans for use in biodiesel production under EISA, the biodiesel volume requirements are relatively small compared to the required volumes of ethanol. Soybean acreage falls by about 0.1 million acres (0.1%) in 2017 and 1.4 million acres (2.1%) in 2022 relative to the Reference Case.

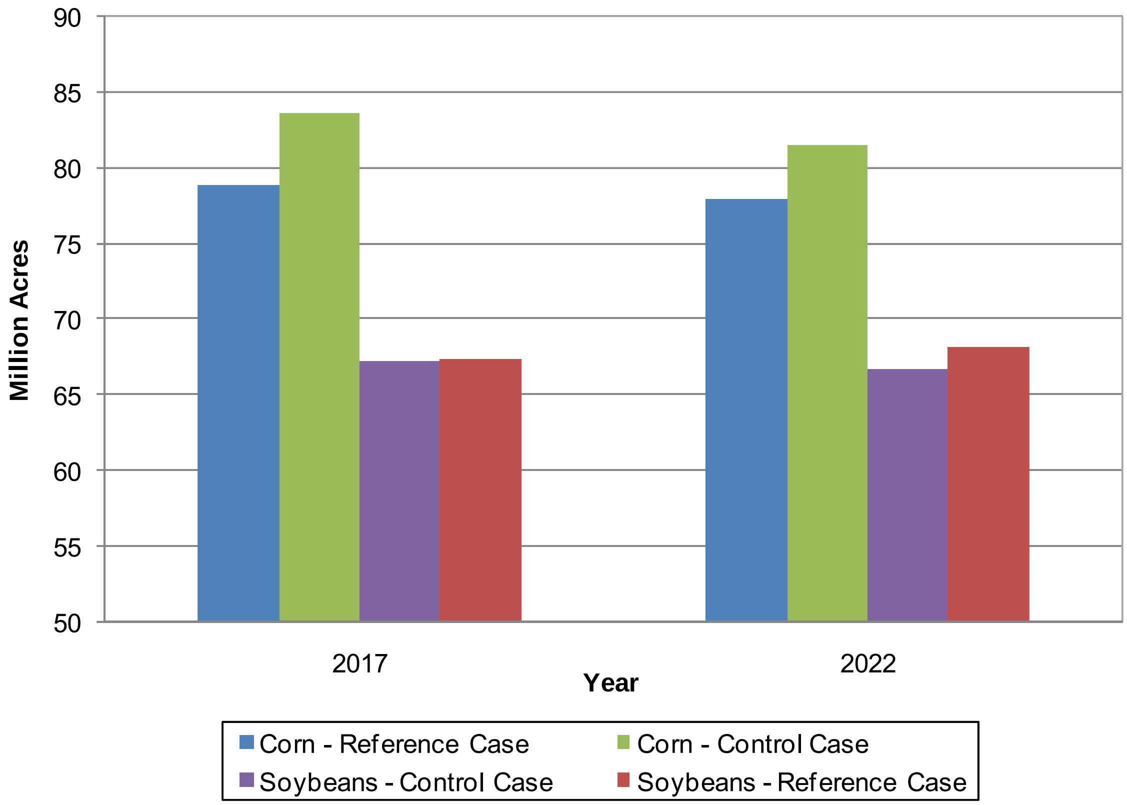

Figure 2-19. U.S. Corn and Soybean Acreage

[64] FASOM does not explicitly include corn-on-corn rotations because it is a long-term model solving in 5-year time steps and is focused on capturing changes in the long-run trends rather than short-term effects on practices such as crop rotations. Crop rotation practices are implicitly reflected in the average annual allocation of agricultural land to different crops.

FASOM assumes annual yield increases for corn and soybeans to be approximately 1.6% and 0.4%, respectively. In 2022, total production of corn in the Control Case is projected to be 15.1 billion bushels, an increase of 3.9% over the Reference Case. FASOM estimates soybean production to be 3.0 billion bushels in 2022 under the Control Case, which represents a decrease of about 1.7% relative to the Reference Case.

2.1.3 Coproducts of Renewable Fuel Production

Rapid increases in the production of renewable fuels have also resulted in large increases in the production of coproducts of renewable fuel production (e.g., DG and soybean meal). These coproducts can account for a substantial share of ethanol plant revenue. In addition, they can be used to partially substitute for grains in animal feeds and play an important and growing role in the market for livestock feed. Because production of these coproducts increases along with renewable fuels production, enabling them to replace a larger share of grain used for animal feed, they can potentially help mitigate environmental impacts of renewable fuels production by reducing land conversion and associated increases in chemical inputs.

FASOM assumes that DG, an ethanol processing by-product from the corn dry milling process, could be used to replace some of the corn and soybean meal used in feed (see Appendix A for more information on DG replacement of other feeds). As corn and other feed prices increase, the demand for DG increases and results in higher DG prices in our model simulations. By 2017, the price of DG increases 6.1% under the Control Case and in 2022, DG prices are 6.8% higher than the Reference Case, as shown in Figure 2-20.

The cost of producing ethanol depends on, among other factors, the price of corn and the price of related by-products. However, the commercial uses for DG are still being developed. This analysis assumes DG technology improves to pelletize and distribute DG to a wider market. At the renewable fuel volumes analyzed in this rule, the amount of DG in feed is unlikely to reach the maximum inclusion levels for cattle,[65] particularly if the ethanol industry continues to make progress in being able to improve the quality of DG and adjust the nutritional content so that it is better suited for pork and poultry production.

In addition to DG, gluten feed and gluten meal produced as coproducts of the corn wet milling process can be used as livestock feed. The prices of these products under the Reference and Control Cases are shown in Figure 2-21. Although the quantities of both increase by the same proportion (equal to the increase in corn wet milling), the price of gluten meal declines

[65] See http://www.ers.usda.gov/Publications/FDS/2007/05May/FDS07D01/fds07D01.pdf.

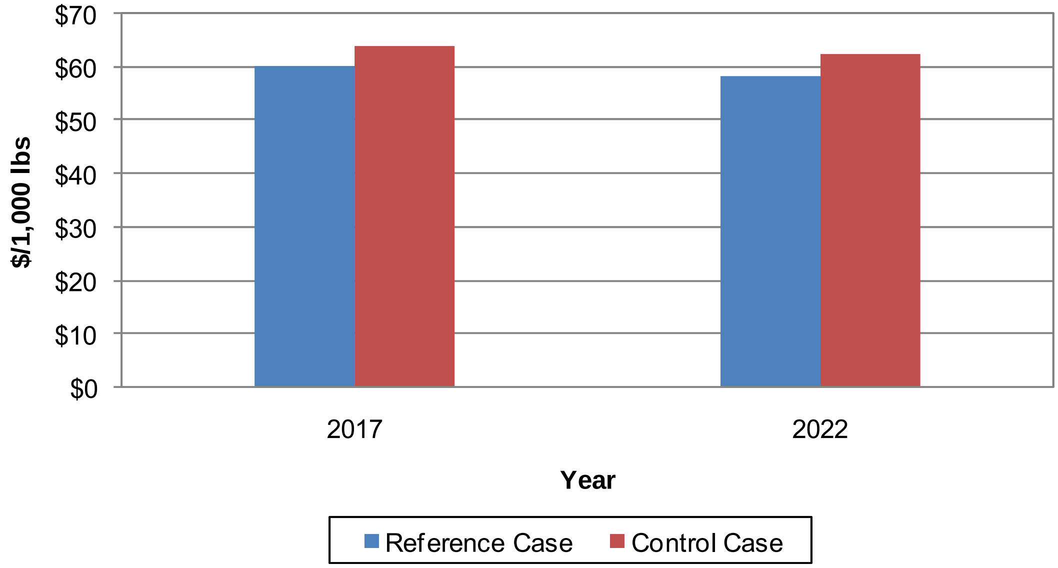

Figure 2-20. DG Prices under the Reference Case and Control Case (2007$)

while the price of gluten feed increases. One of the primary reasons for this difference in price change is the increase in soybean meal, which is a closer substitute for gluten meal than gluten feed, under the Control Case.

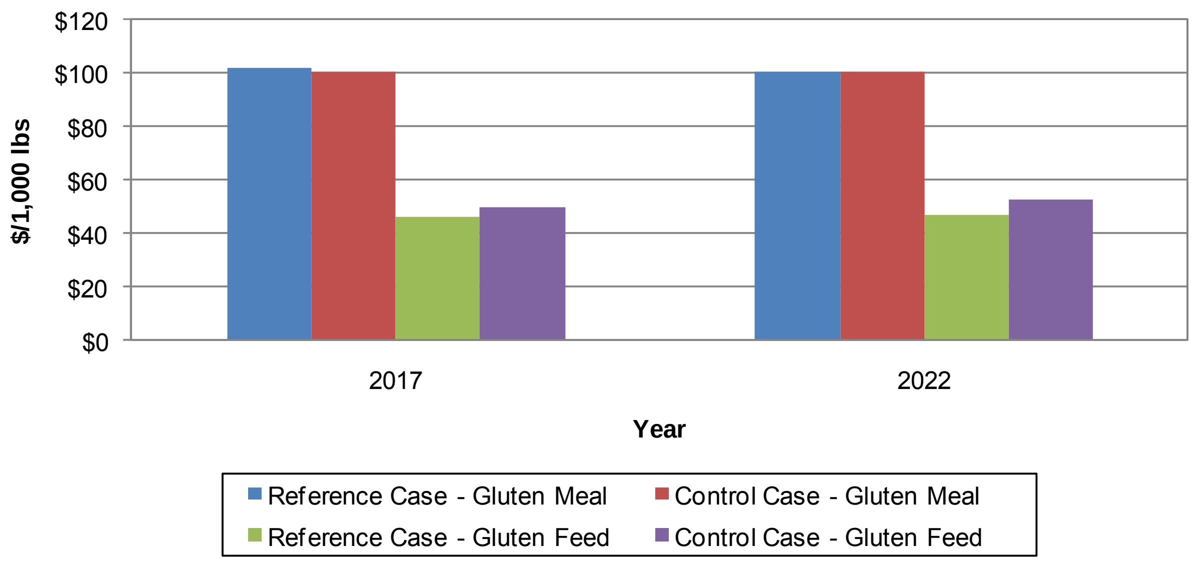

Figure 2-21. Gluten Feed and Gluten Meal Prices under the Reference Case and Control Case (2007$)

Overall, the Control Case results in an increased use of these ethanol coproducts in livestock feed as they replace some of the corn that is being diverted to renewable fuels production. Figure 2-22 shows the change in use of ethanol coproducts as a replacement for corn in livestock feed uses.

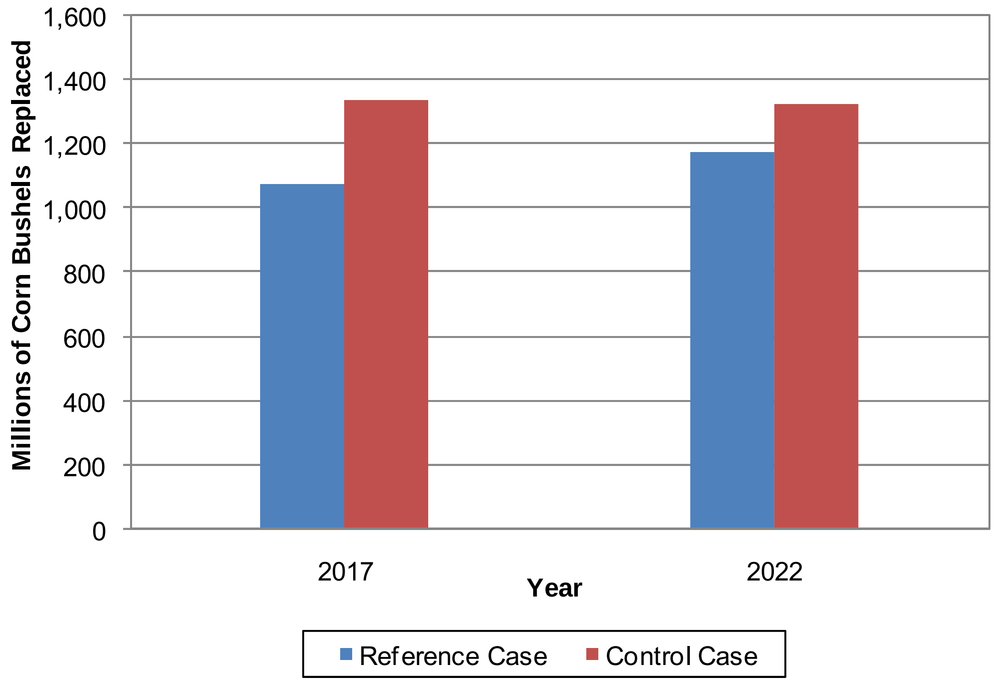

Figure 2-22. Ethanol By-products Used in Livestock Feed

Another product that can be used in livestock feed is soybean meal, which is produced in greater quantities because of the increase in biodiesel production using soybean oil. Although there is increasing demand for soybean meal in livestock feed as a replacement for corn, the increase in supply exceeds the increase in demand and the market price declines under the Control Case, as shown in Figure 2-23.

2.1.4 Livestock and Related Industries

As described above, the livestock sector is affected by increases in feed prices associated with the proposed increase in renewable fuels' production volume. Although ethanol coproducts can be used as livestock feed, they do not fully offset the increased cost of livestock feed due to increased demand for corn in alternative uses. Generally, production of individual livestock

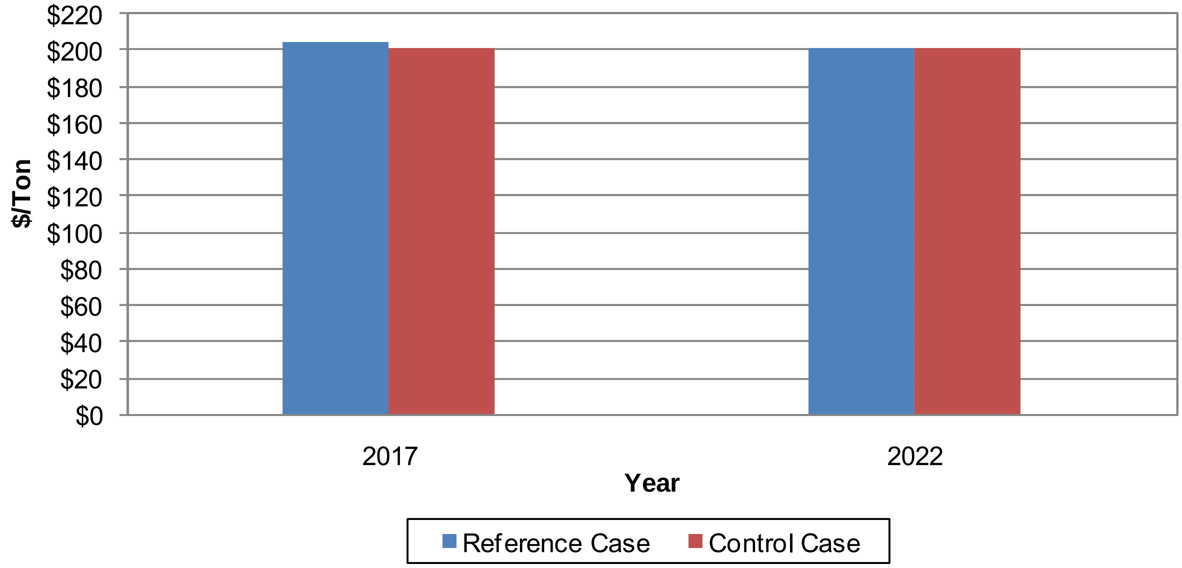

Figure 2-23. Soybean Meal Prices under the Reference Case and Control Case (2007$)

products tracked in FASOM experiences small percentage changes, as shown in Figure 2-13, while prices of most livestock products increase slightly in response to increased production costs.

2.1.5 International Agricultural Trade

In addition to the domestic market impacts, the changes in equilibrium acreage, prices, and production lead to changes in international trade patterns. In particular, the United States is a major exporter of corn, soybeans, and soybean products, which are major feedstocks for renewable fuels production. Thus, the changes taking place in markets for these commodities will affect international markets. Some of the key changes taking place under the Control Case are summarized below.

2.1.5.1 Corn Exports

The increasing demand for corn to make ethanol raises the price of corn, which has a direct impact on the competing uses of corn. FASOM results show that higher U.S. corn prices lead to lower U.S. exports of corn, as shown in Figure 2-24. In 2017, U.S. corn exports drop from about 2.19 billion bushels in the Reference Case to 2.01 billion in the Control Case (8.4% decrease). Similarly, corn exports in 2022 fall from 2.28 billion to 2.09 billion (8.2% decrease). Corn exports rise between 2017 and 2022 under both the Reference and Control Cases as corn production increases faster than the requirement for use in ethanol production. Although corn

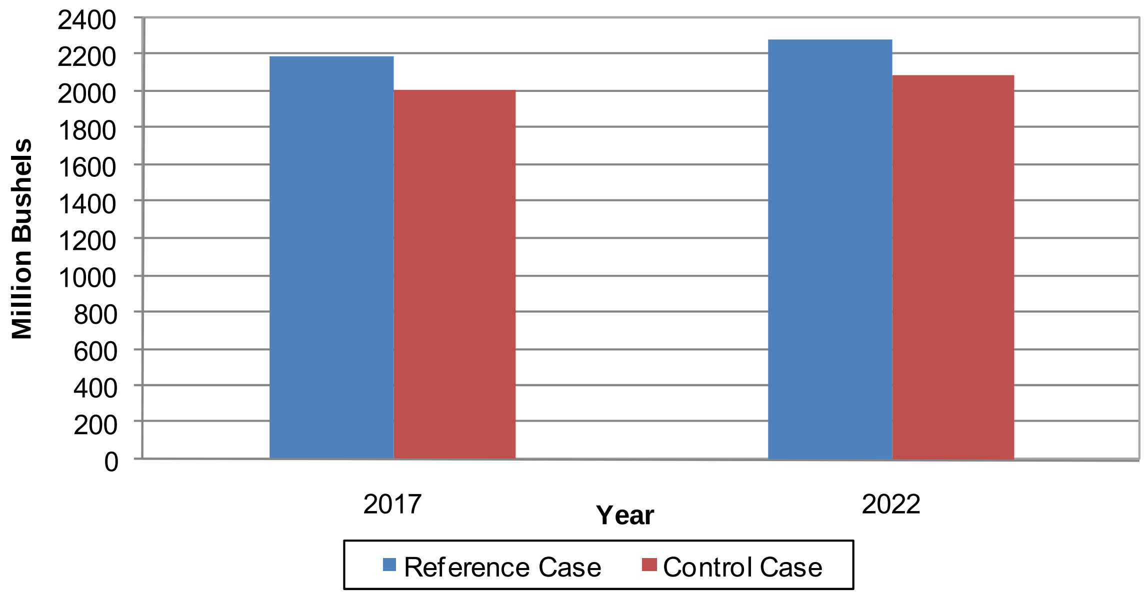

Figure 2-24. Corn Exports

prices increase under the Control Case, they do not increase sufficiently to offset the reduction in exports, and the value of corn exports declines by about $56.6 million (0.7% decrease) in 2017 and $57.2 million (0.8% decrease) in 2022, as shown in Figure 2-25. Lower exports of corn could affect world food prices and consumption patterns, although changes in international food consumption associated with EISA are modeled outside of FASOM.

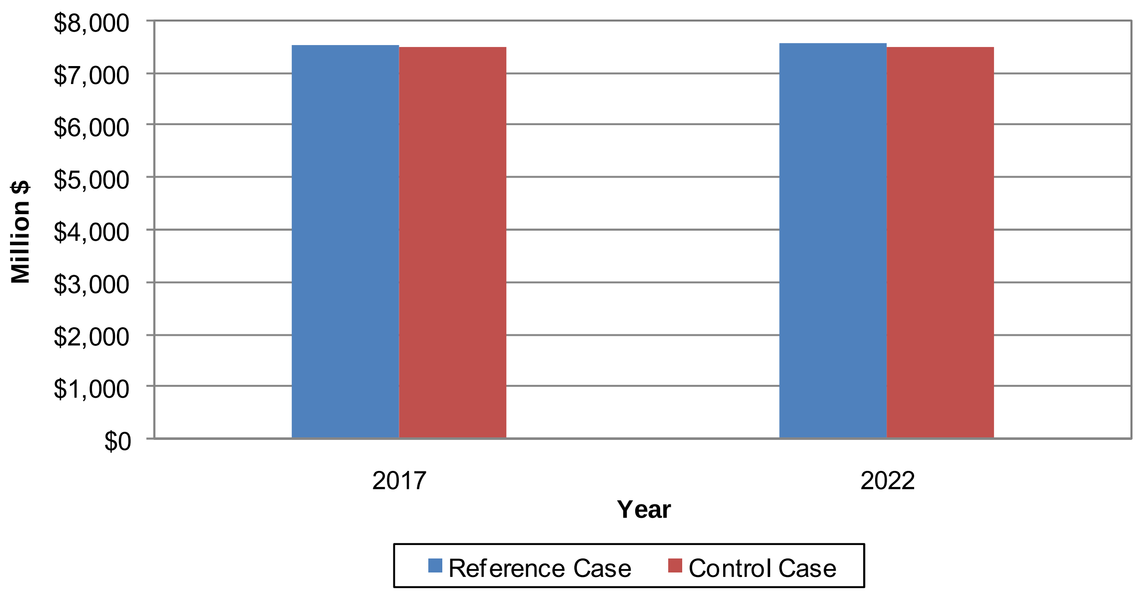

Figure 2-25. Value of Corn Exports (2007$)

2.1.5.2 Soybean, Soybean Oil, and Soybean Meal Exports

As discussed earlier, between increases in biodiesel volumes and reductions in soybean acreage and supply, soybean prices increase over time. This increase in price and reduced supply both contribute to reduced soybean exports relative to the Reference Case, as shown in Figure 2-26. In the model results for 2017, exports of soybeans are 137 million bushels (14.2%) lower under the Control Case than the Reference Case. In 2022, soybean exports fall by 134 million bushels (13.6%) under the Control Case. In value terms, soybean exports decrease by $590 million in 2017 and by $453 million in 2022 (see Figure 2-27).

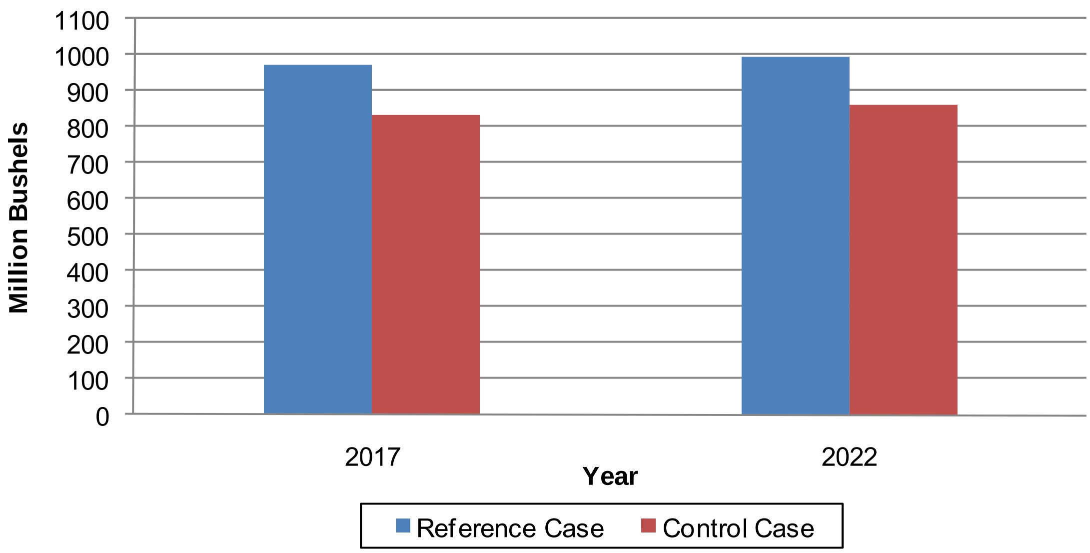

Figure 2-26. Soybean Exports

Figure 2-28 shows the decrease in soybean oil exports associated with the increase in biodiesel volumes in the Control Case. In 2017, the quantity of soybean oil exported falls from 4.2 billion pounds under the Reference Case to 2.1 billion pounds in the Control Case, a decrease of 50.0%. Similarly, exports of soybean oil are 51.2% lower under the Control Case than the Reference Case in 2022.

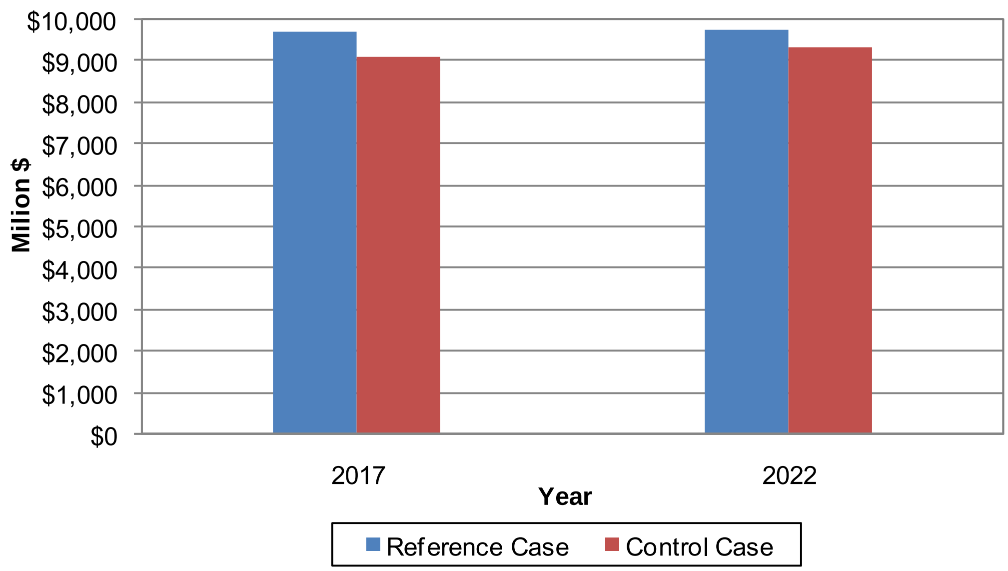

Figure 2-27. Value of Soybean Exports

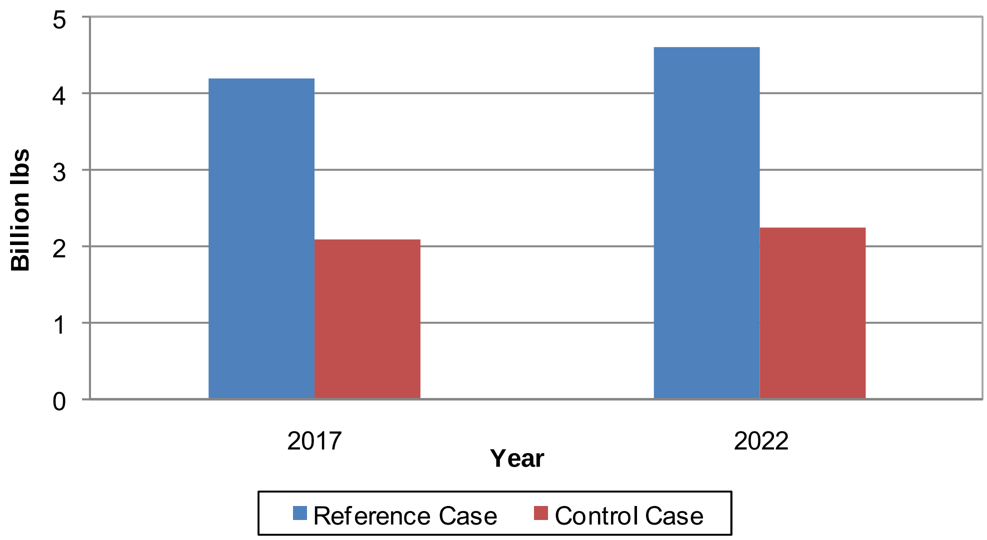

Figure 2-28. Soybean Oil Exports

In contrast to the large decline in U.S. exports of soybean oil, soybean meal exports increase in the Control Case, as shown in Figure 2-29. The volume exported in 2017 increases from 15.2 million tons to 16.2 million tons (6.5% increase), while increasing from 15.8 million tons to 16.3 million tons (2.8%) in 2022. The increase in domestic demand is for soybean oil for biodiesel production, but soybean meal is produced in large quantities as a coproduct of this process. Thus, this increased soybean meal production goes into increased use in both livestock feed and exports.

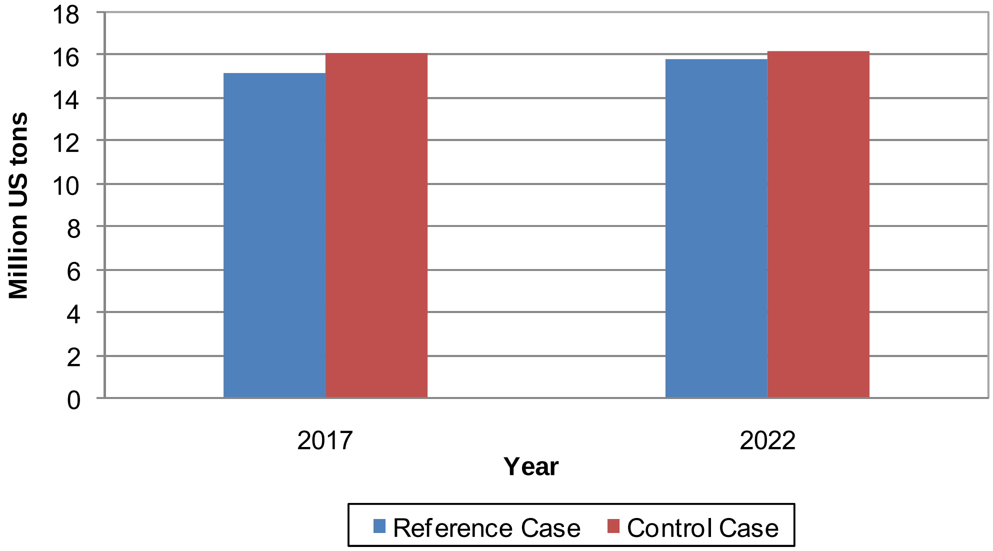

Figure 2-29. Soybean Meal Exports

2.1.6 Environmental Impacts

The changes in acreage allocation and agricultural production practices that result under the EISA requirements lead to changes in environmental impacts as well. FASOM models a number of different types of environmental impacts resulting from policy changes. In this section, we focus on changes in fertilizer use and GHG emissions.

2.1.6.1 Fertilizer Impacts

Corn and soybean production require significant inputs of fertilizer. By 2022, nitrogen inputs are expected to rise 6.8% and 5.8% for corn and soybean production, respectively, as shown in Table 2-5. Phosphorus inputs are predicted to rise 12.6% for corn, but to fall by 1.5% for soybeans, relative to the Reference Case. In addition to increasing corn acreage under the Control Case, the large increase in fertilizer use in corn production is also directly related to the harvesting of corn residue used to make cellulosic ethanol. As the corn residue is harvested, some of the vital nutrients in the soil are removed with the residue, and this requires more fertilizer-intensive corn production. Because there are currently no markets for soybean residues, increased fertilizer usage for soybean production is a function of increased soybean production. Summing across all crops included in FASOM, total use of nitrogen fertilizer increases by 1,501,258,000 pounds (5.7%) in 2022. Total use of phosphorus fertilizer increases by 714,137,000 pounds (12.7%) in 2022.

Table 2-5. Corn, Soybean, and Total Agricultural Fertilizer Usage under the Reference Case and Control Case, 2022 (thousands of pounds)

	2022			
Crop	Reference Case	Control Case	Change	Percentage Change
Corn				
Nitrogen	9,592,165	10,240,942	648,778	6.8%
Phosphorus	2,250,311	2,533,221	282,910	12.6%
Soybeans				
Nitrogen	418,568	442,712	24,144	5.8%
Phosphorus	683,121	673,161	-9,960	-1.5%
All crops in FASOM				
Nitrogen	26,208,645	27,709,903	1,501,258	5.7%
Phosphorus	5,614,163	6,328,300	714,137	12.7%

2.2 Changes in Farm Income and Food Prices

Additional effects of changing market conditions that result from increasing renewable fuels production are changes in farm income and the prices that consumers will pay for their food. Implications for both are discussed below based on FASOM results.

2.2.1 U.S. Farm Income

The increase in renewable fuel production provides a significant increase in farm income to the U.S. agricultural sector. FASOM model results show 2017 U.S. farm income from the sale of agricultural commodities increasing by 27.4% ($13.0 billion) under the Control Case. For 2022, farm income is projected to be 47.4% ($20.3 billion) higher than in the Reference Case (see Figure 2-30). As expected, increasing commodity prices and higher production levels lead to a large increase in farm income under the Control Case. Most of the increase in net income is likely to be concentrated in rural areas.

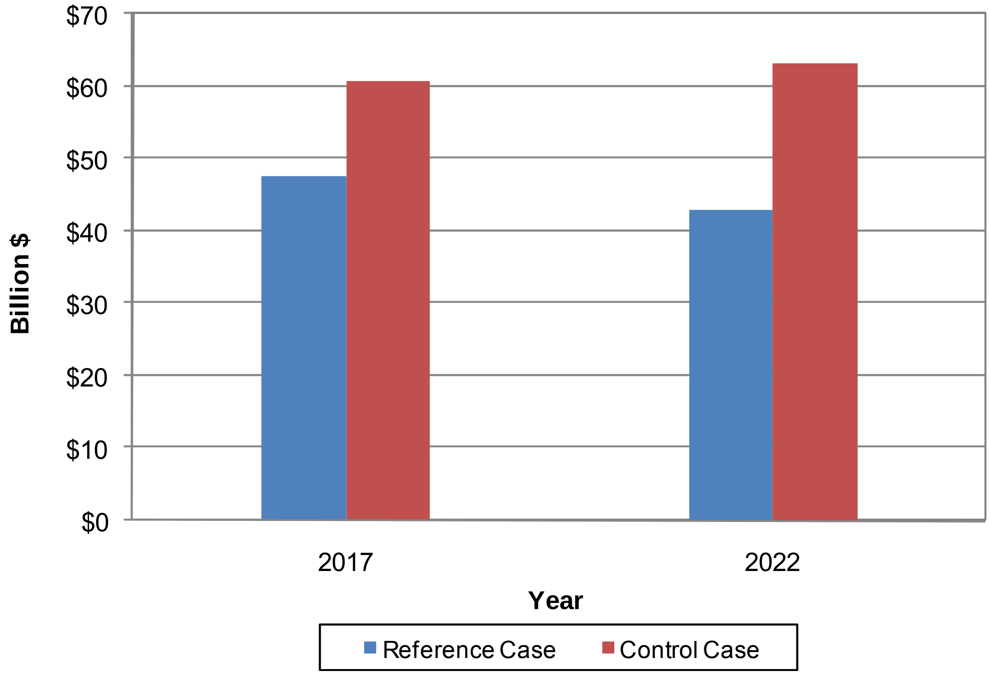

Figure 2-30. U.S. Farm Income under the Reference Case and Control Case (2007$)

2.2.2 Food Prices

Despite the wider use of U.S. agricultural feedstocks for renewable fuels, FASOM estimates only a modest increase in U.S. household food costs. One of the key reasons for this is that the majority of the required increase in renewable fuels is derived from cellulosic feedstocks. The use of these feedstocks, which have no competing use as food, has less of an impact on food costs than the use of starch and sugar-based feedstocks. FASOM does not directly track retail food prices but estimates an increase in wholesale U.S. prices for meat and agricultural products associated with the higher renewable fuel volumes. To evaluate changes in overall U.S. food prices, FASOM generates an index of prices for all farm products included in the model (All Farm Products Price Index), which is a weighted average of prices received by farmers at the farm gate for crop and livestock products.[66] In 2017, FASOM predicts an increase in the All Farm Products Price Index of 6.4% and an increase of 6.1% in 2022, as shown in Figure 2-31. However, the costs of wholesale agricultural inputs are only a portion of ultimate

[66]The FASOM All Farm Products Price Index includes cotton, corn, soybeans, wheat, sorghum, rice, oats, barley, silage, hay, sugarcane, sugar beets, potatoes, tomatoes, oranges, grapefruit, crop residues, switch grass, hybrid poplar, willow, sweet sorghum, beef, cattle, milk, hogs, sheep, lambs, wool, horses and mules, eggs, chicken, and turkey.

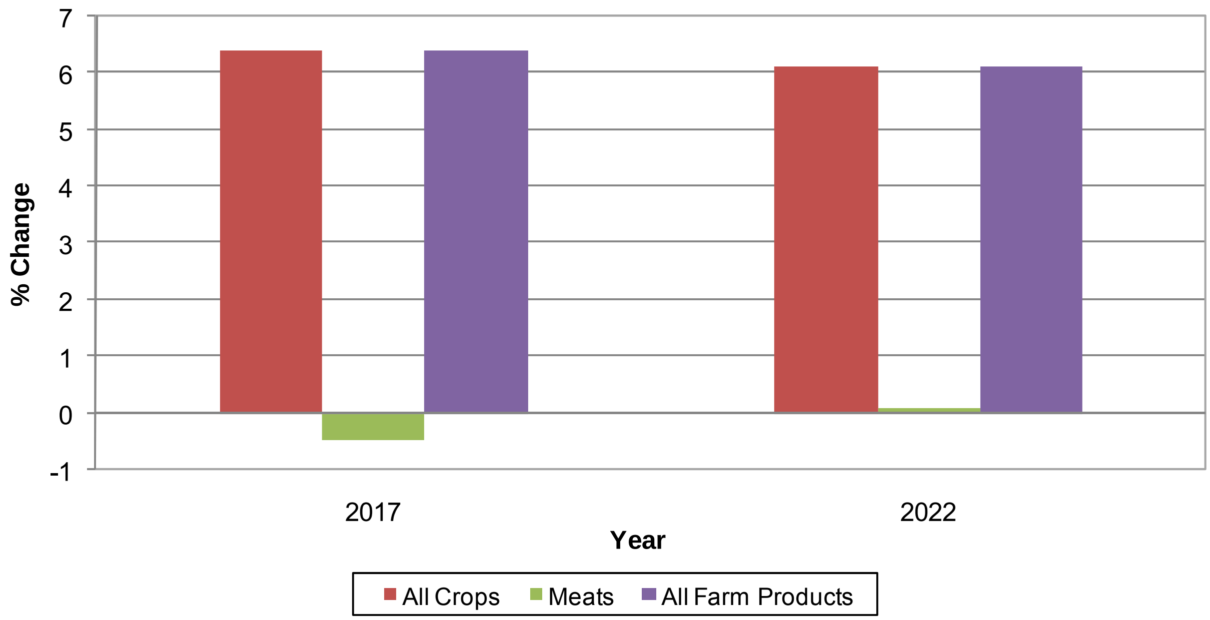

Figure 2-31. Change in Agricultural Product and Food Price Indices under the Control Case

household food costs, so significant increases in corn prices and, to a lesser degree, soybean prices are expected to result in a much smaller relative increase in household food costs.[67]

As seen in Figure 2-31, the percentage change in the All Crops Price Index[68] is very close to the change in the All Farm Products Price Index. The impact of increases in grain prices on the Meat Price Index[69] is much less than the impact on crop prices (and actually a decrease in price in 2017). This likely reflects substitution among meats toward those that are relatively less affected by the simulated increases in feed prices. Feed is an important component in producing meat products, but other costs are associated with meat production; therefore, the total cost of meat production will increase by less than the increase in feed prices. In addition, the higher value of tallow and lard as biodiesel feedstocks increases revenue from beef cattle and hog

[67] According to the U.S. Department of Agriculture (USDA), approximately 80% of consumer food expenditures are marketing costs (e.g., processing, wholesaling, packaging, and distributing). The price at the farm gate is only 20% of the retail price of food items. Marketing costs consist of a complex set of variables and do not necessarily change proportionately to an increase in farm gate costs. In fact, these interim processes can absorb price shocks to some extent, thereby dampening the impacts on the consumer. Therefore, only a portion of farm gate price changes are often reflected at the retail level. See http://www.ers.usda.gov/publications/foodreview/septdec00/FRsept00e.pdf.

[68] The FASOM All Crops Price Index includes cotton, corn, soybeans, wheat, sorghum, rice, oats, barley, silage, hay, sugarcane, sugar beets, potatoes, tomatoes, oranges, grapefruit, crop residues, switch grass, hybrid poplar, willow, and sweet sorghum.

[69] The FASOM Meat Price Index includes beef, pork, turkey, and chicken.

production and leads to increased production of non-fed beef and hogs in 2017 and 2022 as well as increased production of fed beef in 2017. These increases in production of beef and pork are contributing to the observed patterns in modeled meat prices, where the Meat Price Index actually experiences a decline in 2017 and only a small increase in 2022.

2.3 Forest Commodity Impacts

The forestry sector is a second source of feedstock for the production of cellulosic ethanol. Production of the required increases in cellulosic ethanol production is expected to rely partially on forest feedstocks; consequently, forest management could be affected as well. As modeled in FASOM, the amount of cellulosic ethanol expected to be produced from forest feedstocks is low, approximately about 0.05% of the total volume of renewable fuels production in 2022 in our model simulations. Because the actual quantity of feedstock coming from forests is relatively low compared to other cellulosic feedstocks (total ethanol production from all forest feedstocks is expected to be 109 million gallons in 2022, whereas sweet sorghum pulp is expected to produce 110 million gallons), the direct impacts of using forest-derived feedstocks are small. Estimated impacts of EISA on the use of forest feedstocks for ethanol production are presented below. As for results presented for agricultural feedstocks, we focus on estimated impacts in 2017 and 2022.

2.3.1 Commodity Prices and Quantities

Within FASOM, U.S. forest products are broken down into two major categories: softwoods and hardwoods. Currently, the model assumes that either milling residues or logging residues can be used to produce ethanol. Under the Control Case, hardwood logging residues and softwood logging residues are expected to contribute 73 million gallons and 36 million gallons of ethanol in 2022, respectively. The logging residues used as cellulosic ethanol feedstock are generally considered non-merchantable in the Reference Case and would be left in the woods. The exogenous increase in demand for hardwood and softwood logging residues under EISA will potentially create a market for these residues. Table 2-1 illustrates the production of renewable fuels across feedstocks, which provides an indication of the relative impact on the commodities markets most directly affected by increasing renewable fuels production. Implications for prices and quantities of hardwood and softwood logging residues are discussed below.

2.3.1.1 Hardwood Residues

Currently, FASOM does not consider the possibility of cellulosic ethanol production competing for the wood used in the wood products sector. Instead, it is only the residues from processing mills or logging residues that would otherwise be left in the woods that are considered as potential feedstocks. Therefore, there are no impacts on the wood products market associated with using logging residues in ethanol production. Logging residues from harvesting comprise the majority of the entire feedstock supply generated by hardwoods. As a market is created for hardwood logging residues, their price reaches $20.18/dry ton in 2017 and $23.22/dry ton in 2022 under the Control Case.

2.3.1.2 Softwood Residues

Softwoods constitute 80 to 90% of the timber used for lumber in the U.S. and are used extensively in the manufacture of fiberboard and paper. However, as discussed above for hardwoods, FASOM is not currently modeling the possibility that cellulosic ethanol production would compete with the wood products industry. It is the milling and logging residues that can potentially be used in ethanol production. In this analysis, the price for softwood logging residues rises from $0 in the Reference Case to $15.61/dry ton in 2017 and $18.37/dry ton in 2022 under the Control Case.

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APPENDIX A:
DESCRIPTION OF THE FORESTRY AND AGRICULTURAL SECTOR OPTIMIZATION MODEL

In this appendix, we include a more detailed description of the Forestry and Agricultural Sector Optimization Model (FASOM). Our focus in this report is on model assumptions and parameters most directly relevant to analyses of the impacts of large-scale renewable fuels production on agricultural and forestry market and environmental conditions.[70] The increase in demand for renewable fuels feedstocks associated with EISA is expected to affect the relative prices of alternative agricultural and forestry products, which will influence landowner decisions regarding land allocation, input use, and crop management decisions. In addition, changes in crop prices will affect animal feed prices and returns to livestock production. Section A.1 provides an overview of agricultural and forest land use and land use change modeling in FASOM. Section A.2 discusses chemical and energy inputs modeled in FASOM as well as GHG accounting for crop production activities. In Section A.3, modeling of land management decisions such as changes in tillage and implications for energy use and GHG emissions are presented. Finally, in Section A.4 we discuss treatment of the livestock and poultry sectors in FASOM.

A.1 Agricultural and Forestry Land Use

One of the unique features of FASOM that make the model particularly well-suited to analyses of major policies affecting the agricultural and forest sectors, such as the impacts of EISA renewable fuels standards, is FASOM's ability to simulate the allocation of land across competing uses over time. The model simulates the allocation of land to multiple activities in both the forest and agricultural sectors over time and the resultant consequences for the commodity markets supplied by these lands as well as changes in net GHG emissions and other environmental impacts. In this section, we discuss the regions included in FASOM; the types of land tracked; potential land uses modeled; assumptions regarding land conversion costs; crop yields and technology change over time; and GHG emissions associated with land use and land use change.

A.1.1 Regions

The FASOM model includes the 48 states in the contiguous United States divided into 63 production regions and 11 market regions, as listed in Table A-1. In addition, these regions are displayed in Figure A-1. Each of the production regions is uniquely mapped to one of the 11

[70] The focus of this appendix is primarily on key data and assumptions expected to influence analyses of the impacts of EISA. See http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf for a more detailed description of FASOM, particularly for the underlying equations and model programming structure and implementation in the General Algebraic Modeling System (GAMS) language.

Table A-1. Definitions of 11 Market Regions in FASOM

Key	Market Region	Production Region (States/Subregions)
NE	Northeast	Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, West Virginia
LS	Lake States	Michigan, Minnesota, Wisconsin
CB	Corn Belt	All regions in Illinois, Indiana, Iowa, Missouri, Ohio (IllinoisN, IllinoisS, IndianaN, IndianaS, IowaW, IowaCent, IowaNE, IowaS, OhioNW, OhioS, OhioNE)
GP	Great Plains	Kansas, Nebraska, North Dakota, South Dakota
SE	Southeast	Virginia, North Carolina, South Carolina, Georgia, Florida
SC	South Central	Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Tennessee, Eastern Texas
SW	Southwest (agriculture only)	Oklahoma, All of Texas but the Eastern Part (Texas High Plains, Texas Rolling Plains, Texas Central Blacklands, Texas Edwards Plateau, Texas Coastal Bend, Texas South, Texas Trans Pecos)
RM	Rocky Mountains	Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming
PSW	Pacific Southwest	All regions in California (CaliforniaN, CaliforniaS)
PNWE	Pacific Northwest—East side (agriculture only)	Oregon and Washington, east of the Cascade mountain range
PNWW	Pacific Northwest—West side (forestry only)	Oregon and Washington, west of the Cascade mountain range

larger market regions. The majority of production regions are defined at the state level. However, for selected major production areas with significant differences in production conditions within states, the states are broken into subregions. In addition to the regions defined for the United States, international regions are defined for the purposes of modeling international trade in agricultural products.[71]

[71] FASOM's forest sector includes endogenous trade with only Canada.

Figure A-1. Map of FASOM Regions

International regions are generally defined in a more simple way than domestic regions, with individual region-level supply and demand curves specified only for the commodities with the largest trade volumes, such as corn, wheat, soybeans, sorghum, and rice. In addition, only certain regions are defined for exporters and importers of a given commodity. In cases where commodities are traded in markets with spatial equilibrium sub-models defined, then the regions that can supply and demand that commodity in the model can either export them to another explicit region or to the United States. Similarly, demand in a region can be met through imports from the United States or from other countries. The model solves for the spatial market equilibrium and trading patterns for these heavily traded commodities.

For many other commodities (e.g., cotton, oats, barley, beef, pork, poultry), trade is modeled as total excess import supply and export demand functions facing the United States rather than trying to model individual region supply and demand. In these cases, there are single curves representing the import supply and export demand facing the United States. In addition, there are many commodities without any explicit opportunities for international trade, such as hay, silage, citrus fruits, energy crops, and livestock, among others. Generally, trade is not explicitly modeled for commodities where international trade volumes for the United States are small or the commodity is not actively traded.

A.1.2 Types of Land

FASOM accounts for land used in agricultural and forestry production within the conterminous United States, separating the land area into multiple categories that are tracked separately based on differences in their characteristics and potential uses. Different types of land tracked in the model are used as inputs into different agricultural and forestry production processes or may provide different levels of productivity. There is potential for certain types of land to move between categories subject to constraints, though, as discussed in Sections A.1.3 and A.1.4.

A.1.2.1 Agricultural Land

The major categories of agricultural land modeled within FASOM are

- cropland,
- Conservation Reserve Program (CRP) land,
- cropland pasture,
- forest pasture, and
- rangeland.

Cropland is land that is suitable for crop production and can potentially be used in the production of any of the crops included in FASOM for the particular production region being considered. Land in the cropland category is the most productive land available for producing primary agricultural commodities, although cropland in some regions is more productive than in others. Therefore, crop yields vary across regions based on historical data. The area of baseline cropland included in the model is land in crop production based on USDA National Resources Inventory (NRI) data and USDA National Agricultural Statistics Service (NASS) data on country-level harvested acreage, i.e., cropland area included in FASOM is equivalent to estimated harvested cropland. Cropland enrolled in the CRP is included under the CRP land category and cropland used as pasture is implicitly included in the pastureland category in FASOM (i.e., both of these categories of cropland are included in other categories rather than being reported under cropland). The average annual areas of cropland with failed crops[72] or idle cropland are not included in the reported FASOM cropland and are not explicitly tracked in FASOM. Cropland can potentially be converted to cropland pasture or private forestland.

[72] USDA data for planted area exceeds the harvested area because there will inevitably be some fraction of planted cropland area that is not harvested due to crop failure associated with poor weather, extreme events, or other conditions. In that case, the cost of harvesting may exceed the value of the crop. Thus, farmers will choose not to harvest those areas.

In addition to tracking aggregate cropland area, cropland is also tracked by crop tillage system and irrigated/dryland status as well as the duration of time the land has been in such a system[73] to allow tracking of sequestered soil carbon and the transition to a new soil carbon equilibrium following a change in tillage. Also, there are differences in crop yields between irrigated and dryland systems as well as differences in input use, GHG emissions, and other environmental impacts. Different tillage systems also have differences in input usage and environmental impacts in FASOM.

CRP land is cropland that has been enrolled in the Conservation Reserve Program (CRP), which is a USDA program providing payments to encourage activities providing conservation and environmental benefits. The land that farmers choose to enroll in the program is typically marginal cropland that farmers have agreed to retire from production for a contracted period. The land is generally converted to vegetative cover such as grass, trees, or woody vegetation to conserve soil, improve water quality, enhance wildlife habitat, or produce other environmental benefits. The area of CRP land in FASOM in the baseline is based on 2007 data on CRP enrollment by state available from the USDA Farm Service Agency.[74] Because landowners can choose to remove their land from the CRP program when their contract expires (or before expiration, subject to a financial penalty), FASOM also tracks the area of CRP land with expiring contracts in each year. As CRP contracts expire, landowners will move land back into agricultural production if the returns to agricultural production exceed the returns associated with maintaining land in the CRP. However, based on the 2008 Farm Bill, which specifies a maximum of 32 million acres in the CRP, and indications from USDA that they plan to provide sufficient funding to maintain that maximum level of 32 million acres in the CRP, FASOM model runs generally place a constraint of 32 million acres in CRP land in future years. That was the assumption employed in modeling the reference and control cases.

Both cropland pasture and forest pasture are suitable for livestock grazing (i.e., land that provides sufficient forage to support the needs of grazing livestock within a region), but cropland

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[73] Crop tillage systems in FASOM include conventional tillage, conservation tillage, and no-till. Conservation tillage and no-till reduce the exposure of carbon in the soil to oxidation and allow larger soil aggregates to form. These practices also leave crop residues on the soil, thereby potentially increasing carbon inputs. Tillage changes from more intensive conventional tillage practices, such as moldboard plowing, to conservation or zero tillage practices will generally increase levels of soil carbon over time. In addition, emission reductions may also result because less-intensive tillage typically involves less direct fossil fuel use for tractors. However, there are also alterations in chemical usage (possibly increases in pesticide usage and alterations in rate of fertilization), which can potentially increase emissions from their manufacture and usage. FASOM has the ability to track these indirectly induced GHG effects associated with changes in tillage.

[74] USDA Farm Service Agency. CRP Contract Summary and Statistics. http://www.fsa.usda.gov/FSA/webapp?area=home&subject=copr&topic=rns-css.

pasture tends to be more productive. Cropland pasture is managed land that is suitable for crop production and is classified specifically in this category in NRI and NASS data, but that is currently being used as pasture. Because it has sufficient quality to be used in crop production, cropland pasture can potentially be converted to crop production within the model. It can also be converted to forestland. Forest pasture, on the other hand, refers to land that has varying amounts of tree cover but can also be used as pasture. Forage production on these lands tends to be relatively low, however. This land category is further subdivided into forest pasture in forest (pasture on private timberland), forest pasture in agriculture (woodland pasture on farmland), and forest pasture in public (pasture on forested public lands that can be grazed). Forest pasture in agriculture can be converted to private timberland, but the other two categories of forest pasture cannot be converted to any other uses.

The area of pastureland or rangeland required per animal is calculated in FASOM for each combination of livestock type and pasture or rangeland category available in each region. These values are based on forage requirements for each livestock species and estimated forage productivity per acre for each category of pasture in FASOM, defined on a regional basis.[75] The area of pastureland used in livestock production is limited to the pastureland inventory by time period and region. It is possible to have idle pastureland in FASOM and idle pastureland area and associated soil carbon sequestration are tracked in the model. In particular, reductions in livestock populations may result in a reduction in pastureland used for animal production and an increase in idle pastureland in the model. Changes in feed costs are one reason why livestock populations may be impacted by EISA. The impacts of these changes on livestock markets and input use, including pastureland, are tracked within FASOM.

Rangeland in FASOM includes both public and private rangeland. Rangeland differs from pastureland primarily in that it is assumed to be generally unimproved land where a significant portion of the land cover is native grasses and shrubs. The productivity of rangeland varies considerably across regions of the U.S. Therefore, the area of rangeland required per animal for a given species can be very different across regions. Overall, rangeland typically provides lower forage production per acre than pastureland and is considered unsuitable for cultivation. In addition, much of the rangeland in the U.S. is publicly owned. Thus, it is assumed that rangeland cannot be used for crop production or forestland.

[75]The calculation of acres of pasture required by a given type of livestock in a particular region is implicitly based on estimates of AUMs available for each category of pastureland in that region.

A.1.2.2 Forestland

FASOM does not track all forestland in the United States. Instead, the model focuses on timberland available for timber production. The distinction between the two is that timberland refers to forestland that provides at least a minimum level of productivity (at least 20 cubic feet of live growing stock per acre per year) and is not reserved for uses other than timber production (e.g., wilderness use). Lands under forest cover that do not produce at least 20 cubic feet per acre per year, called unproductive forestland, and timberland that is reserved for other uses are not considered part of the U.S. timber base and are therefore not tracked by the model.[76]

In FASOM, endogenous land use modeling is only done for privately held parcels, not publicly owned or managed timberlands. However, the quantity of timber harvested on U.S. public lands is accounted for as an exogenous assumption, and timber inventory levels for public timberlands are simulated based on the exogenous timber harvest levels set by government administrative decree. On private lands, landowners choose their forest management activities and decide when to harvest and whether to replant or convert their land to another use following a harvest based on the relative returns to alternative actions.

Private timberland is tracked by its quality and its transferability between forestry and agricultural use. FASOM includes three different site classes to reflect differences in forestland productivity (these site groups were defined based on ATLAS inputs[77]), where yields vary substantially between groups:

- HIGH—high site productivity group (sites that produce >85 cubic feet of live growing stock per acre per year);
- MEDIUM—medium site productivity group (sites that produce between 50 and 85 cubic feet of live growing stock per acre per year); and
- LOW—low site productivity group (sites that produce between 20 and 50 cubic feet of live growing stock per acre per year).

Sites that offer higher productivity in timber production are also assumed to provide higher agricultural productivity if they are transferred to agricultural production following timber harvest. These differences in assumed productivity affect potential transferability between timberland and agricultural uses, as described in Section A.1.3.

[76] Because these unproductive forestlands are assumed to offer low productivity for agricultural uses as well, these land areas are not available for conversion to agricultural uses in FASOM.

[77] Haynes, R.W., D.M. Adams, and J. Mills. 1995. *The 1993 RPA Timber Assessment Update*. General Technical Report RM-259. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 66 p.

Another distinction in land ownership tracked in FASOM is between two major classes of private forest owner groups: forest industry (FI) and non-industrial private forest (NIPF) landowners. The traditional definitions are used for these ownership groups: industrial timberland owners are those that possess processing capacity for the timber, and NIPF owners do not. In FASOM, it is assumed that timberland owner by the FI cannot be converted to agriculture, whereas NIPF lands can move into agricultural production, subject to the constraints, opportunity costs, and conversion costs described in the following two sections.

In addition, FASOM tracks land in terms of the type of timber management, the species group on the land, and the stand age. There are 18 different possible management intensity classes included in the model depending on whether thinning, partial cutting, passive management, or other management methods are used. There are also 25 different forest species types, which vary by region (e.g., Douglas fir and other species types in the West and planted pine, natural pine, and various hardwood types in the South). Stand age is explicitly accounted for in 5-year cohorts ranging from 0 to 4 years up to 100+ years. Differences in these variables affect forest growth rates, optimal rotation length, and carbon sequestration.

A.1.2.3 Developed Land

FASOM also tracks the movement of agricultural and forest land into developed uses. The economic returns to developed land uses typically exceed the returns available to agricultural or forestry land uses. Thus, FASOM assumes an exogenous rate of land conversion into developed uses by region for each of the agricultural and forest land categories included in the model (with the exception of forest pasture in forest and forest pasture in public) based on projections of future U.S. population and income, with endogenous competition between agriculture and forestry for the remaining land base available for these uses over time.

A.1.3 Potential Land Uses, Opportunity Costs, and Conversion Costs

FASOM tracks many possible changes in the primary agricultural and forestry commodities produced and production practices employed on a given type of land as well as movements between the different types of land described above. Underlying the commodity production decisions and the associated environmental impacts is the decision by landowners on how much, where, and when to allocate land across potential uses. The primary factor driving changes in production practices and land use in FASOM is the relative returns available, accounting for all relevant costs. Below we describe key model assumptions driving results related to land use.

A.1.3.1 Cropland

Cropland can move freely between production of alternative crops (that are available for production within a region) with no conversion costs associated with moving between crops. However, opportunity costs of switching from the original crop influence switching between different crops produced on available cropland. In addition, there are crop mix constraints in place that constrain regional production to be a convex combination of typical historical crop mixes (with adjustments to allow for the adoption of new crops that have not been produced historically, such as energy crops). The primary rationale for this constraint is that observed historical outcomes reflect landowners' consideration of all production possibilities and constraints imposed by rotation requirements, available resources, and other technical factors. Consequently, forcing the model to use a convex combination of observed regional crop mixes implicitly incorporates all firm production processes and constraints.[78]

In addition, cropland tillage can be altered at no explicit cost, but there are differences in input use that are taken into consideration. In many cases, the choice of tillage may change along with a change in crop to be produced based on the relative returns to alternative tillage types across different crops. FASOM includes constraints on the number of acres that can change tillage status in a given time period and land changing tillage types is forced to remain in the new tillage category for a minimum amount of time before changing again. Cropland can also move between irrigated and dryland production (subject to regional constraints on production possibilities). Irrigated cropland provides higher yields for a given crop-region combination, but also requires additional inputs and is subject to water resource availability on a regional level.

Cropland can also be converted to CRP land, pastureland, or timberland.[79] The quantity of cropland in the CRP is typically based on historical data and held constant over time unless changes to CRP policy are being considered in a model run. In this study, our primary assumption for CRP land is that it will decline from the starting value of just over 37 million acres to the 32 million acre maximum level authorized by the 2008 Farm Bill. Cropland can be converted to pasture for a minimal conversion cost. However, the opportunity cost of the land being kept in cropland rather than converted is generally a major cost of switching from cropland

[78] In applications where FASOM is run over an extended time period, these crop mix constraints are typically phased out beginning after about 35 years. This reflects an assumption that observed crop mixes become less representative of future production possibilities the further one moves out into the future given technological and other advancements in production.

[79] There is no explicit movement of any land types into or out of rangeland (with the exception of rangeland moving to developed land) because that category of land use is considered to be unsuitable for cultivation and to offer lower productivity than the pasture categories.

to pastureland. The higher the returns to crop production in a given region, the less likely that cropland will move to pastureland, other things being equal. Transferability between cropland and timberland is described below under Section A.1.3.4.

Finally, there is exogenous movement of cropland to developed land based on increases in future developed land area associated with projected future U.S. population and income. Conversion to developed land is discussed in more detail in Section 1.3.5.

A.1.3.2 CRP Land

The acreage of CRP land in the model is based on historical data regarding the acreage in CRP by state as described above. In this study, acres in the CRP are permitted to revert to cropland if the returns to crop production exceed available CRP payments. However, we assume that CRP acreage will not fall below the 32 million acre maximum level authorized by the 2008 Farm Bill. A.1.3.3 Pastureland

Cropland pasture can be converted to cropland or timberland and forest pasture in agriculture can be converted to forestland. The other forest pasture categories cannot be converted to another land category, but any of the pasture categories can move to idle pastureland. The cost of converting pastureland to cropland in FASOM is equal to the difference in their regional land rental rates based on the assumed equilibration of land markets. For instance, if regional pasture rents for $20 per acre and regional cropland rents for $100 per acre, then the conversion cost[80] is the net present value of $80 per year over an infinite horizon, which is equal to $2,080 based on the 4% discount rate used in FASOM.[81] In addition to the conversion cost, there is an opportunity cost associated with the returns to keeping the land in pasture used for livestock production. Thus, the net present value of land use in cropland has to exceed that of use in pastureland by a large enough margin to justify incurring the initial conversion costs. Transferability between pastureland and timberland is described below under Section A.1.3.4.

Depending on the demand for pastureland from the livestock sector, the costs of land conversion to cropland or timberland, and the overall regional constraints on pastureland conversion, it is also possible for pastureland to move into an idle pastureland category. Essentially, this indicates that the amount of pasture being used in regional livestock production

[80] The conversion cost used in FASOM embodies both costs of converting land as well as the difference in land productivity.

[81] The real (inflation-adjusted) discount rate used in FASOM is 4%, which is broadly consistent with opportunity costs of capital in agriculture and forestry. Higher discount rates devalue future revenue and cost streams, while lower discount rates have just the opposite effect.

is less than the available pastureland in that region, but the costs of moving the land into another use (for those pasture categories that can be converted) are too high to justify conversion.

In addition, as in the case of cropland, there is exogenous movement of pastureland to developed land. Pastureland conversion to developed land is discussed in more detail in Section A.1.3.5.

A.1.3.4 Timberland

In addition to tracking endogenous land transfers between agricultural uses, FASOM is one of the few models that incorporates endogenous movements of land between the U.S. agriculture and forestry sectors.

To enable the modeling of land exchanges, additional information on land suitability was added beyond what was used in the ATLAS modeling. There were five land suitability classes defined that relate to the movement of land between forestry and agriculture:

- FORONLY—includes timberland acres that cannot be converted to agricultural uses
- FORCROP—includes acres that begin in timberland but can potentially be converted to cropland
- FORPAST—includes acres that begin in timberland but can potentially be converted to pastureland
- CROPFOR—includes acres that begin in cropland but can potentially be converted to timberland
- PASTFOR—includes acres that begin in pasture but can potentially be converted to timberland

FASOM reflects the mobility of the land resource between the sectors subject to controls for land quality/growing conditions and investments needed to mobilize land. The land quality factors generally restrict some lands to be only in forest, due to topography or soil characteristics. Likewise, the growing conditions render some lands unsuitable for forest uses at all, particularly in the drier plains areas of the country, and would thus be suitable only for some agricultural uses.

In the timberland inventory, acres that could potentially be converted from forest to crop or pasture use were included in the FORCROP and FORPAST classes, respectively. To reflect differences in land productivity and feasibility of converting timberland to crop production, movements between forestry and cropland are only permitted within the high-quality forest site productivity class. Similarly, changes in land allocation involving pastureland occur only within the medium-quality forest site productivity class. Thus, there are limits on the area of timberland within a region that can potentially move to cropland or to pastureland that reflect the regional distribution of timberland site productivity. In addition, land movements in forestry are only allowed in the NIPF owner category, reflecting an assumption that land held by the FI ownership group will not be converted out of timberland. All private timberland acres that were not eligible for transferring between sectors were assigned to the FORONLY land class.

For land beginning in agricultural production, acres by region that could potentially be converted from crop or pastureland to forestland were included in the CROPFOR and PASTFOR land classes, respectively, based on National Resource Inventory data of the USDA Natural Resources Conservation Service[82,83] and a study by Moulton and Richards.[84] Agricultural land can move to other uses during any of the 5-year model periods, but when afforested it begins in the youngest age cohort of timberland. The land then remains in timberland until timber harvest, at which time the land could potentially be converted back to agricultural use.

The investments to mobilize land from forest to agriculture generally involve stump clearing, leveling, etc., of forested lands. In addition, the model can include additional hurdle costs to reflect conditions where it may take an income differential beyond the opportunity cost in agriculture to get agricultural producers to switch to forestry. Given these model attributes, the economic conditions for land movement are that when land moves into forestry, the net present value of the returns from one rotation in forestry plus the future value of forestland beyond the first rotation must be greater than the net present value of the land remaining in agriculture by at least the hurdle cost. For land moving from forest to agriculture, the net present value of land in agriculture must exceed returns to a rotation in forestry plus the future value of forested land by the investment cost to transfer land plus any hurdle cost (this term is currently set to zero). In both land transfer cases, the land moves between sectors until the markets equilibrate and the net present value plus the investment and market wedges are equal across the sectors for lands on the margin. Naturally, land movement does not occur if the differences in the land returns are less than the hurdle cost plus the land transformation investment costs.

Land conversion costs include those for land clearing, wind rowing, and burning, and any necessary leveling and removing large chunks of woody debris for seedbed preparation. Any

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[82] U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) (formerly Soil Conservation Service) (SCS). 1989. *1987 National Resources Inventory Summary Report*. USDA, NRCS. 88p.

[83] U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS). 2001. *1997 National Resources Inventory Summary Report*. USDA, NRCS. 90 p.

[84] Moulton, R., and K.R. Richards. 1990. *Costs of sequestering carbon through tree planting and forest management in the United States*. General Technical Report WO-58. Washington, D.C.: U.S. Department of Agriculture, Forest Service, Washington Office. 17 p.

timberland converted to agricultural land is assumed to occur after harvest of any merchantable trees, and 75% of timber volume removed in land clearing is assumed to be hauled to market.[85] Constraints on the amount of timberland that could be converted to agricultural uses were derived from data from the Natural Resource Inventory by the Natural Resources Conservation Service,[86] pertaining to NIPF timberland with medium or high potential for conversion to cropland and pastureland. The data were checked against that for NRI prime farmland, representing forest, pastureland, cropland, rangeland, or other minor land uses that have good potential for cultivated crops (e.g., slope less than 5%, not excessively eroded, not wetlands). The published NRI data do not identify forestland qualifying as prime cropland below our FASOM region, thus allocation of prime cropland by forest type, management intensity class, and age cohort is by assumption (proportional to what is in the highest forestry site group).

Another important portion of the conversion cost information is estimates of acres of available prime cropland and pastureland in each state that are currently under the cover of forestland.[87,88] NRI data (1997 national survey) were used to estimate these land areas. To determine the proportion of forested cropland and pastureland available in each state, the ratio of "active" crop and pastureland was used to disaggregate the total prime agricultural land in forest cover. The amount of crop and pastureland eligible for conversion to timberland was established using information from Moulton and Richards.[89] One stipulation is that reforestation establishment costs must be greater than or equal to crop to forest or pasture to forest conversion establishment costs.[90]

Costs are represented in each region by step functions to reflect increasing costs, as the percentage of land base being converted increases. Costs for land conversion in a region are less expensive for the initial 10% of land converted and subsequently higher for the next 50%, and

[85] Adams, D.M., R.J. Alig, J.M. Callaway, B.A. McCarl, and S.M. Winnett. 1996. *The Forest and Agricultural Sector Optimization Model (FASOM): Model Structure and Policy Applications.* PNW-RP-495. U.S. Department of Agriculture, Pacific Northwest Research Station, Portland, Oregon.

[86] U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS). 2001. *1997 National Resources Inventory Summary Report*. USDA, NRCS. 90 p.

[87] Ibid.

[88] These areas are included under the timberland category in either the high or medium site productivity classes.

[89] Moulton, R., and K.R. Richards. 1990. *Costs of sequestering carbon through tree planting and forest management in the United States*. General Technical Report WO-58. Washington, D.C.: U.S. Department of Agriculture, Forest Service, Washington Office. 17 p.

[90] Adams, D.M., R.J. Alig, J.M. Callaway, B.A. McCarl, and S.M. Winnett. 1996. *The Forest and Agricultural Sector Optimization Model (FASOM): Model Structure and Policy Applications.* PNW-RP-495. U.S. Department of Agriculture, Pacific Northwest Research Station, Portland, Oregon.

even more so for the final 40%. This reflects the increasing marginal cost of land conversion due to varying topography, moisture, and other factors.[91]

Table A-2 summarizes the costs of land conversion between agriculture and forest for each of these three steps and baseline acreage available for conversion by region. All conversion of agricultural lands to forestland are in the low cost category because site preparation costs are expected to be minimal for these sites. In general, it is more expensive to convert forestland to cropland than pastureland because there is more site preparation work involved.

In addition to the land conversion costs, some forest establishment costs are considered by FASOM as part of the land allocation decision. Forest establishment costs include those for site preparation, tree seedlings, and tree planting. Intermediate timber management costs include those for pre-commercial thinning, prescribed burning, fertilization, and any other practices between stand establishment and harvest. Establishment costs vary by FASOM land class, with generally higher costs for reforested acres, such as those for FORONLY acres, and lower costs for afforesting CROPFOR and PASTFOR acres. Costs are lower on agricultural lands because they are typically well-suited to planting trees and there is less preparation work required than for reforestation of forestland, which requires more land clearing and site preparation.

For regional averages of forest establishment in the South, *Forest Farmer* reports cost trends every 2 to 3 years in the *Manual Edition*. Cost estimates and trends over the period 1952 to 1994 were reported for specific forestry practices common to the South.[92,93,94] These cost data are based on surveys of forest industry, consultants, and public agencies, and most are on a per acre basis. Those practices with a high percentage of labor experienced the greatest cost increases.[95] Updated cost functions were used from the previous FASOM model to estimate establishment and growing costs on a per acre basis.[96] Establishment costs for naturally

[91] Adams, D., R. Alig, B.A. McCarl, and B.C. Murray. 2005. "FASOMGHG Conceptual Structure and Specification: Documentation." Available at http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf.

[92] Dubois, M.R., K. McNabb, and T.J. Straka, 1999. Costs and cost trends for forestry practices in the South. *The Forest Landowner*, 32nd Manual Edition, 58(2):3-8.

[93] Dubois, M.R., K. McNabb, and T.J. Straka, 2000. Costs and cost trends for forestry practices in the South. *The Forest Landowner*, 33rd Manual Edition.

[94] Dubois, M.R., K. McNabb, and T.J. Straka, 2003. Costs and cost trends for forestry practices in the South. *The Forest Landowner*, 34th Manual Edition.

[95] Dubois, M.R., K. McNabb, and T.J. Straka, 1999. Costs and cost trends for forestry practices in the South. *The Forest Landowner*, 32nd Manual Edition, 58(2):3-8.

[96] Adams, D.M., R.J. Alig, J.M. Callaway, B.A. McCarl, and S.M. Winnett. 1996. *The Forest and Agricultural Sector Optimization Model (FASOM): Model Structure and Policy Applications.* PNW-RP-495. U.S. Department of Agriculture, Pacific Northwest Research Station, Portland, Oregon.

Table A-2. FASOM Conversion Costs Between Agricultural and Forest Land ($/acre) and Acres Available for Conversion

Land Class	Definition	Region	Land Conversion Cost Level			Total Acres
			Low	Medium	High	
FORCROP	Cost per acre	Corn Belt	$434	$761	$986	
	Available acreage	Corn Belt	422,259	2,111,293	1,689,035	4,222,587
FORPAST	Cost per acre	Corn Belt	$282	$479	$609	
	Available acreage	Corn Belt	38,391	191,957	153,565	383,913
CROPFOR	Cost per acre	Corn Belt	$434			
	Available acreage	Corn Belt	78,000,000			78,000,000
PASTFOR	Cost per acre	Corn Belt	$282			
	Available acreage	Corn Belt	10,200,000			10,200,000
FORCROP	Cost per acre	Lake States	$423	$676	$902	
	Available acreage	Lake States	561,685	2,808,424	2,246,740	5,616,849
FORPAST	Cost per acre	Lake States	$254	$423	$592	
	Available acreage	Lake States	58,195	290,976	232,780	581,951
CROPFOR	Cost per acre	Lake States	$423			
	Available acreage	Lake States	24,800,000			24,800,000
PASTFOR	Cost per acre	Lake States	$254			
	Available acreage	Lake States	2,600,000			2,600,000
FORCROP	Cost per acre	New England	$451	$789	$1,014	
	Available acreage	New England	395,726	1,978,629	1,582,903	3,957,258
FORPAST	Cost per acre	New England	$282	$507	$620	
	Available acreage	New England	77,324	386,621	309,297	773,242
CROPFOR	Cost per acre	New England	$451			
	Available acreage	New England	11,100,000			11,100,000
PASTFOR	Cost per acre	New England	$282			
	Available acreage	New England	3,900,000			3,900,000

(continued)

Table A-2. FASOM Conversion Costs Between Agricultural and Forest Land ($/acre) and Acres Available for Conversion (continued)

Land Class	Definition	Region	Land Conversion Cost Level Low	Medium	High	Total Acres
FORCROP	Cost per acre	Rocky Mountains	$733	$902	$1,014	
	Available acreage	Rocky Mountains	3,261	16,306	13,045	32,612
FORPAST	Cost per acre	Rocky Mountains	$451	$564	$676	
	Available acreage	Rocky Mountains	219	1,094	875	2,188
CROPFOR	Cost per acre	Rocky Mountains	$733			
	Available acreage	Rocky Mountains	10,900,000			10,900,000
PASTFOR	Cost per acre	Rocky Mountains	$451			
	Available acreage	Rocky Mountains	1,800,000			1,800,000
FORCROP	Cost per acre	Pacific SW	$423	$648	$874	
	Available acreage	Pacific SW	1,052	5,260	4,208	10,520
FORPAST	Cost per acre	Pacific SW	$282	$423	$564	
	Available acreage	Pacific SW	48	240	192	480
CROPFOR	Cost per acre	Pacific SW	$423			
	Available acreage	Pacific SW	1,100,000			1,100,000
PASTFOR	Cost per acre	Pacific SW	$282			
	Available acreage	Pacific SW	400,000			400,000
FORCROP	Cost per acre	Pacific NW East	$366	$592	$817	
	Available acreage	Pacific NW East	37,970	189,852	151,881	379,703
FORPAST	Cost per acre	Pacific NW East	$254	$372	$507	
	Available acreage	Pacific NW East	9,567	47,836	38,269	95,672
CROPFOR	Cost per acre	Pacific NW East	$366			
	Available acreage	Pacific NW East	2,600,000			2,600,000
PASTFOR	Cost per acre	Pacific NW East	$254			
	Available acreage	Pacific NW East	300,000			300,000

(continued)

Table A-2. FASOM Conversion Costs Between Agricultural and Forest Land ($/acre) and Acres Available for Conversion (continued)

Land Class	Definition	Region	Land Conversion Cost Level Low	Medium	High	Total Acres
FORCROP	Cost per acre	South Central	$254	$451	$564	
	Available acreage	South Central	1,301,600	6,508,000	5,206,400	13,016,000
FORPAST	Cost per acre	South Central	$169	$282	$366	
	Available acreage	South Central	520,800	2,604,000	2,083,200	5,208,000
CROPFOR	Cost per acre	South Central	$254			
	Available acreage	South Central	38,900,000			38,900,000
PASTFOR	Cost per acre	South Central	$169			
	Available acreage	South Central	15,200,000			15,200,000
FORCROP	Cost per acre	Southeast	$282	$434	$535	
	Available acreage	Southeast	968,896	4,844,481	3,875,585	9,688,962
FORPAST	Cost per acre	Southeast	$208	$276	$344	
	Available acreage	Southeast	370,574	1,852,869	1,482,296	3,705,739
CROPFOR	Cost per acre	Southeast	$282			
	Available acreage	Southeast	13,900,000			13,900,000
PASTFOR	Cost per acre	Southeast	$208			
	Available acreage	Southeast	5,200,000			5,200,000
FORCROP	Available acreage	US	3,692,449	18,462,245	14,769,797	36,924,491
FORPAST	Available acreage	US	1,075,118	5,375,593	4,300,474	10,751,185
CROPFOR	Available acreage	US	181,300,000			181,300,000
PASTFOR	Available acreage	US	39,600,000			39,600,000

regenerated stands include site preparation costs, but are significantly less than for planted stands. Sources for updated cost estimates included Dubois, McNabb, and Straka[97] and Cathcart,[98] primarily for establishment of planted stands in the Southern regions and Pacific Northwest Westside, respectively.

[97] Dubois, M.R., K. McNabb, and T.J. Straka, 2003. Costs and cost trends for forestry practices in the South. *The Forest Landowner*, 34th Manual Edition.
[98] Cathcart, J. 2003. Oregon Department of Forestry Cost Share Rates for the Forest Land Enhancement Program (FLEP). [Internal Report]. Oregon Department of Forestry. Salem, OR.

A.1.3.5 Developed Land

As noted in the sections above, land use change in FASOM reflects endogenous transfers of land between the agriculture and forest sectors based on relative returns to alternative land allocations. However, the model also incorporates exogenous projections of the conversion of cropland, pastureland, and timberland to developed uses such as shopping centers, housing, and other developed and infrastructural uses. Demand for such developed land is driven by an addition of more than 130 million people in the United States over the next 50 years, who on average will have higher personal incomes, increasing demand for housing and infrastructure. With developed uses typically occupying the top of the economic hierarchy of land use in the United States,[99] a consistent approach to modeling land conversion in FASOM is to satisfy demand for developed land before the endogenous competition for the reduced rural land base between the agricultural and forest sectors. In other words, FASOM assumes that the conversion of agricultural and forest land to developed land is a function of population, personal income, and other demographic factors, but does not depend on agricultural or forest products commodity prices or land values. This assumption is made because the land value for developed uses in those areas where development is taking place is expected to greatly exceed the land value of keeping the land in agricultural or forestry uses.

Projections of conversion of forest and agricultural land to developed use were obtained from land-use modeling for the 2010 Resources Planning Act (RPA) Land Base Assessment by the U.S. Forest Service. The RPA model provides area projections of forest, pasture, crop, range, and developed uses by region and projection decade. The main land-use data source is the NRI developed by the USDA Natural Resources Conservation Service.[100] The NRI data allow matrices to be estimated that contain regional transition rates among the major land uses, such as between forest and pasture uses or between forest and developed use (e.g., urban use). This detail in the land-use data is unique among major sources of land-use data that provide coverage for the contiguous 48 states and informs the exogenous land conversion assumptions used in FASOM.

The values used in FASOM for regional land movement from cropland, pastureland, and timberland to developed uses change over time based on the RPA projections data. In general, growth in the area of developed land is projected to slow as one moves farther out into the future.

[99] Alig, R.J., J.D. Kline, and M. Lichtenstein. 2004. "Urbanization on the U.S. Landscape: Looking Ahead in the 21st Century." Landscape and Urban Planning 69(2-3):219-234.

[100] U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS). 2001. *1997 National Resources Inventory Summary Report*. USDA, NRCS. 90 p.

Table A-3 presents a snapshot of the exogenous movement of agricultural land to developed land assumed in FASOM for 2022.

Table A-3. Exogenous Land Movement from Forestry and Agriculture to Developed Uses (Acres per Year), 2022

	CB	GP	LS	NE	PNWE	PNWW	PSW	RM	SC	SE	SW
Cropland	129,204	19,194	44,524	20,330	11,301	NA	27,252	2,321	38,311	19,899	22,055
Pastureland	17,641	3,899	29,574	19,247	24,920	NA	33,385	588	50,474	32,245	21,206
Rangeland	252	8,100	NA	NA	6,456	NA	31,138	1,154	2,758	2,265	55,681
Timberland	94,644	NA	80,974	125,146	27,641	61,206	35,825	5,525	164,649	132,446	NA

A.1.4 Crop Yields and Technology Change

Changes in technology over time are incorporated within a number of different components of FASOM, including crop yields, input use, ethanol conversion rates, electricity generation, and other processes. Projected crop yields, both domestically and internationally, constitute one of the most influential factors of this agricultural analysis. Conversion rates of feedstocks to renewable fuels over time also play an important role in determining the market equilibrium outcome. Below we discuss projected crop yields, assumptions regarding price-induced yield changes, renewable fuel feedstock conversion rates, and assumptions regarding the impacts of yield changes on input use requirements.

A.1.4.1 Crop Yields

Yields for most crops have increased significantly over time due to technological improvements. Thus, FASOM adjusts crop yields over time based on historical growth in yields. Assumed yield increases for corn and soybeans were modified for this study to ensure consistency of the national weighted average yields of these commodities with USDA projections through 2017 (the last year included in their baseline projections report) and then extrapolated out to 2022. Table A-4 summarizes 2022 national average yields for major commodities in FASOM as well as the assumed rate of annual growth.

A.1.4.2 Price-Induced Changes in Yields

If the costs of increasing productivity on existing land were lower than the value of the increased production, then agricultural landowners would presumably have already adopted these productivity-enhancing actions. Although it is possible that sufficient increases in commodity prices could induce farmers to adopt higher cost practices that increase productivity

Table A-4. FASOM National Average Yields for Major Commodities and Annual Yield Growth

Agricultural Commodity	Units	2022 Yield (units/acre)	Annual Yield Growth Rate
Barley	bu	57.3	0.10%
Corn	bu	186.3	1.62%
Cotton	480 lb bales	1.7	0.43%
Hay	tons	3.2	0.84%
Hybrid Poplar	dry tons	4.6	0.75%
Oats	bu	60.6	0.02%
Rice	cwt	79.2	1.33%
Silage	tons	19.8	1.90%
Sorghum	cwt	63.5	0.09%
Soybeans	bu	45.3	0.43%
Switchgrass	dry tons	9.1	2.04%
Sugarcane	tons	38.3	0.00%
Willow	dry tons	4.2	0.75%
Wheat, Durham	bu	34.9	1.11%
Wheat, Hard Red Spring	bu	44.0	1.00%
Wheat, Hard Red Winter	bu	73.1	1.31%
Wheat, Soft White	bu	78.3	1.11%

but are not profitable at lower commodity prices, FASOM does not directly incorporate yield responses to changes in price. However, landowners can potentially switch from dryland to irrigated production, change tillage practices, or make other management adjustments in response to the changes in price.[101]

A.1.4.3 Renewable Fuel Feedstock Conversion Rates

FASOM assumes that starch- and sugar-based ethanol production and biodiesel production are both mature technologies that have essentially already reached technical limits on feedstock conversion. Thus, while conversion rates differ across feedstocks, all feedstock conversion rates for producing these fuels remain constant over time in the model. For cellulosic ethanol production, on the other hand, there are substantial increases in conversion rates anticipated over time as cellulosic feedstock conversion technology improves and enables us to approach the technical limits on conversion. Table A-5 summarizes 2022 renewable fuel

[101] In addition, we did not model decreases in yields that might occur due to increased planting on marginal land in response to higher commodity prices. This effect is expected to at least partially offset any potential price-induced increase in yield that could be associated with expansion of biofuels production to meet the RFS2 volumes.

Table A-5. FASOM Biofuel Feedstock Conversion Rates and Index Value (2002=100)

Feedstock	2022 Yield (gallons/unit)	2022 Index Value (2002=100)
Starch- and Sugar-Based Ethanol		
Barley	1.66 gallons/bu	100
Corn (dry mill process)	2.71 gallons/bu	100
Corn (wet mill process)	2.50 gallons/bu	100
Oats	1.10 gallons/bu	100
Rice	3.98 gallons/cwt	100
Sorghum	4.25 gallons/cwt	100
Refined Sugar	141.00 gallons/ton	100
Sweet Sorghum	9.00 gallons/ton	100
Sweet Sorghum (ratooned)	11.00 gallons/ton	100
Wheat, Durham	2.56 gallons/bu	100
Wheat, Hard Red Spring	2.56 gallons/bu	100
Wheat, Hard Red Winter	2.56 gallons/bu	100
Wheat, Soft White	2.56 gallons/bu	100
Biodiesel		
Soybean Oil	0.13 gallons/lb	100
Corn Oil	1.02 gallons/gallon	100
Edible Tallow	0.13 gallons/lb	100
Non-edible Tallow	0.13 gallons/lb	100
Lard	0.13 gallons/lb	100
Cellulosic Ethanol		
Barley crop residues	92.30 gallons/dry ton	128.4
Corn crop residues	92.30 gallons/dry ton	128.4
Oat crop residues	92.30 gallons/dry ton	128.4
Rice crop residues	92.30 gallons/dry ton	128.4
Sorghum crop residues	92.30 gallons/dry ton	128.4
Wheat crop residues	92.30 gallons/dry ton	128.4
Hybrid poplar	101.50 gallons/dry ton	128.4
Switchgrass	92.30 gallons/dry ton	128.4
Willow	101.50 gallons/dry ton	128.4
Hardwood logging residues	101.50 gallons/dry ton	128.4
Softwood logging residues	92.30 gallons/dry ton	128.4
Bagasse	92.30 gallons/dry ton	128.4
Hardwood milling residues	101.50 gallons/dry ton	128.4
Softwood milling residues	92.30 gallons/dry ton	128.4
Sweet sorghum pulp	92.30 gallons/dry ton	128.4

Source: Tao, Ling and Aden, Andy. November 2008. Techno-economic Modeling to Support the EPA Notice of Proposed Rulemaking. National Renewable Energy Laboratory (NREL).

feedstock conversion rates in FASOM and an index of 2022 conversion rates relative to baseline values.

A.1.4.4 Impact of Yield Changes on Input Requirements

Another major update in FASOM that takes place along with changes in yields is the calculation of input adjustments for a given change in yield. This adjustment is included to account for the fact that increases in yield over time are related to greater expenditures on inputs, including increases in both quantity and quality of inputs. The procedure used in FASOM employs an elasticity term that gives the percentage response of input usage per acre to a percentage change in yield. The elasticity of input change with respect to crops has been derived from historical data where available. Subsequently, based on the yields, input uses in the production budgets can be updated using the elasticity of input use change with respect to yield change times the projected yield change. Based on data showing little relationship between yields and N fertilizer application since the early 1980s (see Figure A-2), we held fertilizer use constant in this analysis rather than allowing fertilizer use to increase with yield.

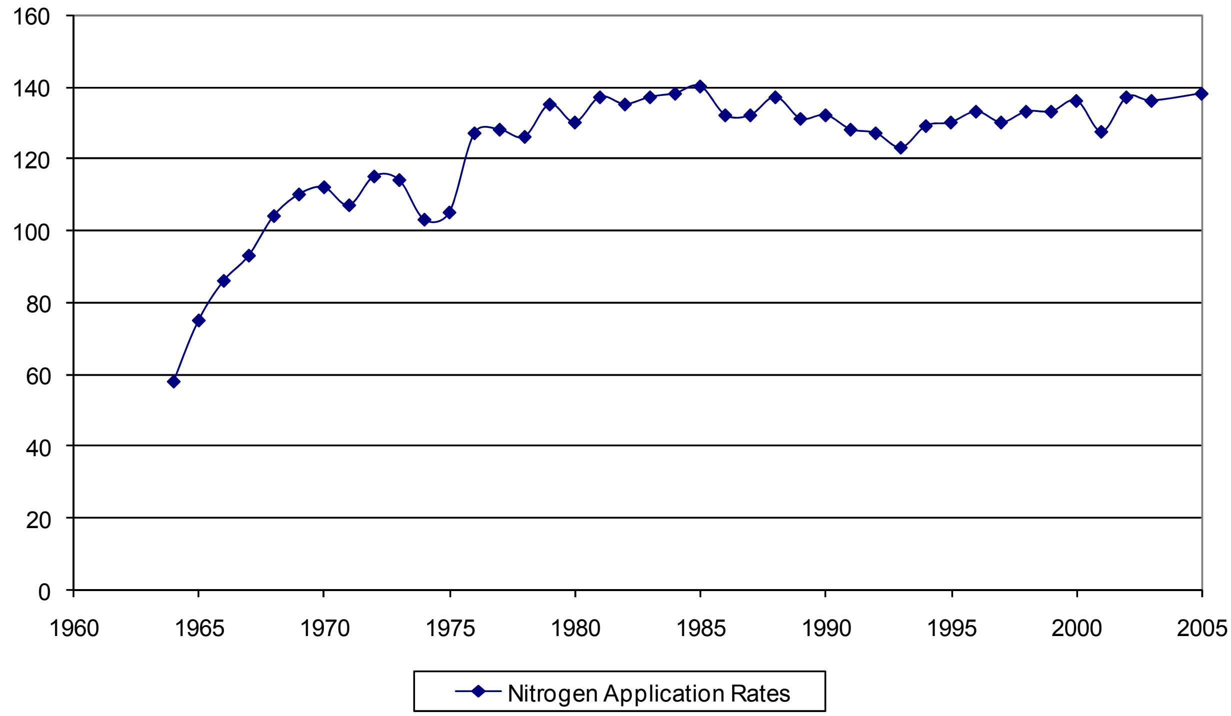

Figure A-2. Nitrogen Application Rates

A.1.5 GHG Emissions Factors for Land Use Change and Crop Production

GHG mitigation opportunities in forestry and agriculture include afforestation (tree planting), forest management (e.g., altering harvest schedules or management inputs), forest preservation, agricultural soil tillage practices, grazing management, riparian buffers, renewable fuel substitutes, fertilization management, and livestock and manure management. Sequestration activities can enhance and preserve carbon sinks and include afforestation, forest management, and agricultural soil tillage practices. Agricultural sources of CH_4, N_2O, and fossil fuel CO_2 can be reduced through changes in fertilizer applications and livestock and manure management. CO_2 emissions can be offset through renewable fuels, such as switchgrass and short-rotation tree species, which can be grown and used instead of fossil fuels to generate electricity or transportation fuels. A detailed list of the categories of GHG sources and sinks quantified in FASOM is shown in Table A-6.

This section focuses on changes in GHG emissions and sequestration related to land use change. The remaining sections in this appendix provide information on GHG emissions associated with crop production, land management, and livestock production.

In addition to quantifying GHG emissions and sinks, FASOM also can distinguish the unique time dynamics and accounting issues of carbon sequestration options. These include issues such as saturation of carbon sequestration over time (i.e., carbon sequestration in a particular sink reaches an equilibrium such that carbon storage is maintained, but is no longer increasing), potential reversibility of carbon benefits (e.g., due to changes in tillage, forest harvests, wildfires), and fate of carbon stored in products after forest harvest. In contrast, these can be compared with the options for agricultural non-CO_2, fossil fuel CO_2, and renewable fuels that do not exhibit saturation or reversibility and are permanent reductions.

GHGs, generally in the form of carbon, can be sequestered in soils, standing trees, other vegetation, and wood products. Sequestration refers to storage of the GHGs for more than one year. As a consequence, the sequestration definition used in the model for standing vegetation is limited to carbon storage in trees, understory, and litter within both forests and plantations of woody renewable fuel feedstocks (poplar and willow) but excludes, for instance, carbon stored in annually cultivated crops.

Carbon sequestration is also modeled within

- cropland soils,
- pastureland soils,
- soils in idled lands,
- timberland soils, and
- harvested wood products.

Table A-6. Categories of GHG Sources and Sinks Included in FASOM

Forest_SoilSequest	Carbon in forest soil
Forest_LitterUnder	Carbon in litter and understory of forests that remain forests
Forest_ContinueTree	Carbon in trees of forests that remain forests
Forest_AfforestSoilSequest	Carbon in forest soil of afforested forests
Forest_AfforestLitterUnder	Carbon in litter and understory of afforested forests
Forest_AfforestTree	Carbon in trees of afforested forests
Forest_USpvtProduct	Carbon from US private forests consumed producing forest products
Forest_USpubProduct	Carbon from US public forests consumed producing forest products
Forest_CANProduct	Carbon in US consumed but Canadian produced forest products
Forest_USExport	Carbon in US produced but exported forest products
Forest_USImport	Carbon in US consumed but imported from non-Canadian source
Forest_USFuelWood	Carbon in US consumed fuelwood
Forest_USFuelResidue	Carbon in US residue that is burned
Forest_USresidProduct	Carbon from US residues consumed producing forest products
Forest_CANresidProduct	Carbon from Canadian residues consumed producing forest products
Carbon_For_Fuel	Carbon emissions from forest use of fossil fuel
Dev_Land	Carbon on land after it moves into developed use
AgSoil_CropSequest	Carbon in cropped agricultural soil
AgSoil_PastureSequest	Carbon in pastureland
Carbon_AgFuel	Carbon emissions from agricultural use of fossil fuels
Carbon_Dryg	Carbon emissions from grain drying
Carbon_Fert	Carbon emissions from fertilizer production
Carbon_Pest	Carbon emissions from pesticide production
Carbon_Irrg	Carbon emissions from water pumping
Carbon_Ethl_Offset	Carbon emission offset by conventional ethanol production
Carbon_Ethl_Haul	Carbon emissions in hauling for conventional ethanol production
Carbon_Ethl_Process	Carbon emissions in processing of conventional ethanol production
Carbon_CEth_Offset	Carbon emission offset by cellulosic ethanol production
Carbon_CEth_Haul	Carbon emissions in hauling for cellulosic ethanol production
Carbon_CEth_Process	Carbon emissions in processing of cellulosic ethanol production
Carbon_BioElec_Offset	Carbon emission offset from bioelecticity production
Carbon_BioElec_Haul	Carbon emissions in hauling for bioelecticity production
Carbon_BioElec_Process	Carbon emissions in processing of for bioelecticity production
Carbon_Biodiesel_Offset	Carbon emission offset from biodiesel production
Carbon_Biodiesel_Haul	Carbon emissions in hauling for biodiesel production
Carbon_Biodiesel_Process	Carbon emissions in processing of biodiesel production
Methane_Liquidmanagement	Methane from emission savings from improved manure technologies
Methane_EntericFerment	Methane from enteric fermentation
Methane_Manure	Methane from manure management

(continued)

Table A-6. Categories of GHG Sources and Sinks Included in FASOM (continued)

Methane_RiceCult	Methane from rice cultivation
Methane_AgResid_Burn	Methane from agricultural residue burning
Methane_BioElec	Methane emissions of biomass power plants below coal power plants
Methane_Biodiesel	Methane emissions from biodiesel production
Methane_Ethl	Methane emission savings from corn ethanol processing
Methane_CEth	Methane emission savings from cellulosic ethanol processing
NitrousOxide_Manure	Livestock manure practices under managed soil categories under AgSoilMgmt
NitrousOxide_BioElec	Nitrous oxide emissions of biomass power plants over coal power plants
NitrousOxide_Biodiesel	Nitrous oxide emissions from biodiesel production
NitrousOxide_Ethl	Nitrous oxide emission savings from corn ethanol processing
NitrousOxide_CEth	Nitrous oxide emissions from cellulosic ethanol processing
NitrousOxide_Fert	Nitrogen fertilizer application practices under managed soil categories under AgSoilMgmt
NitrousOxide_Pasture	Nitrous oxide emissions from pasture
NitrousOxide_Sludge	Emissions from sewage sludge used as crop fertilizer
NitrousOxide_Nfixing	Emissions from nitrogen-fixing crops
NitrousOxide_CropResid	Emissions from crop residue retention
NitrousOxide_Histosol	Emissions from temperate histosol area[a]
NitrousOxide_Volat	Indirect soils volatilization
NitrousOxide_Leach	Indirect soils leaching runoff
NitrousOxide_AgResid_Burn	Agricultural residue burning

[a] Histosols are soils that are composed primarily of organic materials and that form in settings such as wetlands where restricted drainage inhibits the decomposition of plant and animal remains, which enables these organic materials to accumulate over time. Unlike IPCC guidance for other sources of N_2O, direct emissions for histosols are based on area rather than annual N inputs. Emissions were assumed to equal 8 kg N_2O-N per hectare for cultivated temperate histosols.

In addition, changes in sequestration for lands that move out of forestry and agricultural production into some form of developed usage such as housing, shopping centers, roads, and so forth are tracked in the model. In the subsections below, we discuss biomass clearing and changes in soil carbon sequestration—the two major categories of changes in carbon sequestration in the model—in more detail.

A.1.5.1 Biomass Clearing

One of the largest carbon pools is carbon sequestered in forests. Carbon is stored not just in the live and standing dead trees, but also in understory, forest floor and coarse woody debris, and forest soil. Harvesting timber will cause a reduction in carbon sequestration, although some of the carbon that was in the harvested trees will continue to be stored in forest products for some time afterward. If harvested stands are replanted, then there is little loss in forest soil carbon, and carbon sequestration in trees planted in that stand will increase over time. However, land converted from forestry to agricultural or other uses will have a much greater permanent reduction in carbon sequestration. We summarize the forest carbon accounting procedures used in FASOM below in Section A.1.5.1.1.[102]

In addition, converting grasslands (pastureland or land in the CRP) to crop production typically results in a reduction in carbon sequestration per acre. FASOM tracks dynamic changes in soil carbon sequestration associated with land conversion. These carbon accounting calculations are described in Section A.1.5.1.2.

A.1.5.1.1 Forest Carbon Accounting

Forest carbon accounting in FASOM follows the FORCARB model developed by the U.S. Forest Service and used in the periodic aggregate assessments of forest carbon sequestration. Tree carbon is the largest forest carbon pool and is modeled as a function of three factors: (1) merchantable volume, (2) the ratio of growing stock volume to merchantable volume, and (3) and parameters of a forest volume-to-biomass model developed by U.S. Forest Service researchers.[103] Harvest age is allowed to vary; thus, the growth of existing and regenerated/afforested stands must be modeled. Timber growth and yield data are included for existing stands, reforested stands, and afforested lands that track the volume of wood in each unharvested stand, which, in turn, is used in computing forest carbon sequestration. These data indicate the wood volume per acre in unharvested timber stands for each timber stand strata (e.g., a stand giving location, forest type, management intensity class) by age cohort. The data used are derived largely from the U.S. Forest Service RPA modeling system.[104] Merchantable volume, by age, on each representative stand is obtained from the timber growth and yield tables included in FASOM. The volume factors and biomass model parameters vary by species and region and are obtained from[105,106] and Smith et al. (2003).[107]

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[102] See Adams et al. (2005) for additional detail on the FASOM forest carbon accounting procedures.

[103] Smith, J., L.S. Heath, and J. Jenkins. 2003. Forest Volume-to-Biomass Models and Estimates of Mass for Live and Standing Dead Trees of U.S. Forests. Newton Square, PA: USDA Forest Services.

[104] Haynes, R.W. (Technical coordinator). 2003. *An Analysis of the Timber Situation in the United States: 1952 to 2050*. General Technical Report PNW-GTR-560. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 254 p.

[105] Birdsey, R.A. 1996a. "Regional Estimates of Timber Volume and Forest Carbon for Fully Stocked Timberland, Average Management after Cropland and Pasture Revision to Forest." In *Forests and Global Change. Volume II: Forest Management Opportunities for Mitigating Carbon Emissions,* D. Hair, and Neil R. Sampson, eds., Washington, DC: American Forests: 309-333.

[106] Birdsey, R.A. 1996b. "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In *Forests and Global Change. Volume II: Forest management opportunities for mitigating carbon emissions, Chapter 1,* D. Hair and Neil R. Sampson, eds. Washington, DC: American Forests: 1-25.

Carbon in live and standing dead trees is calculated using the parameters of the forest volume-to-biomass model equations for live and dead tree mass densities (above- and below-ground) in Smith et al.,[108] weighted for the FASOM region/forest type designations. Forestland area data reported by the RPA assessment[109] are used to calculate the appropriate weights. Birdsey's assumption that the mass of wood is approximately 50% carbon is used to derive the associated levels of carbon.[110]

Soil carbon is the second-largest carbon pool of carbon. Treatment of soil carbon follows Birdsey[111,112] and recent work by Heath, Birdsey, and Williams.[113] FASOM computes soil carbon profiles using soil carbon data over time from Birdsey.[114,115] As Heath, Birdsey, and Williams[116] noted, little change in soil carbon occurs if forests are regenerated immediately after harvest. As a result, FASOM assumes soil carbon on a reforested stand remains at a steady-state value. Currently, the age that this value is reached is assumed to be the minimum harvest age for FASOM region/forest type. This assumption is generally consistent with the ages at which steady-state levels of soil carbon are achieved in Birdsey.[117,118] Afforested land coming from crop

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107 Smith, J., L.S. Heath, and J. Jenkins. 2003. Forest Volume-to-Biomass Models and Estimates of Mass for Live and Standing Dead Trees of U.S. Forests. Newton Square, PA: USDA Forest Services.

108 Ibid.

109 Miles, P., U.S. Forest Service, electronic file 2002_RPA_Tables.xls to Brooks Depro, RTI International, July 30, 2003.

110 Birdsey, R.A. 1992. Changes in forest carbon storage from increasing forest area and timber growth. In: Sampson, R.N.; Dwight, H.; eds. *Forest and Global Change, Volume 1: Opportunities for Increasing Forest Cover*. Washington, DC: American Forests: 23-29.

111 Birdsey, R.A. 1996a. "Regional Estimates of Timber Volume and Forest Carbon for Fully Stocked Timberland, Average Management after Cropland and Pasture Revision to Forest." In *Forests and Global Change. Volume II: Forest Management Opportunities for Mitigating Carbon Emissions*, D. Hair, and Neil R. Sampson, eds., Washington, DC: American Forests: 309-333.

112 Birdsey, R.A. 1996b. "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In *Forests and Global Change. Volume II: Forest management opportunities for mitigating carbon emissions, Chapter 1,* D. Hair and Neil R. Sampson, eds. Washington, DC: American Forests: 1-25.

113 Heath, L.S.; Birdsey, R.A.; Williams, D.W. 2002. "Methodology for estimating soil carbon for the forest carbon budget model of the United States, 2001." *Environmental Pollution*, 116: 373-380.

114 Birdsey, R.A. 1996a. "Regional Estimates of Timber Volume and Forest Carbon for Fully Stocked Timberland, Average Management after Cropland and Pasture Revision to Forest." In *Forests and Global Change. Volume II: Forest Management Opportunities for Mitigating Carbon Emissions*, D. Hair, and Neil R. Sampson, eds., Washington, DC: American Forests: 309-333.

115 Birdsey, R.A. 1996b. "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In *Forests and Global Change. Volume II: Forest management opportunities for mitigating carbon emissions, Chapter 1*, D. Hair and Neil R. Sampson, eds. Washington, DC: American Forests: 1-25.

116 Heath, L.S.; Birdsey, R.A.; Williams, D.W. 2002. "Methodology for estimating soil carbon for the forest carbon budget model of the United States, 2001." *Environmental Pollution*, 116: 373-380.

117 Birdsey, R.A. 1996a. "Regional Estimates of Timber Volume and Forest Carbon for Fully Stocked Timberland, Average Management after Cropland and Pasture Revision to Forest." In *Forests and Global Change. Volume II: Forest Management Opportunities for Mitigating Carbon Emissions*, D. Hair, and Neil R. Sampson, eds., Washington, DC: American Forests: 309-333.

or pasture use start with the initial soil carbon value for that land/region combination reported by the Century Model, which was developed by Colorado State University.[119] The land then accumulates carbon until reaching the steady-state value for forests of the type planted in the region afforestation takes place (where steady state is assumed to be reached at the minimum harvest age in FASOM for that region/forest type).

Forest floor carbon constitutes the third largest carbon storage pool, but is much smaller than tree or soil carbon pools. Smith and Heath[120] developed a model estimating forest floor carbon mass and it forms the basis for forest floor carbon estimates in FASOM. The model's definition of forest floor excludes coarse woody debris materials; that is, pieces of down dead wood with a diameter of at least 7.5 cm that are not attached to trees.[121] In order to account for this material, coarse woody debris is assumed to be a fixed fraction of live tree carbon based on ratios of coarse woody debris carbon to live tree carbon.[122] This value is then added to the forest floor carbon values generated by Smith and Heath's forest floor model. The model for net accumulation of forest floor carbon is a continuous and increasing function of age, although the rate of accumulation eventually approaches zero (i.e., forest floor carbon reaches a steady state).

Understory vegetation comprises the smallest component of total carbon stock and includes all live vegetation except trees larger than seedlings. FASOM assumes that understory carbon is a fixed fraction of live tree carbon and uses published ratios reported in U.S. EPA[123] as the basis for these calculations.

When timber is harvested, FASOM tracks the fate of the carbon that had been sequestered on the harvested land. Figure A-3 summarizes the disposition of carbon following harvest. To calculate carbon in harvested logs, cubic feet of roundwood (the units in which

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[118] Birdsey, R.A. 1996b. "Carbon Storage for Major Forest Types and Regions in the Conterminous United States." In *Forests and Global Change. Volume II: Forest management opportunities for mitigating carbon emissions, Chapter 1,* D. Hair and Neil R. Sampson, eds. Washington, DC: American Forests: 1-25.

[119] The current version of the CENTURY agroecosystem model simulates carbon, nitrogen, phosphorus, and sulfur dynamics through an annual cycle over time scales and centuries and millennia. CENTURY is capable of modeling a wide range of cropping system rotations and tillage practices for analysis of the effects of management and climate on agroecosystem productivity and sustainability. The model has undergone numerous enhancements since the original version developed in Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Science Society of America Journal 51:1173-1179.

[120] Smith, J., and L.S. Heath. 2002. A Model of Forest Floor Carbon Mass for United States Forest Types. Newton Square, PA: USDA Forest Service.

[121] Smith, J., USDA Forest Service, email communication to Brian Murray, RTI International. August 11, 2004.

[122] U.S. Environmental Protection Agency. 2003. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2001*. Annex O.

[123] U.S. Environmental Protection Agency. 2003. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2001*. Annex O.

timber is quantified in the model) is converted into metric tons of carbon using factors reported in Skog and Nicholson.[124] These factors vary by region and are reported for logs coming from an aggregate softwood and hardwood stand. They exclude carbon in logging residue left onsite. Logging residue is tracked separately in the forest floor carbon pool described above. Table A-7 presents an example of carbon disposition over time based on FASOM accounting procedures.[125]

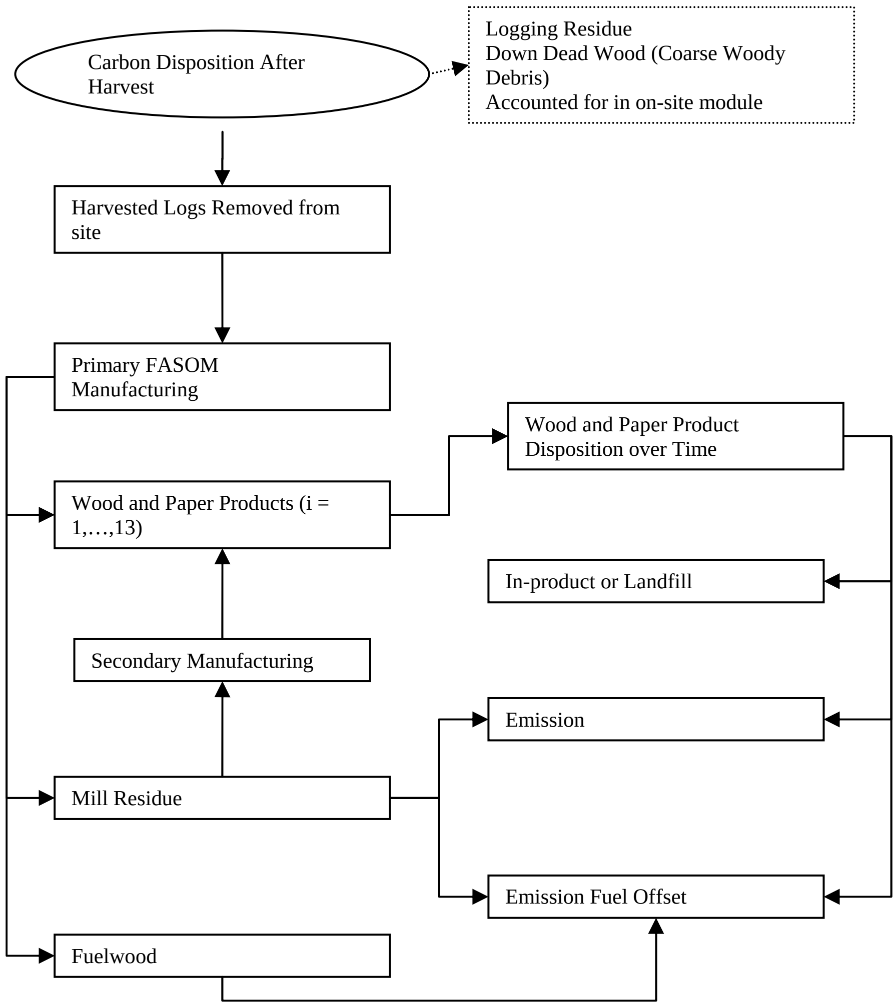

Figure A-3. Carbon Disposition after Timber Harvest

Source: Adams, D., R. Alig, B.A. McCarl, and B.C. Murray. 2005. "FASOMGHG Conceptual Structure and Specification: Documentation." Available at http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf.

[124] Skog, K, and G. Nicholson. 2000. Carbon Sequestration in Wood and Paper Products. In *The Impact of Climate Change on American Forests, Chapter 5*, L. Joyce and R. Birdsey, eds. USDA Forest Service, General Technical Report RMRS-GTR-59, Chap. 5:79-88.

[125] Depro, B.M., B.C. Murray, R.J. Alig, and A. Shanks. 2008. Public land, timber harvests, and climate mitigation: Quantifying carbon sequestration potential on U.S. public timberlands. *Forest Ecology and Management* 255(3-4):1122-1134.

Table A-7. Example of Disposition Patterns of Harvested Wood by Region and Harvest Type, 100-Year Period: Southeast

Region	Type	Product	Disposition	Years after Harvest										
				0	10	20	30	40	50	60	70	80	90	100
Southeast	Softwood	Pulpwood	Products	0.30	0.07	0.05	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.02
Southeast	Softwood	Pulpwood	Landfills	0.00	0.16	0.16	0.16	0.10	0.14	0.14	0.13	0.12	0.11	0.11
Southeast	Softwood	Pulpwood	Energy	0.44	0.45	0.45	0.46	0.46	0.46	0.46	0.46	0.46	0.46	0.46
Southeast	Softwood	Pulpwood	Emissions	0.26	0.32	0.34	0.35	0.41	0.37	0.38	0.39	0.40	0.41	0.41
Southeast	Softwood	Sawtimber	Products	0.47	0.28	0.24	0.21	0.18	0.17	0.15	0.14	0.13	0.13	0.12
Southeast	Softwood	Sawtimber	Landfills	0.00	0.13	0.16	0.17	0.18	0.19	0.19	0.19	0.18	0.18	0.18
Southeast	Softwood	Sawtimber	Energy	0.38	0.40	0.40	0.40	0.40	0.40	0.41	0.41	0.41	0.41	0.41
Southeast	Softwood	Sawtimber	Emissions	0.15	0.19	0.20	0.22	0.24	0.24	0.25	0.26	0.28	0.28	0.29
Southeast	Hardwood	Pulpwood	Products	0.30	0.07	0.05	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03
Southeast	Hardwood	Pulpwood	Landfills	0.00	0.16	0.16	0.15	0.15	0.14	0.13	0.12	0.12	0.11	0.10
Southeast	Hardwood	Pulpwood	Energy	0.39	0.40	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
Southeast	Hardwood	Pulpwood	Emissions	0.31	0.37	0.38	0.40	0.40	0.42	0.43	0.44	0.44	0.45	0.46
Southeast	Hardwood	Sawtimber	Products	0.27	0.12	0.08	0.07	0.06	0.05	0.05	0.04	0.04	0.04	0.04
Southeast	Hardwood	Sawtimber	Landfills	0.00	0.11	0.13	0.14	0.14	0.14	0.13	0.13	0.13	0.13	0.12
Southeast	Hardwood	Sawtimber	Energy	0.42	0.43	0.43	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Southeast	Hardwood	Sawtimber	Emissions	0.31	0.34	0.36	0.35	0.36	0.37	0.38	0.39	0.39	0.39	0.40

Note: These are proportions of the harvested stock allocated to each pool in the years following harvest. Column totals may not sum to one due to independent rounding.

Source: Depro, B.M., B.C. Murray, R.J. Alig, and A. Shanks. 2008. Public Land, Timber Harvests, and Climate Mitigation: Quantifying Carbon Sequestration Potential on U.S. Public Timberlands. *Forest Ecology and Management* 255(3-4):1122-1134.

Harvested logs removed from site are converted into three types of outputs through primary manufacturing processes: FASOM wood and paper products, mill residues, and fuel wood. The fate of each of these outputs is discussed in turn below.

FASOM contains the following 13 wood and paper products:

- softwood sawlogs for export

- hardwood sawlogs for export
- softwood lumber
- softwood plywood
- oriented strand board
- hardwood lumber
- hardwood plywood
- softwood miscellaneous products
- hardwood miscellaneous products
- softwood used in non-OSB reconstituted panel
- hardwood used in non-OSB reconstituted panel
- softwood pulpwood
- hardwood pulpwood

The distribution of product carbon changes over time and FASOM tracks the fate of product carbon for each end-use using two pools: carbon remaining in-product and carbon leaving the product (Figure A-4). Carbon that leaves the product ultimately makes its way to emissions or is permanently sequestered in landfills.

The fraction remaining in the product is based on a model specifying half-life values for a set of end-use categories (Table A-8).[126] The half-life represents the time it takes for approximately half of the product to decompose. For instance, carbon that is stored in paper products is assumed to have a relatively short half-life, with 50% of carbon decomposing within two years, whereas carbon stored in wood used for single-family homes has a half-life of 100 years. These values from Skog and Nicholson[127] were mapped to FASOM wood and paper products categories, weighting by wood and paper product use in various end uses.

[126] Skog, K, and G. Nicholson. 2000. Carbon Sequestration in Wood and Paper Products. In *The Impact of Climate Change on American Forests*, *Chapter 5*, L. Joyce and R. Birdsey, eds. USDA Forest Service, General Technical Report RMRS-GTR-59, Chap. 5:79-88.

[127] Ibid.

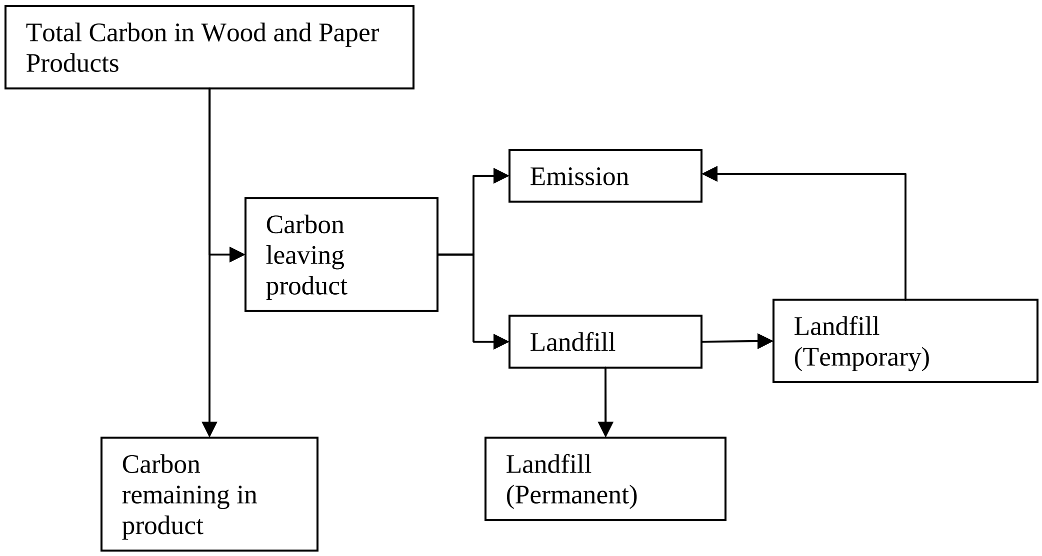

Figure A-4. Wood and Paper Product Carbon Disposition

Source: Adams, D., R. Alig, B.A. McCarl, and B.C. Murray. 2005. "FASOMGHG Conceptual Structure and Specification: Documentation." Available at http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf.

As shown in Figure A-4, carbon leaving the product pool moves to either the emissions or landfill pools.[128] Skog and Nicholson[129] assumed that 67% of carbon leaving the wood product pool and 34% of carbon leaving the paper product pool goes to landfills. The remainder of the carbon leaving the wood and paper product pools goes into CO_2 emissions to the atmosphere.

In addition, FASOM tracks the fate of mill residue using two different pools. The first is for mill residue that is used as an intermediate input in the production of wood and paper products. This carbon is tracked using the appropriate product category as described above. The second pool is for carbon in mill residue that is burned for fuel, with the fraction burned in each

[128] There are two landfill pools that are tracked: permanent and temporary. Carbon in permanent landfills is sequestered forever, but carbon in temporary landfills decays and is eventually released as emissions. The model assumes that approximately 77% of wood products and 44% of paper products going into landfills remain permanently sequestered. The rest is eventually released to the atmosphere as emissions based on an assumed half-life of 14 years.

[129] Skog, K, and G. Nicholson. 2000. Carbon Sequestration in Wood and Paper Products. In *The Impact of Climate Change on American Forests, Chapter 5,* L. Joyce and R. Birdsey, eds. USDA Forest Service, General Technical Report RMRS-GTR-59, Chap. 5:79-88.

Table A-8. Half-life for Forest Products in End Uses

End Use or Product	Half-Life in Years
Paper	2
New residential construction	
Single family	100
Multifamily	70
Mobile homes	12
Residential upkeep & improvement	30
New nonresidential construction	
All ex. railroads	67
Railroad ties	12
Railcar repair	12
Manufacturing	
Household furniture	30
Commercial furniture	30
Other products	12
Shipping	
Wooden containers	6
Pallets	6
Dunnage etc.	6
Other uses for lumber and panels	12
Uses for other industrial timber products	12
Exports	12

Source: Adams, D., R. Alig, B.A. McCarl, and B.C. Murray. 2005. "FASOMGHG Conceptual Structure and Specification: Documentation." Available at http://agecon2.tamu.edu/people/faculty/mccarl-bruce/papers/1212FASOMGHG_doc.pdf.

region based on Smith et al.[130] It was assumed that one-third of mill residue burned is used to offset fossil fuels.

Harvested fuel logs and the associated carbon are used as to produce energy at mills. For fuel wood, FASOM assumes that 100% of fuel wood burned in the sawtimber and pulpwood production process is used to offset fossil fuels.

A.1.5.1.2 Effects of Changes in Forest Area on Carbon Storage

In FASOM, land used in forestry can move to agriculture or developed use, resulting in a dynamic change in carbon storage levels on the previously forested land. When land moves

[130] Smith, W.B., J.S. Vissage, D.R. Darr, and R.M. Sheffield. 2001. Forest Resources of the United States, 1997. US Forest Service General Technical Report NC-219. St. Paul, MN: U.S. Dept. of Agriculture, Forest Service, North Central Research Station.

from forestry to one of these other uses, two carbon pools associated with the land are tracked (Figure A-5):

- residual forest floor carbon
- soil carbon (in agricultural or in developed use)

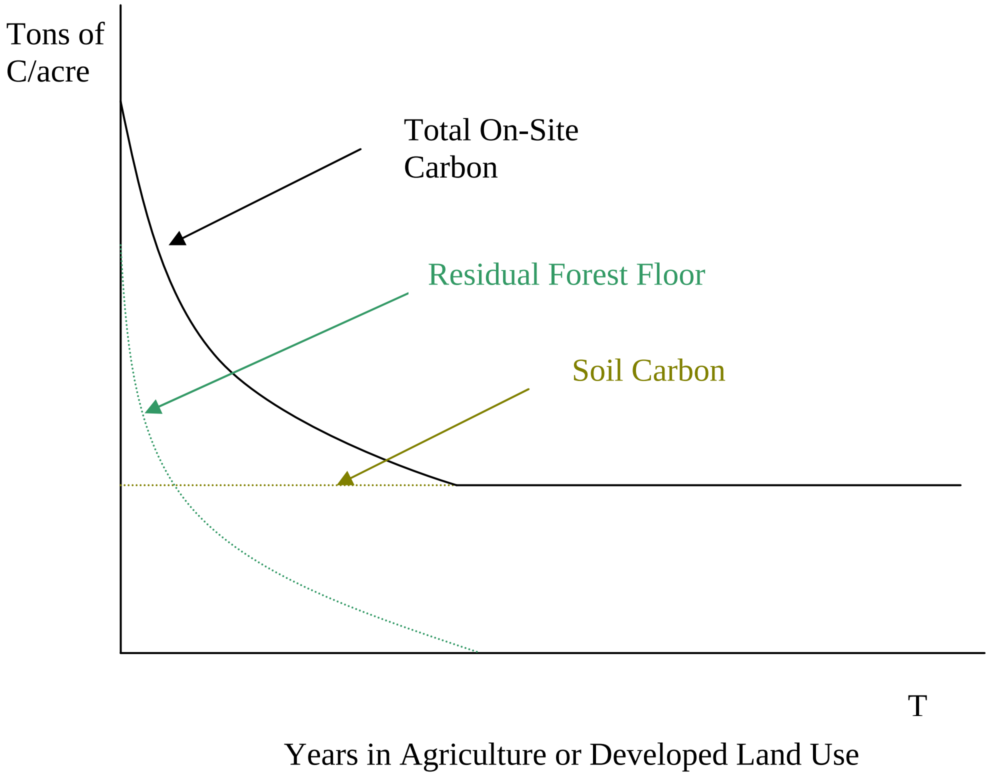

Figure A-5. Disposition of On-Site Carbon after Deforestation

For agriculture and developed land uses, the path of residual forest floor carbon stock is assumed to be the same as for the forest floor carbon profile after a harvest, which is described above. This model of decay is based on the average forest floor of mature forests and regional averages for decay rates, as described in Smith and Heath.[131]

The approaches used in FASOM to account for transition paths of soil carbon following deforestation are defined as follows. When forested land switches to agriculture, soil carbon levels are assumed to be consistent with Century Model data on agricultural soil carbon for the appropriate category of agricultural land and do not vary over time. In the case of timberland

[131] Smith, J. and L.S. Heath. 2002. A Model of Forest Floor Carbon Mass for United States Forest Types. Newton Square, PA: USDA Forest Service.

switching to developed land uses, the soil carbon levels are assumed to be consistent with the steady-state value of the minimum harvest age. As for land moving to agriculture, the soil carbon level does not vary over time.

In addition, the carbon stored in the forest products produced from the harvest that cleared the land is tracked over time as described in the previous section. The change in forest sequestration associated with a policy change is calculated as the difference in carbon sequestration in each of the carbon pools tracked between the model simulation with the policy in place and the baseline model simulation. Thus, any potential foregone sequestration that may be associated with reallocation of forestland to agricultural land in response to a change in policy would be captured in the calculation of the difference between the forest carbon sequestration values under baseline and policy conditions.

A.1.5.2 Soil Carbon Sequestration

Agricultural soil carbon sequestration depends on management activities that influence carbon storage per acre. Key factors that affect soil carbon sequestration include the following:

- **Intensity of agricultural tillage**. Agricultural soils have traditionally been tilled to create a suitable seedbed, reduce weed competition, and remove restrictions to crop root growth. However, by loosening the soil, tillage breaks up soil aggregates and increases the exposure of soil organic matter to oxygen, which speeds oxidation and results in reduced soil carbon with an associated release of CO_2 into the atmosphere. The use of tillage alternatives that reduce soil disturbance and therefore reduce oxidation of soil organic matter will increase soil carbon sequestration. Reduced tillage practices also leave crop residues on the soil, thereby potentially increasing carbon inputs. Typically, reduced tillage involves movement from intensive tillage practices such as moldboard plowing to conservation or zero tillage practices.[132]
- **Irrigation status**. Based on data from the Century model, there are differences in soil carbon sequestration per acre for a given region between irrigated and dryland cropland systems.[133] For sites receiving irrigation, the increased yields are expected to increase biological activity and hence soil carbon sequestration throughout the year. FASOM incorporates these differences in soil carbon storage within tables of soil carbon storage that vary by irrigation status.

[132] In addition to changes in soil carbon, there are additional changes in emissions associated with tillage changes that are tracked in FASOM. Less-intensive tillage typically reduces emissions from fossil fuel use by tractors, but may result in increases in the use of pesticides and changes in the rate of fertilization, which can increase emissions associated with agricultural chemical production and use. FASOM tracks these indirect effects on GHG emissions.

[133] All pastureland and CRP land in FASOM are assumed to be produced in dryland systems.

- **Relative abundance of grasslands**. Normally, pasturelands and land in the CRP experience less soil disturbance than actively tilled croplands and tend to store more carbon per acre. Thus, changes in the distribution of land between pastureland, cropland, and land in the CRP will affect agricultural soil carbon sequestration.
- **Mix of annuals versus perennials**. Because perennial crops would not be tilled on an annual basis, there will typically be a reduction in soil disturbance relative to actively tilled annual crops. By definition in FASOM, perennial crops such as switchgrass, hybrid poplar, and willow are produced under zero tillage. Similarly, as described in the previous section on forest carbon sequestration, forest soils have higher rates of carbon sequestration per acre.

Baseline carbon storage is estimated from the baseline distribution of land across tillage practices, irrigation status, land use, and cropping patterns, assuming carbon sequestration rates are equal to those at equilibrium. Soil carbon accounting for changes in tillage practices is done as if land remained in the initial tillage forever.

Changes in soil carbon due to changes in tillage, irrigation status, or land use are generally assumed to take place over a number of years as the soil carbon levels adjust to a new equilibrium. In FASOM, soil carbon levels are assumed to reach a new equilibrium after 25 years, although almost 94% of the adjustment takes place within 15 years (see Figure A-6).[134]

Because movement of soil carbon sequestration towards equilibrium levels is not constant over time, FASOM yields non-uniform changes in soil carbon consistent with the generally accepted scientific finding that carbon sequestered in an ecosystem approaches steady-state equilibrium under any management alternative. As shown above, the rate of change in carbon storage decreases over time and eventually reaches zero at the new equilibrium (saturation).[135] Soil carbon per acre may increase or decrease depending on the land use change or change in land management taking place. For instance, Figure A-7 presents examples of changes in soil carbon for the Northern California region in FASOM. In the cases shown, soil carbon initially decreases when moving from the initial equilibrium state to a new state, but then it increases per acre over time until reaching a new equilibrium at a higher level of carbon storage per acre.

[134] There is an immediate jump in carbon storage in year 0 due to changing tillage, irrigation, and/or land use that depends on the initial state and the new state. The dynamics discussed and shown in Figure A-5 refer to the change over time from the initial state under new management/land use conditions to the equilibrium for that state.

[135] West, T.O., and W.M. Post. 2002. "Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation." *Soil Science Society of America Journal* 66:1930-1936.

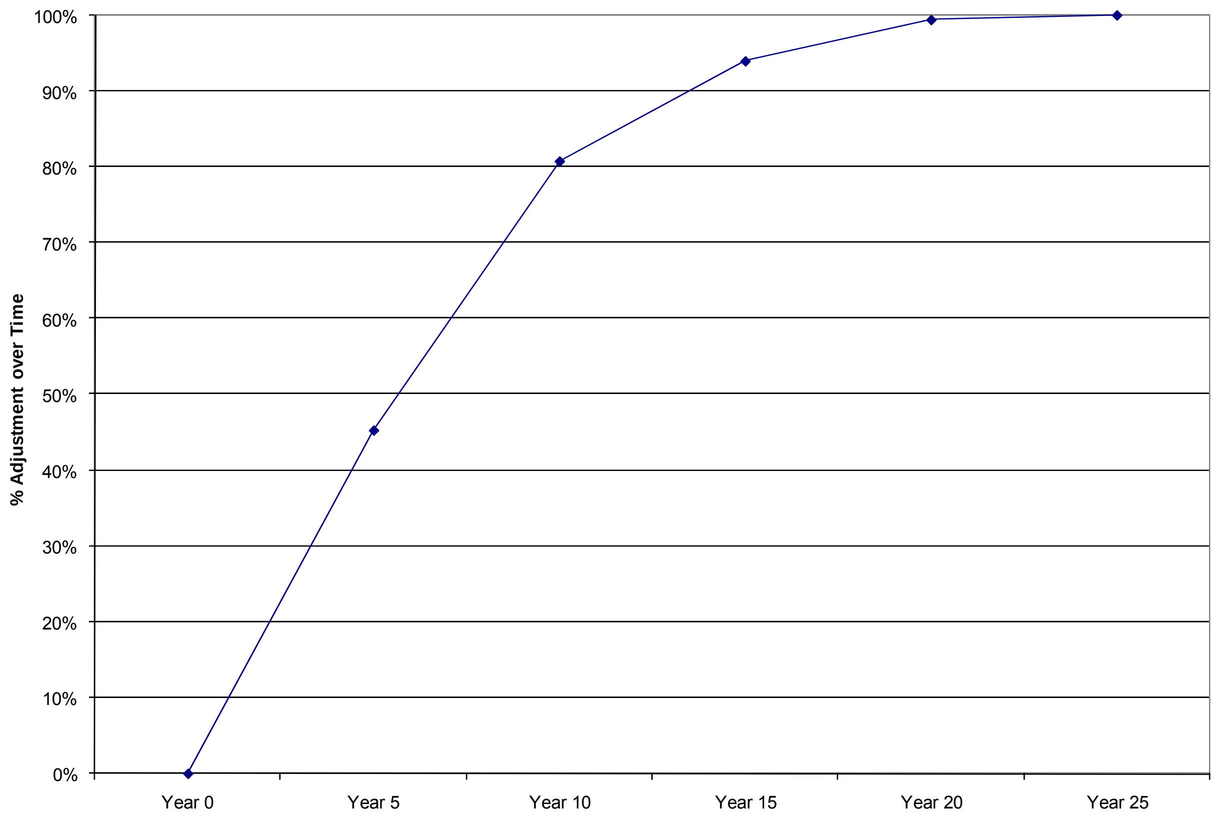

Figure A-6. Percentage Adjustment over Time to New Soil Carbon Equilibrium Following Change in Land Use or Management

To reflect the timing of changes in soil carbon, FASOM output on GHG emissions associated with increases or decreases in agricultural soil carbon represents changes in cumulative soil carbon relative to the baseline. Values reported reflect all changes in soil carbon that are taking place in a given period, including those changes associated with land use change or alterations in management practices that occurred in earlier periods, but where soil carbon levels continue to adjust to their new equilibrium values. For instance, emissions from changes in soil carbon sequestration reported for 2022 would reflect the appropriate portion of emissions related to all changes in tillage, irrigation status, land use change, and cropping patterns that have taken place at all points between the baseline and 2022 based on the assumed rate of saturation over time. For analogous reasons, changes in land use in 2022 would continue to affect soil carbon emissions calculated in the model for the next 25 years.

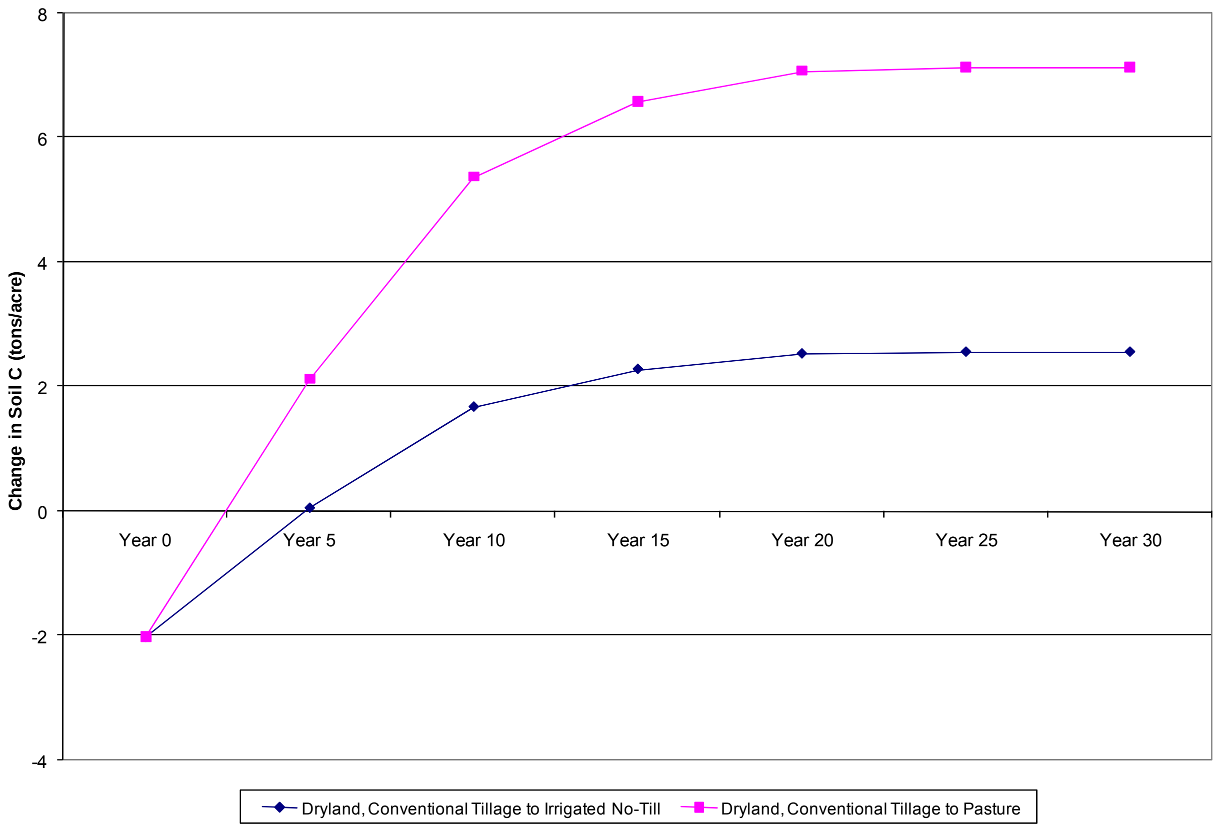

Figure A-7. Change in Soil Carbon for FASOM Northern California Region for Selected Changes in Land Use and Management

For the analysis of the RFS2 renewable fuels volumes, the control case reduces net soil carbon sequestration and increases CO_2 emissions. There are increases in cropland soil carbon relative to the reference case, reflecting the reduced conversion of cropland to pasture over time relative to the baseline simulation when demand for agricultural commodities is increased by the policy. However, reductions in pastureland soil carbon more than outweigh the increases in cropland soil carbon, resulting in net reductions in soil carbon sequestration under the control case.

A.2 Chemical and Energy Inputs and GHG Emissions

In addition to changes in carbon storage associated with changes in forest carbon and agricultural soil carbon sequestration, agricultural chemical and energy use also result in GHG emissions that are calculated and tracked within FASOM. Key assumptions used in calculating these emissions within the model are described in the subsections below.

A.2.1 Fertilizer, Pesticide, and Lime Use

The crop budgets included in the FASOM model include data on input use that varies by crop, management practices, and region. There is often considerable variation in the inputs used per acre, which implies that total input use and associated GHG emissions and other environmental impacts will be affected by changes in crop mix and management practices that result under alternative policies.

Tables A-9 and A-10 summarize the use of nitrogen and phosphorus fertilizers, respectively, based on average application per acre by crop and irrigation status for major crops in each of the FASOM market regions where agricultural crops are produced. FASOM calculates energy use in fertilizer production as a function of the quantity of fertilizer produced.

In addition, both CO_2 emissions from fertilizer production and N_2O emissions resulting from nitrogen fertilizer use are calculated in the model based on the quantity of fertilizer produced and applied as discussed in Section A.2.2. Because residue collection increases fertilizer requirements due to the removal of nutrients,[136] regional average fertilizer use is reported both with and without residue removal in these tables for those crops where residue removal is included as a possibility in the model.

Table A-9. Nitrogen Fertilizer Usage (lbs/acre) by Crop, Irrigation Status, and Region, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Dryland										
Barley (no residue harvest)	66.3	45.5	63.3	75.1	59.9	41.1	43.3	71.9	72.6	45.4
Barley (with residue harvest)	71.0	49.7	67.4	80.5	64.7	44.3	46.8	77.7	78.5	49.0
Corn (no residue harvest)	130.8	103.6	103.8	91.8	NA	NA	79.3	125.5	109.5	94.9
Corn (with residue harvest)	143.0	113.8	115.2	101.0	NA	NA	86.7	136.7	119.5	101.7
Cotton	100.9	55.0	NA	NA	NA	NA	NA	88.2	81.4	43.6
Hay	162.0	173.4	173.4	122.0	173.4	173.4	165.3	165.2	155.2	169.1
Hybrid Poplar	171.5	173.5	173.5	123.3	173.5	NA	NA	161.3	151.6	181.0
Oats (no residue harvest)	50.1	33.7	44.4	47.5	49.1	59.7	30.3	39.1	53.0	36.3
Oats (with residue harvest)	53.8	36.8	47.8	51.0	53.4	63.7	33.0	41.3	56.3	38.7

(continued)

[136] Additional fertilizer application amounts are based on the GREET defaults, as described in the November 7, 2006 report by M. Wu, M. Wang, and H. Huo, "Fuel-Cycle Assessment of Selected Bioethanol Production Pathways in the United States"(ANL/ESD/06-7).

Table A-9. Nitrogen Fertilizer Usage (lbs/acre) by Crop, Irrigation Status, and Region, 2022 (continued)

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Silage	137.7	75.7	123.7	173.0	179.9	143.0	87.9	172.7	180.7	167.3
Sorghum (no residue harvest)	74.4	57.0	NA	67.0	NA	50.2	34.1	88.1	50.3	57.1
Sorghum (with residue harvest)	85.0	64.1	NA	75.7	NA	55.9	39.1	97.4	56.7	62.5
Soybeans	7.8	7.2	3.5	7.8	NA	NA	NA	4.9	8.2	6.3
Sugarbeets	110.0	NA	95.0	NA	NA	NA	NA	NA	NA	NA
Switchgrass	100	100	100	100	NA	NA	100	100	100	100
Wheat, Durham (no residue harvest)	NA	52.9	51.0	NA	NA	NA	41.0	NA	NA	NA
Wheat, Durham (with residue harvest)	NA	55.4	54.8	NA	NA	NA	43.2	NA	NA	NA
Wheat, hard red spring (no residue harvest)	NA	70.9	84.7	NA	66.0	NA	48.5	NA	NA	NA
Wheat, hard red spring (with residue harvest)	NA	74.2	88.8	NA	70.3	NA	51.0	NA	NA	NA
Wheat, hard red winter (no residue harvest)	77.4	50.3	68.1	73.8	NA	60.0	37.3	84.1	91.3	58.6
Wheat, hard red winter (with residue harvest)	86.7	56.3	77.5	83.3	NA	66.3	42.4	91.7	99.5	63.5
Wheat, soft white (no residue harvest)	NA	NA	NA	NA	57.8	NA	86.4	NA	NA	NA
Wheat, soft white (with residue harvest)	NA	NA	NA	NA	64.2	NA	92.6	NA	NA	NA
Willow	173.5	NA	173.4	123.3	NA	NA	NA	NA	161	NA
Irrigated										
Barley (no residue harvest)	NA	63.9	NA	NA	85.0	92.4	88.5	NA	NA	NA
Barley (with residue harvest)	NA	69.4	NA	NA	91.4	98.9	94.6	NA	NA	NA
Corn (no residue harvest)	NA	137.3	NA	NA	214.3	197.1	129.5	141.8	NA	185.8
Corn (with residue harvest)	NA	151.4	NA	NA	229.1	210.9	141.0	151.3	NA	199.8
Cotton	NA	NA	NA	NA	NA	109.3	117.7	115.2	NA	118.2
Hay	NA	173.4	NA	NA	NA	NA	171.2	NA	NA	NA
Oats (no residue harvest)	NA	48.0	NA	NA	96.0	96.0	51.8	NA	NA	NA
Oats (with residue harvest)	NA	51.0	NA	NA	101.7	101.5	56.1	NA	NA	NA
Rice	100.0	NA	NA	NA	NA	156.0	NA	144.3	NA	142.3
Silage	NA	222.0	NA	NA	NA	NA	247.8	NA	NA	230.0

(continued)

Table A-9. Nitrogen Fertilizer Usage (lbs/acre) by Crop, Irrigation Status, and Region, 2022 (continued)

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Sorghum (no residue harvest)	NA	96.2	NA	NA	NA	NA	77.1	82.0	NA	85.2
Sorghum (with residue harvest)	NA	106.8	NA	NA	NA	NA	83.4	90.1	NA	93.3
Soybeans	NA	5.3	NA	NA	NA	NA	NA	4.2	NA	9.9
Sugarbeets	140.0	98.4	140.0	NA	157.1	160.0	190.6	NA	NA	200.0
Sugarcane	NA	NA	NA	NA	NA	NA	NA	40.0	40.0	40.0
Wheat, Durham (no residue harvest)	NA	118.7	NA	NA	NA	98.0	176.8	NA	NA	NA
Wheat, Durham (with residue harvest)	NA	124.1	NA	NA	NA	108.1	185.5	NA	NA	NA
Wheat, hard red spring (no residue harvest)	NA	114.8	NA	NA	122.0	NA	124.8	NA	NA	NA
Wheat, hard red spring (with residue harvest)	NA	119.7	NA	NA	130.4	NA	131.2	NA	NA	NA
Wheat, hard red winter (no residue harvest)	NA	69.0	NA	NA	NA	117.0	81.5	75.0	NA	91.3
Wheat, hard red winter (with residue harvest)	NA	77.5	NA	NA	NA	129.6	91.8	83.5	NA	99.6
Wheat, soft white (no residue harvest)	NA	NA	NA	NA	91.1	NA	73.8	NA	NA	NA
Wheat, soft white (with residue harvest)	NA	NA	NA	NA	102.9	NA	122.1	NA	NA	NA

Note: NA indicates not applicable, i.e., those crops were not cultivated under that irrigation status in that FASOM region. In addition, there is no dryland rice or sugarcane production or irrigated hybrid poplar, switchgrass, or willow production in FASOM.

Table A-10. Phosphorus Fertilizer Usage (lbs/acre) by Crop, Irrigation Status, and Region, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Dryland										
Barley (no residue harvest)	10.2	5.2	21.4	17.8	5.0	10.0	8.3	9.6	10.0	11.7
Barley (with residue harvest)	12.6	7.4	23.5	20.6	7.5	11.7	10.1	12.6	13.1	13.5
Corn (no residue harvest)	22.9	27.6	40.1	36.2	NA	NA	18.5	37.3	32.6	16.5
Corn (with residue harvest)	29.2	32.8	46.0	40.9	NA	NA	22.3	43.0	37.8	20.0
Cotton	29.2	15.0	NA	NA	NA	NA	NA	36.2	41.0	14.5
Hay	17.0	19.0	18.2	15.3	18.7	15.0	11.1	16.8	15.4	15.0
Oats (no residue harvest)	15.3	10.0	10.6	15.0	13.0	14.8	10.2	14.4	15.0	14.7

(continued)

Table A-10. Phosphorus Fertilizer Usage (lbs/acre) by Crop, Irrigation Status, and Region, 2022 (continued)

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Oats (with residue harvest)	17.3	11.6	12.3	16.8	15.2	16.9	11.6	15.5	16.7	15.9
Silage	25.0	12.4	23.4	24.7	20.5	20.0	10.3	25.0	24.1	22.5
Sorghum (no residue harvest)	18.8	11.1	NA	15.0	NA	19.9	11.5	23.7	21.2	18.6
Sorghum (with residue harvest)	24.2	14.8	NA	19.5	NA	22.8	14.1	28.5	24.5	21.3
Soybeans	6.7	13.7	7.7	5.4	NA	NA	NA	16.1	21.4	7.0
Sugarbeets	22.0	NA	20.0	NA	NA	NA	NA	NA	NA	NA
Switchgrass	40.0	40.0	40.0	40.0	NA	NA	40.0	40.0	40.0	40.0
Wheat, Durham (no residue harvest)	NA	14.5	5.0	NA	NA	NA	5.0	NA	NA	NA
Wheat, Durham (with residue harvest)	NA	15.7	6.9	NA	NA	NA	6.1	NA	NA	NA
Wheat, hard red spring (no residue harvest)	NA	24.5	25.9	NA	10.0	NA	20.4	NA	NA	NA
Wheat, hard red spring (with residue harvest)	NA	26.1	28.0	NA	12.2	NA	21.7	NA	NA	NA
Wheat, hard red winter (no residue harvest)	17.7	17.7	9.9	10.0	NA	5.0	8.2	15.0	15.2	18.1
Wheat, hard red winter (with residue harvest)	22.5	20.9	14.7	14.9	NA	8.2	10.8	19.0	19.4	20.6
Wheat, soft white (no residue harvest)	NA	NA	NA	NA	5.2	NA	13.8	NA	NA	NA
Wheat, soft white (with residue harvest)	NA	NA	NA	NA	8.5	NA	17.0	NA	NA	NA
Irrigated										
Barley (no residue harvest)	NA	10.0	NA	NA	15.8	25.0	14.9	NA	NA	NA
Barley (with residue harvest)	NA	12.8	NA	NA	19.1	28.4	18.0	NA	NA	NA
Corn (no residue harvest)	NA	31.3	NA	NA	41.3	25.0	26.6	25.0	NA	39.7
Corn (with residue harvest)	NA	38.5	NA	NA	48.9	32.1	32.5	29.9	NA	46.9
Cotton	NA	NA	NA	NA	NA	35.0	16.5	30.7	NA	24.7
Hay	NA	30.0	NA	NA	NA	NA	27.4	NA	NA	NA
Oats (no residue harvest)	NA	15.0	NA	NA	25.0	25.0	17.3	NA	NA	NA
Oats (with residue harvest)	NA	16.5	NA	NA	27.9	27.8	19.5	NA	NA	NA
Rice	20.0	NA	NA	NA	NA	35.0	NA	20.0	NA	20.0
Silage	NA	30.5	NA	NA	NA	NA	35.0	NA	NA	30.0
Sorghum (no residue harvest)	NA	35.0	NA	NA	NA	NA	26.4	35.0	NA	35.0
Sorghum (with residue harvest)	NA	40.5	NA	NA	NA	NA	29.7	39.2	NA	39.2
Soybeans	NA	13.5	NA	NA	NA	NA	NA	16.6	NA	15.0
Sugarbeets	50.0	26.7	50.0	NA	50.0	50.0	46.5	NA	NA	50.0

(continued)

Table A-10. Phosphorus Fertilizer Usage (lbs/acre) by Crop, Irrigation Status, and Region, 2022 (continued)

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Sugarcane	NA	NA	NA	NA	NA	NA	NA	50.0	50.0	50.0
Wheat, Durham (no residue harvest)	NA	32.5	NA	NA	NA	10.0	24.1	NA	NA	NA
Wheat, Durham (with residue harvest)	NA	35.3	NA	NA	NA	15.2	28.6	NA	NA	NA
Wheat, hard red spring (no residue harvest)	NA	39.0	NA	NA	5.3	NA	25.0	NA	NA	NA
Wheat, hard red spring (with residue harvest)	NA	41.5	NA	NA	6.4	NA	28.3	NA	NA	NA
Wheat, hard red winter (no residue harvest)	NA	24.7	NA	NA	NA	10.0	14.5	15.0	NA	19.1
Wheat, hard red winter (with residue harvest)	NA	29.0	NA	NA	NA	16.5	19.8	19.4	NA	23.4
Wheat, soft white (no residue harvest)	NA	NA	NA	NA	5.2	NA	18.2	NA	NA	NA
Wheat, soft white (with residue harvest)	NA	NA	NA	NA	13.6	NA	22.4	NA	NA	NA

Note: NA indicates not applicable, i.e., those crops were not cultivated under that irrigation status in that FASOM region. In addition, there is no dryland rice or sugarcane production or irrigated hybrid poplar, switchgrass, or willow production in FASOM.

The three primary categories of pesticides that are tracked in FASOM are herbicides, insecticides, and fungicides. FASOM crop budgets contain hundreds of different active ingredients. However, for the purposes of calculating energy use requirements and CO_2 emissions associated with pesticide production, FASOM uses the total quantity of active ingredients applied. Thus, we summarize the use of pesticides in terms of the combined use of active ingredients in pounds per acre. Tables A-11, A-12, and A-13 present data on the use of these three categories of chemicals, respectively, by crop and FASOM region on a per acre basis.

In addition, lime is used as an input in the production of some crops and is included in those crop budgets in FASOM. Although FASOM does not directly calculate CO_2 emissions from lime production, the model does provide information on the amount of lime used. Thus, CO_2 emissions from this category can be calculated based on the quantity of lime used and emissions factors. Table A-14 presents average lime use per acre for crops that use lime as an input in the model. We calculate GHG emissions from lime use based on GREET assumptions for limestone production and CO_2 emissions associated with calcining limestone to lime.

Table A-11. Herbicide Usage (pounds of active ingredients/acre) by Crop, Irrigation Status, and Region, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Dryland										
Barley	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.04	0.04	0.04
Corn	2.91	2.36	2.34	2.85	NA	NA	1.96	2.16	2.63	2.40
Cotton	1.79	2.17	NA	NA	NA	NA	NA	2.76	2.55	1.77
Hay	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Hybrid poplar	0.01	0.01	0.01	0.01	0.01	NA	NA	0.01	0.01	0.01
Oats	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Silage	2.47	1.49	2.00	1.22	0.85	0.85	0.84	1.42	1.11	1.07
Sorghum	0.11	0.26	NA	0.11	NA	0.11	0.11	0.11	0.11	0.08
Soybeans	1.18	1.29	1.03	0.47	NA	NA	NA	1.18	0.73	0.27
Sugarbeets	1.85	NA	1.74	NA	NA	NA	NA	NA	NA	NA
Switchgrass	0.01	0.01	0.01	0.01	NA	NA	0.01	0.01	0.01	0.01
Wheat, Durham	NA	0.89	0.13	NA	NA	NA	0.16	NA	NA	NA
Wheat, Hard Red Spring	NA	0.76	0.58	NA	0.16	NA	0.96	NA	NA	NA
Wheat, Hard Red Winter	0.24	0.23	0.26	0.22	NA	0.11	0.34	0.27	0.29	0.24
Wheat, Soft White	NA	NA	NA	NA	0.49	NA	0.41	NA	NA	NA
Willow	0.01	NA	0.01	0.01	NA	NA	NA	NA	0.01	NA
Irrigated										
Barley	NA	0.04	NA	NA	0.03	0.03	0.04	NA	NA	NA
Corn	NA	2.44	NA	NA	1.78	1.78	1.92	2.48	NA	2.35
Cotton	NA	NA	NA	NA	NA	2.57	2.53	2.61	NA	1.76
Hay	NA	0.01	NA	NA	NA	NA	0.01	NA	NA	NA
Oats	NA	0.02	NA	NA	0.02	0.02	0.02	NA	NA	NA
Rice	0.78	NA	NA	NA	NA	0.78	NA	0.55	NA	0.83
Silage	NA	1.93	NA	NA	NA	NA	0.83	NA	NA	1.12
Sorghum	NA	0.27	NA	NA	NA	NA	0.11	0.08	NA	0.08
Soybeans	NA	1.32	NA	NA	NA	NA	NA	1.10	NA	0.28
Sugarbeets	1.85	2.11	1.85	NA	2.06	1.92	1.73	NA	NA	1.85
Wheat, Durham	NA	0.90	NA	NA	NA	0.12	0.26	NA	NA	NA
Wheat, Hard Red Spring	NA	0.78	NA	NA	0.16	NA	0.38	NA	NA	NA
Wheat, Hard Red Winter	NA	0.22	NA	NA	NA	0.11	0.27	0.27	NA	0.27
Wheat, Soft White	NA	NA	NA	NA	0.57	NA	0.41	NA	NA	NA

Note: NA indicates not applicable, i.e., those crops were not cultivated under that irrigation status in that FASOM region. In addition, there is no dryland rice or sugarcane production or irrigated hybrid poplar, switchgrass, or willow production in FASOM.

Table A-12. Insecticide Usage (pounds of active ingredients/acre) by Crop, Irrigation Status, and Region, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Dryland										
Barley	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01
Corn	0.69	0.47	0.49	0.74	NA	NA	0.68	0.57	0.78	0.47
Cotton	4.78	4.76	NA	NA	NA	NA	NA	6.53	4.57	4.11
Hay	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Hybrid poplar	0.01	0.01	0.01	0.01	0.01	NA	NA	0.02	0.02	0.02
Oats	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Silage	0.71	0.37	0.54	0.43	0.31	0.31	0.30	0.37	0.32	0.31
Sorghum	0.03	0.09	NA	0.03	NA	0.03	0.03	0.03	0.03	0.03
Soybeans	0.70	0.73	0.66	0.26	NA	NA	NA	0.78	0.46	0.12
Sugarbeets	32.39	NA	32.07	NA	NA	NA	NA	NA	NA	NA
Switchgrass	0.01	0.01	0.01	0.01	NA	NA	0.01	0.02	0.02	0.02
Wheat, Durham	NA	0.39	0.05	NA	NA	NA	0.05	NA	NA	NA
Wheat, Hard Red Spring	NA	0.39	0.36	NA	0.03	NA	0.50	NA	NA	NA
Wheat, Hard Red Winter	0.09	0.12	0.10	0.07	NA	0.03	0.16	0.09	0.09	0.10
Wheat, Soft White	NA	NA	NA	NA	0.20	NA	0.15	NA	NA	NA
Willow	0.01	NA	0.01	0.01	NA	NA	NA	NA	0.02	NA
Irrigated										
Barley	NA	0.02	NA	NA	0.01	0.01	0.02	NA	NA	NA
Corn	NA	0.46	NA	NA	0.48	0.48	0.64	0.48	NA	0.47
Cotton	NA	NA	NA	NA	NA	5.28	5.30	5.04	NA	4.10
Hay	NA	0.01	NA	NA	NA	NA	0.01	NA	NA	NA
Oats	NA	0.01	NA	NA	0.01	0.01	0.01	NA	NA	NA
Rice	0.98	NA	NA	NA	NA	0.98	NA	0.75	NA	1.07
Silage	NA	0.60	NA	NA	NA	NA	0.29	NA	NA	0.33
Sorghum	NA	0.09	NA	NA	NA	NA	0.03	0.03	NA	0.03
Soybeans	NA	0.78	NA	NA	NA	NA	NA	0.73	NA	0.12
Sugarbeets	32.39	32.60	32.39	NA	16.00	59.29	16.81	NA	NA	32.39
Wheat, Durham	NA	0.39	NA	NA	NA	0.04	0.10	NA	NA	NA
Wheat, Hard Red Spring	NA	0.40	NA	NA	0.03	NA	0.17	NA	NA	NA
Wheat, Hard Red Winter	NA	0.11	NA	NA	NA	0.03	0.11	0.10	NA	0.10
Wheat, Soft White	NA	NA	NA	NA	0.23	NA	0.15	NA	NA	NA

Note: NA indicates not applicable, i.e., those crops were not cultivated under that irrigation status in that FASOM region. In addition, there is no dryland rice or sugarcane production or irrigated hybrid poplar, switchgrass, or willow production in FASOM.

Table A-13. Fungicide Usage (pounds of active ingredients/acre) by Crop, Irrigation Status, and Region, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Dryland										
Barley	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Cotton	0.087	0.087	NA	NA	NA	NA	NA	0.112	0.065	0.087
Sugarbeets	30.637	NA	30.904	NA	NA	NA	NA	NA	NA	NA
Wheat, Durham	NA	0.018	0.006	NA	NA	NA	0.018	NA	NA	NA
Wheat, Hard Red Spring	NA	0.018	0.006	NA	0.008	NA	0.018	NA	NA	NA
Wheat, Hard Red Winter	0.020	0.023	0.022	0.018	NA	0.006	0.023	0.037	0.062	0.023
Wheat, Soft White	NA	NA	NA	NA	0.006	NA	0.005	NA	NA	NA
Irrigated										
Barley	NA	0.001	NA	NA	0.001	0.001	0.001	NA	NA	NA
Cotton	NA	NA	NA	NA	NA	0.087	0.087	0.086	NA	0.086
Rice	0.096	NA	NA	NA	NA	0.096	NA	0.048	NA	0.108
Sugarbeets	30.780	30.822	30.668	NA	14.406	57.365	15.290	NA	NA	30.780
Wheat, Durham	NA	0.018	NA	NA	NA	0.006	0.018	NA	NA	NA
Wheat, Hard Red Spring	NA	0.018	NA	NA	0.009	NA	0.010	NA	NA	NA
Wheat, Hard Red Winter	NA	0.023	NA	NA	NA	0.006	0.023	0.023	NA	0.023
Wheat, Soft White	NA	NA	NA	NA	0.010	NA	0.005	NA	NA	NA

Note: NA indicates not applicable, i.e., those crops were not cultivated under that irrigation status in that FASOM region. In addition, there is no dryland rice or sugarcane production or irrigated hybrid poplar, switchgrass, or willow production in FASOM.

Table A-14. Lime Usage (tons of lime/acre) by Crop, Irrigation Status, and Region, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Dryland										
Barley	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.07	0.00
Corn	0.11	0.00	0.00	0.26	NA	NA	0.00	0.00	0.03	0.00
Cotton	0.00	0.00	NA	NA	NA	NA	NA	0.11	0.11	0.00
Hay	0.02	0.00	0.00	0.02	0.00	0.00	0.00	0.11	0.10	0.00
Silage	0.00	0.00	0.00	0.26	0.00	0.00	0.00	0.08	0.08	0.00
Soybeans	0.11	0.00	0.00	0.26	NA	NA	NA	0.00	0.04	0.00
Sugarbeets	0.13	NA	0.00	NA	NA	NA	NA	NA	NA	NA
Wheat, Durham	NA	0.00	0.20	NA	NA	NA	0.00	NA	NA	NA
Wheat, Hard Red Spring	NA	0.00	0.20	NA	0.00	NA	0.00	NA	NA	NA
Wheat, Hard Red Winter	0.14	0.00	0.00	0.50	NA	0.00	0.00	0.03	0.07	0.00

Note: NA indicates not applicable, i.e., those crops were not cultivated under that irrigation status in that FASOM region. In addition, there is no dryland rice or sugarcane production or irrigated hybrid poplar, switchgrass, or willow production in FASOM.

A.2.2 Nitrous Oxide Emissions

For the analysis of the proposed rule, FASOM estimated direct and indirect N_2O emissions from nitrogen fertilizer application and nitrogen-fixing crops based on IPCC default factors.[137] However, recent research suggests N_2O emissions may be significantly higher than those estimated based on current IPCC guidance,[138] with the exception of emissions from nitrogen-fixing crops, which are no longer considered as a direct source of N_2O emissions in the 2006 IPCC guidance. In addition, emissions are more heterogeneous than can be captured using IPCC default emissions factors. Thus, to obtain more accurate estimates of N_2O emissions that better reflect heterogeneity of emissions across crops and production practices and that incorporate the entire N cycling process, EPA worked with the Natural Resource Ecology Laboratory at Colorado State University to conduct further analyses of N_2O emissions and provide updated emissions data.

Specifically, Colorado State University provided several key refinements for a reanalysis of land use and cropping trends and GHG emissions in the FASOM assessment, including the following:

- Direct N_2O emissions based on DAYCENT[139] simulations with an accounting of all nitrogen inputs to agricultural soils, including mineral N fertilizer, organic amendments, symbiotic N fixation, asymbiotic N fixation, crop residue N, and mineralization of soil organic matter. Colorado State University provided (1) the total emission rate on a per-acre basis for each simulated conventional and bioenergy crop in the 63 FASOM regions and (2) total emissions for each N source.
- Indirect N_2O emissions on a per-acre basis using results from DAYCENT simulations of volatilization, leaching and runoff of nitrogen from each conventional and bioenergy crop included in the analysis for the 63 FASOM regions, combined with IPCC factors for the N_2O emission associated with the simulated nitrogen losses.

Rather than relying simply on the rate of fertilizer application and the IPCC default for N_2O emissions per unit of fertilizer, we now account for N cycling within DAYCENT and can generate emissions estimates that vary by region, crop, fertilizer application rate, tillage, irrigation status, and residue removal rate based on a full accounting of all nitrogen inputs.

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[137] See the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapter 11, N_2O emissions from managed soils.

[138] Crutzen, P.J., A.R. Mosier, K.A. Smith, and W. Winiwarter. 2008. N_2O Release from Agro-biofuel Production Negates Global Warming Reduction by Replacing Fossil Fuels. *Atmospheric Chemistry and Physics* 8:389-395.

[139] The DAYCENT model is similar to the CENTURY model described earlier in this section, except that it is capable of simulating detailed daily soil water and temperature dynamics and trace gas fluxes (CH_4, N_2O, NO_x and N_2), which are not simulated in CENTURY.

FASOM applies the estimates available from DAYCENT summary models for direct N_2O emissions, nitrogen leaching/runoff and ammonia volatilization, which were developed based on output from the DAYCENT simulation model using the U.S. national greenhouse gas inventory framework. Simulations were executed to track changes in emissions, leaching/runoff and volatilization for 30 years following a change in crop, land use, tillage, or crop residue removal rate. Models summarizing the relationships between emissions and cropping characteristics were developed for each FASOM region. The data contain parameter estimates for the effects of each predictor variable (e.g., irrigation status, tillage, residue removal rate); with separate parameter estimates for crop and grassland systems (hay is grouped with the crops because hay is considered a crop in the U.S. national GHG inventory framework). Below we briefly describe the procedures used in FASOM to generate estimates of N_2O emissions.

A.2.2.1 Direct Emissions and Emissions Factors

The primary category of direct N_2O emissions is emissions resulting from the application of nitrogen fertilizer. Changes in FASOM direct N_2O emissions from croplands result from either changes in crop acreage or crop mix. There are mitigation options included in the model that enable selection of alternatives such as reduced fertilization and other mitigation options, but these options are only expected to be selected under policies creating incentives to reduce fertilizer N use. Thus, we do not examine those other mitigation options in this analysis. We discuss model calculation of direct N_2O emissions from croplands below.

A.2.2.1.1 Nitrogen Fertilizer

To calculate direct N_2O emissions from N inputs to croplands and grasslands (primarily fertilizer use), FASOM uses DAYCENT data on direct emissions per acre by crop and FASOM region. Estimates of emissions per acre from DAYCENT are defined as a function of the following variables:

- Crop or grass types: crop and grass types vary by region depending on the types simulated in the U.S. Soil N_2O national inventory. This set of variables is treated as a set of indicator variables with a 1 assigned to the crop/grass of interest and 0 for the rest to estimate emissions from each crop relative to the excluded cases of corn for crops and grass pasture for the grass category.

- Mineral fertilizer: this variable is the natural log of the amount of fertilizer applied per unit of area.

- Irrigation status: this variable is an indicator variable indicating whether or not the crop or grass is irrigated. A value of 1 means the crop is irrigated, whereas a value of 0 means that the crop is not irrigated

- Tillage practice: these variables are also treated as indicator variables representing tillage practice, with 0/1 variables for reduced tillage and no-tillage practices. If both reduced tillage and no-tillage variables are zero, then the resulting estimates correspond to conventional tillage. This variable is only relevant for crop models.

- Land use: this set of variables is treated as indicator variables for land use change. There are 0/1 variables for the cases when land use change takes place from CRP land and from native land. If both the CRP and native land indicator variables are 0, then the result represents no land use change (i.e., shift in specific crop or grass on a given piece of land, but no change in broad land use category).

- Residue removal: this variable is the percentage of crop residue removed from the field (including removals for use as a cellulosic feedstock). This variable can take on values between 0% and 100%, although removal rates would be limited in practice by technical and sustainability constraints. This variable is not relevant for hay or grass systems.

- First-order interactions between the variables listed above: first-order interactions between the variables were tested and those that were significant were included in the summary models.

The parameter values from DAYCENT modeling are then used to generate estimates of direct N_2O emissions per acre for each crop, region, and production practice combination available in the FASOM crop budgets.

A.2.2.2 Indirect Emissions and Emissions Factors

In addition to direct N_2O emissions from croplands, there are several additional sources of indirect emissions, including emissions from volatilization, leaching, crop residues, and residue burning. FASOM calculation of each is described below.

A.2.2.2.1 Volatilization

Some of the N applied to agricultural soils as fertilizer volatilizes, entering the atmosphere as ammonia and other oxides of nitrogen. The volatilized N subsequently returns to soils through N deposition and then contributes to N_2O emissions. In FASOM, these emissions are calculated based on the estimates available from DAYCENT modeling. Estimates of emissions due to N lost from a managed field through volatilization were calculated as a function of the same set of variables identified above under modeling of direct N_2O emissions per acre. The results of this modeling are then multiplied by the IPCC indirect emissions factor for volatilization (0.010 kg N_2O-N/kgNH_2-N+NO_x-N/yr) and the conversion factor of 44/28 to convert the loss of nitrogen to volatilization through multiple pathways into N_2O emissions.

A.2.2.2.2 Leaching

After fertilizer application or heavy rain, large amounts of N may leach from the soil into drainage ditches, streams, rivers and eventually estuaries. Some of this N is emitted as nitrous oxide when the leached nitrogen fertilizer undergoes the process of nitrification or denitrification. In FASOM, these emissions are calculated using a similar modeling structure to that described above for the calculation of direct N_2O emissions. The same variables are used in models estimated to generate estimates of emissions from leaching, multiplied by 0.0075 kgN_2O-N/$kgNO_3$-N/yr and the conversion factor of 44/28 to convert to N_2O emissions. IPCC guidelines from 2006 recommend that N leaching not be included in estimates of indirect N2O emissions if annual precipitation minus potential evapotranspiration does not exceed field water holding capacity (with the exception of irrigated lands, which should always be included). Therefore, emissions from nitrate leaching are not included for FASOM regions where the long term average annual precipitation level is less than 70% of the potential evapotranspiration level.

A.2.2.2.4 Residue Burning

As mentioned above, FASOM assumes that a certain fraction of fields is burned each year, which results in N_2O (and methane) emissions. These emissions are calculated using the IPCC default value of 0.7% of N contained in the residue that is burned being emitted as N_2O. In addition, methane emissions are calculated based on the average methane emissions per acre, calculated using total emissions data from this source and the percentage of acreage that is burned by crop based on 2001 data contained in the EPA GHG inventory for 1990–2003.[140] These emissions are typically quite small relative to the other emissions tracked in FASOM.

A.2.3 Rice Methane Emissions

Another source of GHG emissions from crop production is methane production from rice cultivation. The majority of rice produced in the world is grown in flooded fields commonly known as paddies. However, when fields are flooded, aerobic decomposition of organic matter depletes the oxygen present in the soil, leading to anaerobic soil conditions in the flooded fields. Methane is then produced through anaerobic decomposition of soil organic matter by methanogenic bacteria.

FASOM assumes that all rice produced in the United States is grown in flooded fields and has associated methane emissions. Although there are potentially changes in water and soil management practices that could be implemented to reduce methane emissions, FASOM

[140] U.S. Environmental Protection Agency. 2005. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2003*. EPA 430-R-05-003. Available at http://www.epa.gov/climatechange/emissions/downloads06/05CR.pdf.

currently assumes that the only method available for reducing methane emissions from rice cultivation is to reduce rice acreage. Thus, changes in methane emissions from rice cultivation will result only from changes in the acreage planted to rice.

Methane emissions per acre are calculated based on regional emissions factors per acre calculated for each region based on 2001 data from the EPA GHG inventory for 1990–2003.[141] The model then calculates emissions from rice production based on emissions factors for each region and the distribution of rice acreage in the model solution.

A.2.4 Energy Use

Energy is another key input in crop production, including transportation fuels, electricity, and fuels for heating. FASOM includes data on both direct energy use in crop production, which is included within the crop budgets[142], and energy use associated with input production (e.g., fertilizer and pesticide production), grain drying, and transportation of primary agricultural commodities, which are calculated outside of the crop budgets as described in the sections below. Tables A-15 and A-16 summarize FASOM values for on-farm diesel fuel and gasoline use in crop production by crop, irrigation status, and region.

Table A-15. Diesel Fuel Usage (gallons/acre) by Crop, Irrigation Status, and Region, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Dryland										
Barley	5.4	5.3	8.6	8.2	8.3	10.5	4.7	3.1	2.5	8.2
Corn	11.0	9.0	9.6	7.9	NA	NA	11.1	9.2	8.1	10.2
Cotton	3.7	4.1	NA	NA	NA	NA	NA	8.2	4.9	16.9
Hay	6.7	7.8	7.5	5.0	9.3	7.2	5.8	8.4	7.5	9.2
Oats	10.4	5.1	9.5	7.2	4.3	4.0	5.7	3.6	2.5	6.7
Silage	14.8	15.5	14.1	7.9	18.8	20.0	20.3	8.8	12.0	18.2
Sorghum	8.9	11.4	NA	8.8	NA	2.6	10.3	10.4	9.0	10.8
Soybeans	9.7	8.3	9.7	8.3	NA	NA	NA	4.1	7.9	8.1
Sugarbeets	13.8	NA	15.5	NA	NA	NA	NA	NA	NA	NA
Switchgrass	3.0	2.8	2.9	2.9	NA	NA	2.8	3.0	3.0	2.9
Wheat, Durham	NA	10.2	8.2	NA	NA	NA	6.4	NA	NA	NA
Wheat, Hard Red Spring	NA	9.5	8.2	NA	9.4	NA	6.5	NA	NA	NA
Wheat, Hard Red Winter	10.1	11.1	7.6	7.3	NA	4.5	10.7	6.6	7.9	9.1

(continued)

[141] Ibid.

[142] Energy data (e.g., diesel fuel, gasoline, electricity, natural gas) included within the crop budgets are based on USDA Agricultural Resource Management Survey (ARMS) data (http://www.ers.usda.gov/Data/ARMS/) and crop budgets developed by university extension offices.

Table A-15. Diesel Fuel Usage (gallons/acre) by Crop, Irrigation Status, and Region, 2022 (continued)

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Wheat, Soft White	NA	NA	NA	NA	9.6	NA	6.9	NA	NA	NA
Irrigated										
Barley	NA	5.9	NA	NA	8.2	10.5	6.0	NA	NA	NA
Corn	NA	10.9	NA	NA	13.3	14.7	13.9	8.2	NA	13.5
Cotton	NA	NA	NA	NA	NA	34.7	14.0	10.1	NA	16.3
Hay	NA	12.2	NA	NA	10.4	NA	10.4	NA	NA	NA
Oats	NA	4.1	NA	NA	4.9	4.0	5.2	NA	NA	NA
Rice	7.4	NA	NA	NA	NA	18.7	NA	12.0	NA	22.9
Silage	NA	16.4	NA	NA	NA	NA	17.5	NA	NA	15.1
Sorghum	NA	11.7	NA	NA	NA	3.1	7.9	7.0	NA	9.7
Soybeans	NA	9.3	NA	NA	NA	NA	NA	4.4	NA	8.1
Sugarbeets	12.5	15.9	12.5	NA	NA	NA	17.7	NA	NA	22.3
Sugarcane	NA	NA	NA	NA	NA	NA	NA	24.8	24.8	24.8
Wheat, Durham	NA	10.1	NA	NA	NA	3.8	7.2	NA	NA	NA
Wheat, Hard Red Spring	NA	10.1	NA	NA	11.4	NA	6.8	NA	NA	NA
Wheat, Hard Red Winter	NA	11.1	NA	NA	NA	4.5	8.3	4.1	NA	6.3
Wheat, Soft White	NA	NA	NA	NA	11.3	NA	6.3	NA	NA	NA

Note: NA indicates not applicable, i.e., those crops were not cultivated under that irrigation status in that FASOM region. In addition, there is no dryland rice or sugarcane production or irrigated hybrid poplar, switchgrass, or willow production in FASOM.

Table A-16. Gasoline Usage (gallons/acre) by Crop, Irrigation Status, and Region, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Dryland										
Barley	2.1	NA	NA	0.1	3.8	NA	NA	3.4	3.7	NA
Corn	NA	NA	NA	0.7	NA	NA	NA	3.7	3.7	NA
Cotton	NA	NA	NA	NA	NA	NA	NA	2.9	0.3	NA
Hay	3.7	1.7	4.1	NA	2.8	3.7	1.1	NA	NA	NA
Oats	3.2	NA	NA	3.7	1.5	3.7	NA	2.4	3.7	NA
Silage	NA	NA	NA	0.3	NA	0.0	NA	3.8	1.6	0.0
Sorghum	NA	NA	NA	NA	NA	3.7	NA	3.2	3.7	NA
Soybeans	3.7	2.3	NA	3.7	NA	NA	NA	NA	2.1	NA
Wheat, Hard Red Spring	NA	NA	NA	NA	0.4	NA	NA	NA	NA	NA
Wheat, Hard Red Winter	3.7	0.6	NA	3.7	NA	3.7	NA	3.7	3.7	NA

(continued)

Table A-16. Gasoline Usage (gallons/acre) by Crop, Irrigation Status, and Region, 2022 (continued)

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Irrigated										
Barley	NA	NA	NA	NA	3.2	NA	NA	NA	NA	NA
Corn	NA	0.0	NA	NA	2.8	3.7	NA	NA	NA	NA
Cotton	NA	NA	NA	NA	NA	3.7	0.0	2.5	NA	NA
Hay	NA	3.7	NA	NA	NA	NA	0.9	NA	NA	NA
Oats	NA	NA	NA	NA	NA	3.7	0.2	NA	NA	NA
Rice	3.7	NA	NA	NA	NA	3.7	NA	4.2	NA	NA
Silage	NA	0.0	NA	NA	NA	NA	0.0	NA	NA	NA
Soybeans	NA	3.7	NA	NA	NA	NA	NA	NA	NA	NA
Sugarcane	NA	NA	NA	NA	NA	NA	NA	3.7	3.7	3.7
Wheat, Durham	NA	NA	NA	NA	NA	3.7	NA	NA	NA	NA
Wheat, Hard Red Spring	NA	NA	NA	NA	1.0	NA	NA	NA	NA	NA
Wheat, Hard Red Winter	NA	0.8	NA	NA	NA	3.7	NA	NA	NA	NA
Wheat, Soft White	NA	NA	NA	NA	1.4	NA	NA	NA	NA	NA

Note: NA indicates not applicable, i.e., those crops were not cultivated under that irrigation status in that FASOM region. In addition, there is no dryland rice or sugarcane production or irrigated hybrid poplar, switchgrass, or willow production in FASOM.

Crop budgets for some crops also contain direct use of electricity and natural gas in crop production for irrigation water pumping. Rice and sugarbeets are the only crops that are assumed to use natural gas in pumping in some regions. For the rest of the irrigated crops that have private energy use for water pumping, electricity is the assumed energy source.
Tables A-17 and A-18 summarize assumed electricity and natural gas use included within the FASOM crop budgets.

Energy use for grain drying is calculated in FASOM based on assumptions that removing 10 percentage points of moisture from 100 bushels of grain requires 17.5 gallons of propane and 9 kWh of electricity.[143] Thus, energy use per acre is calculated as the number of percentage points of moisture to be removed multiplied by the yield per acre and the energy use per percentage point and yield unit for each crop that is dried. Emissions are then calculated based on assumed emissions factors per unit of energy use by energy type.

[143] These assumptions are based on the Drying Costs for Corn spreadsheet developed by the University of Missouri Extension Program and available at http://agebb.missouri.edu/download/index.htm

Table A-17. Electricity Usage (kWh/acre) by Crop, Irrigation Status, and Region, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Dryland										
Hay	0	0	0	0	0	0	0.1	0	0	0
Irrigated										
Barley	NA	3.6	NA	NA	5.9	3.6	4.0	NA	NA	NA
Corn	NA	11.0	NA	NA	10.9	10.2	9.5	2.8	NA	5.1
Cotton	NA	NA	NA	NA	NA	0	0	1.8	NA	2.9
Hay	NA	7.6	NA	NA	NA	NA	2.1	NA	NA	NA
Oats	NA	3.8	NA	NA	9.1	3.6	1.5	NA	NA	NA
Silage	NA	11.3	NA	NA	NA	NA	3.5	NA	NA	10.6
Sorghum	NA	7.5	NA	NA	NA	7.9	3.1	5.9	NA	4.5
Soybeans	NA	7.4	NA	NA	NA	NA	NA	7.5	NA	4.3
Sugarbeets	0	0	0	NA	0	0	4.2	NA	NA	4.5
Wheat, Durham	NA	6.2	NA	NA	NA	3.7	0	NA	NA	NA
Wheat, Hard Red Spring	NA	6.2	NA	NA	5.3	0	3.7	NA	NA	NA
Wheat, Hard Red Winter	NA	2.4	NA	NA	NA	5.2	2.1	6.8	NA	4.8
Wheat, Soft White	NA	0	NA	NA	5.3	NA	5.3	NA	NA	NA

Note: NA indicates not applicable, i.e., those crops were not cultivated under that irrigation status in that FASOM region. In addition, there is no dryland rice or sugarcane production or irrigated hybrid poplar, switchgrass, or willow production in FASOM.

Table A-18. Natural Gas Usage (1000 cu ft/acre) by Crop, Irrigation Status, and Region, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Irrigated										
Rice	20.8	NA	NA	NA	NA	0.0	NA	17.9	NA	0.0
Sugarbeets	25.9	9.6	25.9	NA	3.8	0.0	0.0	NA	NA	0.0

Note: NA indicates not applicable, i.e., those crops were not cultivated under that irrigation status in that FASOM region. In addition, there are only two irrigated crops that are assumed to use natural gas in irrigation water pumping in FASOM.

In addition to the use of energy on-farm in crop production, FASOM calculates indirect energy requirements associated with the use of fertilizer. However, for this analysis EPA used GHG emissions factors from the GREET model to represent GHG emissions from producing fertilizer. Because fertilizer production requires substantial energy inputs, the more fertilizer required for a given crop-region calculation, the greater the associated energy use per acre for that crop.

Energy use in pesticide manufacturing is estimated in FASOM based on the quantity of active ingredients applied per acre multiplied by an assumed energy requirement per ton of active ingredients that varies across chemicals, assuming that 70% of the energy requirements are met with natural gas and the other 30% with electricity.[144] However, GREET factors were again used to represent GHG emissions from pesticide and herbicide production in this analysis.

GHG emissions from agricultural use of fossil fuels in crop production are calculated in FASOM by multiplying the quantity of each energy category used (diesel fuel, gasoline, natural gas, liquefied petroleum gas, propane, and electricity) by the GHG content of that fuel. Both direct energy uses from the crop budgets as well as indirect use for input production are included. There are also calculations of energy use for grain drying and product transportation. As with the categories above, GREET factors were used in this analysis to calculate GHG emissions.

A.3 Land Management

Other actions that can potentially influence GHG emissions in FASOM are decisions regarding land management. Some of these actions have already been discussed above, such as changes in soil carbon sequestration due to tillage changes, but below we briefly summarize key land management decisions that can influence energy use and GHG emissions in FASOM.

A.3.1 Tillage and Residue Burning

As noted earlier in this appendix, changing tillage practices will result in changes in soil carbon sequestration that will take place over a 25-year period. More intensive tillage also requires more diesel fuel for tractors to plow the land. In addition, the tillage practices selected on a farm will affect the level of residue per acre on the farm, which affects N_2O emissions from incorporation of residues into the soil as described above. In addition, agricultural fields are sometimes burned to remove excess residue. This burning results in N_2O and CH_4 emissions that are tracked in FASOM. Thus, reductions in the reliance on agricultural burning will reduce those emissions in the model.

A.3.2 Crop Rotations

One potential response that farmers may have to higher corn prices is to move from corn-soybean or other rotations patterns into continuous corn production. This type of change in rotation patterns would be expected to have effects on soil productivity, chemical and fertilizer use, crop yields and GHG emissions over time.

[144] The assumed allocation of energy requirements between natural gas and electricity is currently based on professional judgment.

FASOM does not explicitly model the selection of alternative crop rotations. Because the model operates in 5-year time steps, it has not generally been applied to shorter-term decisions such as changes in rotation patterns. Rather, the model data implicitly reflect average conditions for crop production (e.g., yields, input use, etc.) associated with historical rotation patterns on a regional level.

A.3.3 Irrigation

Another important management decision that substantially affects fertilizer and other input use as well as energy use for irrigation water pumping is the allocation of dryland vs. irrigated land. In some regions, production of certain crops is assumed to be exclusively dryland or exclusively irrigated, but for some crop-region combinations, there is some ability of production to move dryland and irrigation. Irrigated lands typically have higher yields, but require more fertilizer and more energy use per acre in FASOM.

A.3.4 Impacts on Chemical and Energy Inputs

In addition to the allocation of crop production across crops, the selection of tillage and irrigation practices will affect the use of both chemical inputs and energy inputs. More intensive tillage practices and the use of irrigation typically increase the energy requirements per acre of production for a given crop.[145] Although FASOM does not explicitly include decisions regarding crop rotations because it focuses on modeling long-run responses, changes in rotations will implicitly be reflected in changes in the average annual land allocation to different crops. To the extent that there was a change in rotation practices to focus more heavily on corn production, that shift in rotations would tend to increase fertilizer inputs, energy use, and associated GHG emissions. FASOM captures a wide array of interactions between agricultural markets and producer allocation among crops as well as the selection of management practices, enabling examination of the complex relationships between sectors and the overall impacts on agricultural chemical and energy use that result.

A.4 Livestock and Poultry Sectors

In addition to the extensive coverage of crop production within FASOM, the model also tracks livestock and poultry production. Analogous to the crop budgets, there are alternative livestock budgets included in the model that vary by region and species. In addition, the budgets are split into multiple stages for livestock products with multi-year production cycles. For

[145] Irrigation also increases yields, however. Thus, it is possible in some cases that emissions per unit of production could decrease even if emissions per acre increase.

instance, in the case of beef cattle production, there is a cow-calf stage in the model, followed by alternatives for intermediate stages, and finally moving to a feedlot for finishing on grain.

One of the primary differences between regional livestock budgets is the availability of pasture and rangeland forage and forage productivity per acre. Thus, the allocation of feed and forage included within each of the livestock budget for a particular region varies based on regional availability of alternative forage sources. In this section, we focus on the use of renewable fuel coproducts such as DGs as an alternative livestock feed, non-CO_2 GHG emissions from livestock, and energy use in livestock production.

A.4.1 Use of Renewable Fuel Coproducts

One factor that can potentially help to mitigate impacts of higher feed prices for the traditional commodities used in livestock feed under EISA is the increased availability of renewable fuel coproducts that can potentially substitute for current feed commodities. The increased availability of these products helps to keep the costs of feeding livestock lower than they would be otherwise. The availability of a market for coproducts also helps increase the returns to renewable fuels production. Use of these products as livestock feed in FASOM is expected to increase rapidly over time under the Reference case and even faster under the Control case. In addition to displacing livestock feed, dry mill ethanol plants that employ a fractionation or extraction process yield corn oil as a coproduct. The corn oil provides a secondary revenue stream, further helping increase the returns to renewable fuels production.

The primary coproducts of starch-based ethanol production that are used as livestock feed are DG, gluten meal, and gluten feed. In particular, DG is produced in large quantities. This coproduct of ethanol production can be used as feed for beef cattle, dairy cattle, swine, and poultry in place of traditional feed sources such as corn and soybean meal (for additional detail, see Appendix B). In addition to replacing some of the corn and soybean-derived livestock feeds, substitution of these renewable fuel coproducts reduces the demand for land, fertilizer, energy, and other inputs needed for crop production relative to a case where these coproducts were not available. The reduced input use also results in lower GHG emissions.

A.4.2 Methane and Nitrous Oxide Emissions

GHG emissions associated with livestock production are primarily associated with manure management (both CH_4 and N_2O) and enteric fermentation (CH_4), although there are also emissions from energy use. Livestock manure under aerobic conditions produces N_2O as part of the nitrogen cycle through the nitrification and denitrification of the organic nitrogen in livestock manure and urine. Under anaerobic conditions, such as in large-scale livestock waste storage facilities, methane is produced during decomposition of the manure. In addition, enteric fermentation is part of the normal digestive process in ruminants such as cattle that results in the production of methane within the rumen, which is then emitted. Calculation of these livestock emissions in FASOM is described below.

A.4.2.1 Manure Management

To calculate emissions from manure management, FASOM calculates the average emissions per head by livestock type for both CH_4 and N_2O emissions. These values are based on the 2001 emissions values by livestock type and the number of livestock in each livestock category reported in the EPA GHG inventory for 1990–2003.[146] The average values per head are multiplied by the number of livestock in each livestock category in each model period to estimate the emissions associated with manure management. Thus, emissions from this source are currently affected only by the number of animals in each livestock category. To the extent that EISA requirements result in higher feed costs, livestock herds are expected to be reduced and manure management emissions will tend to decline relative to the Reference case.

A.4.2.2 Enteric Fermentation

Enteric fermentation emissions from livestock are calculated based on the number of animals of each type and a calculated value of average emissions per head based on the 2001 emissions values by livestock type and the number of livestock in each livestock category reported in the EPA GHG inventory report for 1990–2003.[147] These average values for enteric fermentation emissions per head are multiplied by the number of livestock of each type in a given year to generate the emissions estimate. There are emissions mitigation options included within the FASOM model, but these options do not enter the market in the absence of incentives for reducing CH_4 emissions. Thus, similar to the case of manure management, emissions from this source are currently affected only by the number of animals in each livestock category.

A.4.3 Energy Use

In livestock production budgets, FASOM does not include direct energy inputs. However, because changes in the livestock population influence the demand for crops to be used as livestock feed, changes in livestock populations will have an indirect effect on energy use by inducing changes in crop production.

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[146] U.S. Environmental Protection Agency. 2005. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2003. EPA 430-R-05-003. Available at http://www.epa.gov/climatechange/emissions/downloads06/05CR.pdf.
[147] Ibid.

APPENDIX B:

MODELING STARCH-BASED AND SUGAR-BASED ETHANOL PRODUCTION

This appendix contains an overview of the key methods and assumptions used to model starch-based and sugar-based ethanol production in FASOM. Ethanol processes included in FASOM are described in Section B.1, detailed information on feedstock costs is presented in Section B.2, coproducts are discussed in Section B.3, assumptions regarding technology change are presented in Section B.4, and the types of agricultural market impacts associated with starch ethanol production are discussed briefly in Section B.5.

B.1 Process Types Included in FASOM

FASOM assumes standard sizes for ethanol production plants. The majority of plants producing ethanol from starch or sugar feedstocks are assumed to produce 75 million gallons per year (MGY) of ethanol using a single feedstock. The exception is plants using sweet sorghum as a feedstock, which are assumed to be 40 MGY plants.[148] Plant-level production costs used within the model are based on sources in the literature, adjusted based on communication with EPA to account for updated input costs. These costs are based on standard procedures for fermentation of sugars to produce ethanol. Starches in plants such as corn, wheat, and other grains are chains of sugars that can be readily broken down into simple sugars before fermentation, whereas sugar-based feedstocks such as sugarcane or sugarbeets contain simple sugars that can readily be extracted and fermented.

Feedstock requirements to supply the standard ethanol plant sizes assumed vary by feedstock based primarily on differences in starch/sugar content that lead to variation in ethanol yield per unit of feedstock. Table B-1 lists the categories of starch- and sugar-based feedstocks currently included in FASOM as well as the assumed ethanol yield and corresponding units required per ethanol plant in 2022.[149]

[148] The advantage of sweet sorghum as an ethanol feedstock is its high sugar content. However, the level of sugar in the crop decreases rapidly following harvest. Thus, to efficiently capture these sugars for ethanol processing, sweet sorghum needs to be transported to the ethanol plant as soon as possible after the sweet sorghum is harvested. In addition, sweet sorghum is assumed to be 65% moisture, which greatly increases hauling costs per dry ton and decreases optimal plant size. Therefore, to reduce average transportation distance and hauling cost, FASOM assumes a smaller plant size for sweet sorghum than for any of the other feedstocks. Because smaller plants have higher processing costs per gallon of ethanol produced, sweet sorghum plants also have higher assumed processing costs per gallon than the other feedstocks.

[149] As described earlier in the paragraph, the yields assumed for starch- and sugar-based feedstock conversion to ethanol are constant over time, starting with the 2002 FASOM baseline.

Table B-1. Starch- and Sugar-Based Ethanol Feedstocks Included in FASOM and Annual Quantity Requirements for a 75 MGY Ethanol Plant (40 MGY for Sweet Sorghum), 2022

Feedstock	Units	Ethanol Yield (gallons/unit)	Quantity Required per Plant (units)
Barley	Bushels	1.66	45,276,754
Corn (dry milling process)	Bushels	2.71	27,675,277
Corn (wet milling process)	Bushels	2.50	30,000,000
Oats	Bushels	1.10	68,428,344
Refined sugar	Tons	141.00	531,915
Rice	100 pounds (cwt)	3.98	18,844,221
Sorghum	100 pounds (cwt)	4.25	18,453,427
Sweet sorghum	100 pounds (cwt)	9.00	4,444,444
Sweet sorghum (ratooned)	100 pounds (cwt)	11.00	3,636,364
Wheat, Durham	Bushels	2.56	29,264,758
Wheat, hard red spring	Bushels	2.56	29,264,758
Wheat, hard red winter	Bushels	2.56	29,264,758
Wheat, soft white	Bushels	2.56	29,264,758

Production costs for starch- and sugar-based ethanol are broken into feedstock costs, hauling costs, and processing costs. Revenue is derived from ethanol sales at the market price, government subsidies, and the sale of coproducts produced during the processing of certain feedstocks (e.g., DG from ethanol production using grain feedstocks).

FASOM is used to simulate the quantity of each of the starch- and sugar-based feedstocks considered that would be used in ethanol production, accounting for competing demands for those feedstocks for use in food production or in animal feed under alternative policy scenarios. In addition, FASOM provides estimates of the number of standard size starch- or sugar-based ethanol plants that would be located in each of the 11 FASOM market regions over time.

B.2 Feedstock Costs

Costs of using starch crops for ethanol production include the cost of the crop, the cost of hauling the crop from the roadside at the farm to the ethanol production plant, and the per-gallon processing cost of the crop to ethanol. This section describes the costs of purchasing sufficient crops to produce a given amount of starch ethanol, which depends on crop energy content (i.e., quantity of crop required to produce a given amount of ethanol varies across crop). The quantity of crop required also affects hauling costs.

Plant-level crop costs reflect the cost per unit of crop multiplied by the number of units required to provide enough crop to produce 75 million gallons of ethanol. Crop quantity requirements for starch ethanol vary by crop and are measured in bushels (bu), hundred weight (cwt), or tons, depending on the crop. The relevant comparison for ethanol production plants is the cost of purchasing the quantity of feedstock that will generate a given amount of ethanol.

For a plant using a given crop, the plant-level quantity requirements are multiplied by the regional farm-level market price for that crop generated by FASOM to calculate the total plant-level feedstock costs. The regional farm-level market price reflects the market-clearing price based on all possible uses for the crop, including feed use in livestock, exports, international and domestic food consumption, and use in ethanol production. Increases in demand for crops used to produce starch- and sugar-based ethanol place upward pressure on the market-clearing price for crops used in ethanol production. However, if increases in crop acreage and yield increases meet or exceed increases in demand, then inflation-adjusted equilibrium prices could remain steady or even decline over time. Increasing yields also mitigate pressure to convert land to agricultural production both in the United States and abroad.

Thus, projected crop yields, both in the United States and internationally, are one of the most influential factors influencing the market and environmental outcomes of this analysis. The regional average crop yields presented in Table B-2 are based on USDA projections through 2017[150] (the final year reported in the baseline projections report) and then extrapolated out to 2022 assuming yield continues to grow at the same annual rate in the future. Baseline yields are based on historical averages for each region, and yields are assumed to increase at the same rate over time in both the Reference and Control Cases.[151]

[150] USDA Office of the Chief Economist, World Agricultural Outlook Board. USDA Agricultural Projections to 2018. Report prepared by the Interagency Agricultural Projections Committee. Long-term Projections Report OCE-2009-1. Available at http://www.ers.usda.gov/Publications/OCE091/

[151] This implicitly assumes that there are no price-induced yield increases. It is possible that higher prices may spur landowners to modify their practices to adopt more expensive production technologies that increase yields, for instance. Also, higher returns to production may lead to an increase in research funding and speed up technological improvements. On the other hand, higher prices may induce planting on marginal land that would have lower yields than land currently in production.

Table B-2. Regional Average Crop Yields, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Barley (bu/acre)	61.5	62.9	54.6	70.5	72.9	64.3	62.4	75.7	77.7	46.9
Corn (bu/acre)	197.2	196.1	185.2	147.1	NA	223.1	154.0	166.9	160.7	168.3
Oats (bu/acre)	72.8	59.4	65.1	67.8	97.0	91.8	67.5	42.2	62.7	46.4
Sugarcane (tons/acre)	NA	NA	NA	NA	NA	NA	NA	31.1	44.6	46.2
Rice (cwt/acre)	94.4	NA	NA	NA	NA	129.4	NA	97.3	NA	108.6
Sorghum (bu/acre)	100.0	83.8	NA	82.3	NA	53.9	53.9	82.4	60.1	63.6
Sweet sorghum (tons/acre)	32.3	24.3	NA	NA	NA	NA	17.2	28.7	NA	17.8
Sweet sorghum (ratooned) (tons/acre)	43.8	33.0	NA	NA	NA	NA	23.3	38.9	NA	24.2
Wheat, Durham (bu/acre)	NA	50.5	48.2	NA	NA	129.8	70.4	NA	NA	NA
Wheat, hard red spring (bu/acre)	NA	51.1	51.2	NA	80.5	NA	55.8	NA	NA	NA
Wheat, hard red winter (bu/acre)	110.2	85.4	110.8	111.2	NA	110.2	90.0	94.7	96.1	77.7
Wheat, soft white (bu/acre)	NA	NA	NA	NA	92.8	NA	80.9	NA	NA	NA

Note: CB = Corn Belt; GP = Great Plains; LS = Lake States; NE = Northeast; PNWE = Pacific Northwest—East side (agriculture only); PSW = Pacific Southwest; RM = Rocky Mountains; SC = South Central; SE = Southeast; SW = Southwest (agriculture only).
NA = Not applicable

The market price for each alternative ethanol feedstock will vary by scenario. Because starch- and sugar-based feedstocks considered in FASOM are generally being used in numerous competing markets, they have positive market prices, unlike the case of cellulosic ethanol where there is no market for most of the feedstocks in FASOM in the Reference Case.[152] Table B-3 summarizes market equilibrium prices in FASOM under the Reference and Control Cases. As expected, the introduction of increased demand for ethanol feedstocks to increase ethanol production under EISA leads to increases in price for these feedstocks, including positive values for sweet sorghum.

[152]The exception is sweet sorghum, which is in experimental stages and not widely traded in markets.

Table B-3. FASOM Market Prices for Ethanol Feedstock Crops (2007$/unit) in Reference and Control Cases, 2022

Feedstock	Unit	Reference Case Price ($/unit)	Control Case Price ($/unit)	% Change in Price
Barley	bu	4.70	5.81	23.6
Corn	bu	3.32	3.60	8.2
Oats	bu	3.01	4.04	34.2
Sugarcane	tons	31.87	37.46	17.5
Rice	cwt	10.61	10.86	2.4
Sorghum	cwt	6.35	6.52	2.6
Sweet sorghum	tons	10.68	10.86	9.9
Wheat, Durham	bu	8.57	9.12	6.4
Wheat, hard red spring	bu	5.91	5.71	-3.3
Wheat, hard red winter	bu	5.61	6.16	9.9
Wheat, soft white	bu	5.20	4.91	-5.6

NA = Not applicable

In addition to revenue from selling feedstocks in the market, eight of the eleven FASOM market regions offer state subsidies that offset some of the ethanol production costs. These subsidies are in addition to the $0.45 per gallon national ethanol subsidy included in the model.[153] Regional averages for subsidies per gallon of ethanol produced are presented in Table B-4.[154]

Table B-4. Average State Ethanol Subsidy by Region Used in FASOM (cents/gallon of ethanol produced)

	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Average state subsidy	0.02	15.0	15.4	0.01	0	0	0.86	0.50	2.00	10.4

Note: CB = Corn Belt; GP = Great Plains; LS = Lake States; NE = Northeast; PNWE = Pacific Northwest—East side; PSW = Pacific Southwest; RM = Rocky Mountains; SC = South Central; SE = Southeast; SW = Southwest.

[153] The national subsidy included in FASOM is the Volumetric Ethanol Excise Tax Credit (VEETC), which was created in 2004 as part of H.R. 4520, the American Jobs Creation Act of 2004. The credit was 51 cents per gallon on pure ethanol (5.1 cents per gallon for E10 and 42 cents per gallon for E85) until January 1, 2009, when it was reduced to 45 cents per gallon of pure ethanol.

[154] The values used were based on a review of available state-level subsidies within each FASOM region.

B.3 Coproducts

There are four primary coproducts of the starch-to-ethanol production process tracked within FASOM and they are DG, gluten meal, gluten feed, and corn oil, all of which are produced during the process of converting starches in grain crops into ethanol. DG has the potential to replace some of the corn used for feed, and FASOM includes feed substitution using DG as a corn and soybean meal replacement possibility. Based on research conducted by Argonne National Laboratory,[155] FASOM assumes that one pound of DG can potentially substitute for 1.196 pounds of total corn and soybean meal for cattle because the DG has higher nutritional content per pound. The model assumes that replacement rates increase over time from a 1:1 replacement rate of DG for corn and soybean meal initially to the maximum technological replacement rate estimated by Argonne of 1:1.196 in 2017 for beef and dairy cattle. We continue to use a replacement rate of 1:1 throughout the entire modeling timeframe for swine and poultry. We also implemented maximum DG inclusion rates in livestock feed as a percentage of total feed based on the Argonne study. These limits vary by species and are assumed to increase between 2007 and 2017, reaching maximum levels of 50% for beef cattle, 30% for dairy cattle, and 25% for both swine and poultry by 2017 and remaining at those levels after 2017.

In addition, DG produced as a byproduct of a dry milling process with corn oil fractionation/extraction has different nutritional characteristics than traditional DG, which contain higher levels of oil.[156] Based on this research, the proportion of soybean meal vs. corn replaced by fractionated/extracted DG is higher than for traditional DG when used for swine or poultry feed, although the total replacement rate of DG for a combination of corn and soybean meal remains 1:1. Therefore, we have modified the model to apply different replacement rates for fractionated/extracted DG and traditional DG when used in swine and poultry feed. Because there was no comparable research identified for cattle diets, we assumed that replacement rates for cattle remain the same for fractionated/extracted DG as for traditional DG.

Another change that has been implemented since the proposal is the incorporation of an export market for DG into FASOM. In the analysis for the proposal, it was assumed that all DG produced would be supplied into the domestic market. However, the model has been modified to

155 Salil, A., M. Wu, and M. Wang. 2008. "Update of Distillers Grains Replacement Ratios for Corn Ethanol Life-Cycle Analysis." Available at http://www.transportation.anl.gov/pdfs/AF/527.pdf.

156 Shurson, G.C. 2006. "The Value of High-Protein Distillers Compounds in Swine Feeds." *Distillers Grains Quarterly*, First Quarter 2006:22-25.

account for potential exports of DG. This change expands the market for DG and is consistent with historical experience in recent years. Exports of DG have increased rapidly over the last few years. The majority of U.S. exports are shipped to Mexico and Canada, but there has also been expansion in exports to the Middle East and Asia. Based on values reported by the National Corn Growers Association,[157] the corn wet mill process is assumed to produce 13.5 pounds of gluten feed, 2.5 pounds of gluten meal, and 0.2078 gallons of corn oil per bushel of corn. Thus, the standard 75 MGY plant used in FASOM will produce 405,000 pounds of gluten feed, 75,000 pounds of gluten meal, and 62,337 gallons of corn oil per year as coproducts of ethanol production. The corn dry mill process is assumed to produce 17 pounds of DG per bushel of corn, or about 510,000,000 pounds of DG per year without using fractionation or extraction. However, plants can also use two different processes to separate corn oil during the dry milling process: the “front-end” fractionation process and the “back-end” extraction process. Both processes yield DG and corn oil as coproducts. Although fractionation produces food grade corn oil, the dry mill extraction process produces non-food grade corn oil that cannot be used as vegetable oil for food production but can be used to produce biodiesel. Based on projections included in Chapter 1.4 of the RIA, beginning in 2010 10% of dry mill ethanol plants will use extraction and 3% will use fractionation. These shares are assumed to climb to 70% for the extraction process, 20% for the fractionation process, and 10% that use neither fractionation nor extraction by 2022. In addition to by-products from using corn, the use of grains other than corn as ethanol feedstocks can also produce DG as a coproduct. Table B-5 summarizes the coproducts produced when using different grain feedstocks for ethanol production.

Table B-5. Production of Ethanol Coproducts by Feedstock

	Gluten Feed (lbs/bu)	Gluten Meal (lbs/bu)	Corn Oil (gallons/bu)	DG (lbs/bu)
Barley	NA	NA	NA	14.6
Corn (wet milling process)	13.5	2.5	0.2078	NA
Corn (dry milling process – no fractionation or extraction)	NA	NA	NA	17.0
Corn (dry milling process – fractionation)	NA	NA	0.1439	15.9
Corn (dry milling process – extraction)	NA	NA	0.1929	15.5
Oats	NA	NA	NA	9.7
Rice	NA	NA	NA	30.4
Sorghum	NA	NA	NA	30.4
Wheat	NA	NA	NA	18.2

NA = Not applicable; those coproducts are not produced from that feedstock/process combination.

[157] National Corn Growers Association. 2006 World of Corn.

Revenue provided by selling these coproducts is an important factor affecting the economic viability of ethanol processing plants. In the Reference Case, the 2022 prices of these feed coproducts were $93.62 per ton for gluten feed, $201.05 per ton for gluten meal, $116.75 per ton for traditional DG, and $118.88 per ton for DG from the fractionation or extraction process. The added revenue from biodiesel and corn oil will be another factor affecting ethanol producer decisions to fractionate or extract. Under the Control Case, prices for these coproducts increase with the exception of gluten meal, which experiences a price decline of 0.1%. Gluten feed, traditional DG, and fractionated/extracted DG prices increase by 13.6%, 6.8%, and 6.5%, respectively.

In addition, these coproducts play a vital role in mitigating impacts on the livestock sector by providing substitutes for grain feeds and keeping price increases lower than they would be otherwise. Total use of these products as livestock feed in FASOM is expected to increase rapidly over time under the Reference Case and even faster under the Control Case. Although use of gluten meal decreases by 4.5% under the Control Case in 2022, use of gluten feed increases by 6.4%, and use of DG increases by 15.2%. Overall, use of ethanol by-products in livestock feed increases by 12.6% in 2022 relative to the Reference Case.

B.4 Technology Change

As noted earlier, fermentation using starch- and sugar-based feedstocks is assumed to be a relatively well-developed technology that has reached physical limits on ethanol conversion potential, and ethanol conversion yields are assumed to remain constant over time. Since FASOM uses an "average" ethanol plant, we assumed an average that takes into account older, less efficient plants. In addition, processing costs per gallon of ethanol are assumed to remain constant over time. This is in contrast to cellulosic ethanol, which, as described in Appendix D, is assumed to experience substantial improvements in ethanol yield over time as well as reductions in processing costs per gallon. As a result, the quantities of feedstock required at standard FASOM ethanol plants and the inflation-adjusted costs of processing those feedstocks remain the same over time.

However, improvements in feedstock yields will reduce hauling costs over time. As shown in Table B-6, yield improvements assumed between 2002 and 2022 vary across the crops that can potentially be used as feedstocks in ethanol production. Other things being equal, those crops with greater yield increases over time will become more attractive feedstocks over time as their higher yields reduce hauling costs and tend to mitigate future price increases.

B.5 Agricultural Market Impacts

FASOM tracks the impacts on agricultural markets associated with changing production practices to allocate different levels of grain crops and sugar from production of food and animal feed to ethanol production. Large-scale expansion of crop production to provide starch- and sugar-based feedstocks for ethanol production will potentially have major implications for land uses and values as well as the production of competing food and animal feed products. Production increases must be induced through higher equilibrium market prices and will result in production shifting toward the crops that experience the greatest increase in demand and price and away from other crops. However, as land shifts out of other crops, the supply of those crops will decline and result in price increases in those markets until a new equilibrium is reached. In addition, changes in prices of animal feeds will affect livestock production. Because FASOM captures the opportunity costs of land and other resources, results reflect the changes in market equilibrium associated with introducing a renewable fuels policy that increases the market demand for certain feedstocks.

Table B-6. FASOM Assumptions Regarding Changes in Crop Yields Over Time

	Average Annual Change in Yield (%)	Aggregate Change in Yield, 2002–2022 (%)
Barley (bu)	0.10%	1.9%
Corn (dry milling process) (bu)	1.62%	38.0%
Corn (wet milling process) (bu)	1.62%	38.0%
Oats (bu)	0.02%	0.3%
Sugarcane (tons)	0.00%	0.1%
Rice (cwt)	1.33%	30.3%
Sorghum (cwt)	0.09%	1.8%
Sweet sorghum (cwt)	0.00%	0.0%
Wheat, Durham (bu)	1.11%	24.6%
Wheat, hard red spring (bu)	1.00%	21.9%
Wheat, hard red winter (bu)	1.31%	29.7%
Wheat, soft white (bu)	1.11%	24.6%

Because EISA focuses on increasing renewable fuels production from advanced sources such as cellulosic ethanol production, the incremental volume of starch- and sugar-based ethanol under EISA is relatively small. This reduces the market impacts of increasing renewable fuels production considerably by creating a market for crop residues, which would be collected from lands being used primarily for other crop production purposes rather than competing for land. Nonetheless, the increased volumes of ethanol production will affect the agricultural sector by further increasing the demand for corn, sugarcane, and other feedstocks; increasing the equilibrium prices for agricultural products; and increasing the competition for agricultural land.

Generally, the demand for agricultural crops for use as feedstocks in ethanol production is expected to shift land use in FASOM as landowners respond to changes in the relative returns to alternative crops under EISA. Because of relatively high ethanol yields, hauling cost advantages, and valuable coproducts, corn is likely to continue to be the primary feedstock for expanded noncellulosic ethanol production under EISA. In addition, the creation of a market for cellulosic ethanol leads to a substantial increase in the value of crop residues, particularly corn stover, which further increases the returns to corn production. One of the major factors influencing market outcomes is the future change in crop yields, particularly corn yields. Given the yield improvements incorporated into FASOM, corn production is likely to grow faster than corn demand in the future even with additional use as an ethanol feedstock. Thus, improvements in corn yield will contribute to reductions in the price of corn and other commodities in the future and will help mitigate land use and environmental impacts.

APPENDIX C:
MODELING BIODIESEL PRODUCTION

In this appendix, we present key assumptions and methods used to model biodiesel production in FASOM. The processes used for biodiesel production in the model are described in Section C.1, information on feedstock costs is presented in Section C.2, assumptions regarding coproducts of biodiesel production are briefly described in Section C.3, assumptions regarding biodiesel production technology change over time are presented in Section C.4, and the types of agricultural market impacts associated with biodiesel production are briefly discussed in Section C.5.

C.1 Process Types Included in FASOM

In FASOM, biodiesel production is treated differently than starch- or sugar-based ethanol or cellulosic ethanol in that biodiesel production is assumed to rely on inputs that are already produced as part of existing processing activities. For instance, existing regional soybean crushing and corn milling processing budgets produce a supply of soybean and corn oil. In addition, fed and nonfed cattle slaughter activities produce edible and nonedible tallow, and pork slaughter produces lard. Thus, it was assumed in FASOM that biodiesel would be produced at the same site where the inputs are produced. Unlike ethanol production, which relies on a specific standard size plant to calculate the average regional hauling costs to supply a plant of that size, biodiesel production is assumed to require no hauling costs and to be available at constant returns to scale. Biodiesel producers within a region can produce any quantity of biodiesel, and FASOM measures production in thousands of gallons of biodiesel without estimating a specific number of plants that are generating that quantity of biodiesel. Processing costs per gallon of biodiesel produced used within FASOM were based on analyses included in the RIA for this rule.

The quantity of feedstock required to produce a gallon of biodiesel varies across feedstocks to some extent, but with less variance than for ethanol production. Table C-1 lists the categories of biodiesel feedstocks being included in FASOM, the assumed biodiesel yield, and the quantity of feedstock required per 1,000 gallons of biodiesel produced. Feedstock requirements and processing costs per gallon of biodiesel are assumed to remain constant over time (in inflation-adjusted dollars). In addition, the production of biodiesel feedstocks as a proportion of the amount of soybean crushing, corn milling, and livestock slaughter activities taking place remains constant over time.

Table C-1. Biodiesel Feedstocks Included in FASOM and Quantity Requirements per 1,000 Gallons of Biodiesel, 2022

Feedstock	Unit	Biodiesel Yield (gallons/unit)	Quantity Required per 1,000 Gallons of Biodiesel Produced (units)
Soybean oil	Pounds	0.1288	7,763.0
Corn oil (non-food grade)	Gallons	1.0239	976.7
Nonedible tallow	Pounds	0.1302	7,679.0
Edible tallow	Pounds	0.1302	7,679.0
Lard	Pounds	0.1302	7,679.0

Production costs for biodiesel consist of feedstock costs and processing costs. Revenue at biodiesel plants is derived only from biodiesel sales at the market price; unlike ethanol production, no state-level government subsidies are included in FASOM, and no valuable coproducts are produced during biodiesel processing. However, there are federal subsidies of $1 per gallon for both virgin oil and waste oil and greases included in the model.[158] These subsidies are assumed to remain constant at those levels indefinitely. FASOM simulates the supply of biodiesel by feedstock for each of the 10 FASOM market regions with agricultural production over time in response to the demand for biodiesel under specified scenarios.[159]

C.2 Feedstock Costs

The costs of using biodiesel feedstocks for biodiesel production include only the opportunity costs of not using the oils to produce alternative competing products and the costs of processing the feedstocks into biodiesel. Because it is assumed that the crop feedstock used in biodiesel production is located on site, FASOM assumes zero handling and hauling costs in biodiesel production, whereas these costs represent a substantial proportion of total production costs in ethanol production.

[158] The national subsidy included in FASOM is based on the subsidy included in the Emergency Economic Stabilization Act of 2008 (H.R.1424), signed into law in October 2008. The Energy Policy Act of 2005 (H.R.6), which extended the biodiesel credit specified as part of the Volumetric Ethanol Excise Tax Credit (VEETC) under the American Jobs Creation Act of 2004 (H.R. 4520), provided a subsidy equal to $1 per gallon for “agri-biodiesel” (diesel fuel made from virgin oils derived from agricultural commodities and animal fats) and $0.50 per gallon for “biodiesel” (diesel fuel made from agricultural products and animal fats). The Emergency Economic Stabilization Act of 2008 eliminated the distinction between agri-biodiesel and biodiesel such that all biodiesel now qualifies for the $1 per gallon subsidy.

[159] Only 10 of the 11 market regions in FASOM have agricultural production. The PNWW region has only forestry production. Because there are no biodiesel production options in FASOM involving feedstocks derived from the forestry sector, no biodiesel production is available in the PNWW region.

Plant-level feedstock costs reflect the cost per unit of feedstock multiplied by the number of units required to provide enough feedstock to produce 1,000 gallons of biodiesel. The prices of the primary biodiesel feedstocks in the Reference and Control Cases for 2022 are presented in Table C-2.

Table C-2. FASOM Market Prices for Biodiesel Feedstocks (2007$/unit) in Reference and Control Cases, 2022

Feedstock	Unit	Reference Case Price ($/unit)	Control Case Price ($/unit)	% Change in Price
Soybean oil	Pounds	$0.24	$0.33	37.9%
Corn oil (non-food)	Gallons	$0.34	$1.26	270.9%

For a plant using a given feedstock type, the plant-level quantity requirements are multiplied by the regional market price for that feedstock generated by FASOM to calculate the total plant-level feedstock costs. The price for biodiesel feedstocks reflects the equalizing of the supply and demand for that particular product and will vary based on the specific scenario being modeled. Changes in soybean and corn yields over time relative to changes in demand for oils derived from these crops, along with agricultural producer adjustments in land use and production due to changing relative crop prices, will determine changes in prices of soybean and corn oils over time. Table C-3 presents information on the quantity of corn and soybean oils that can be produced per acre of crops by region.

In addition, to the extent that more efficient techniques for collecting and using waste oils in biodiesel production are developed, those feedstocks may also play a larger role in biodiesel production in the future. Expanded use of waste oil feedstocks could contribute to moderating price increases for corn and soybean oils to meet EISA biodiesel production levels, but currently it is expected that the majority of the increase in biodiesel production would be derived from soybean and corn oils.

Table C-3. Regional Average Potential Production of Soybean and Corn Oil per Acre, 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Corn (bu/acre)	197.2	196.1	185.2	147.1	NA	223.1	154.0	166.9	160.7	168.3
Corn oil (gallons/acre) (wet mill)	41.0	40.8	38.5	30.6	NA	46.4	32.0	34.7	33.4	35.0
Soybeans (bu/acre)	50.3	40.1	42.6	38.0	NA	NA	NA	36.7	31.5	23.8
Soybean oil (lbs/acre)	561.1	447.5	475.4	424.1	NA	NA	NA	409.6	351.5	265.6

Note: CB = Corn Belt; GP = Great Plains; LS = Lake States; NE = Northeast; PNWE = Pacific Northwest—East side (agriculture only); PSW = Pacific Southwest; RM = Rocky Mountains; SC = South Central; SE = Southeast; SW = Southwest (agriculture only).

C.3 Coproducts

No coproducts are associated with biodiesel production in FASOM. Although soybean crushing to produce soybean oil generates a coproduct of 47.6 lbs of soybean meal per bushel of soybeans along with 11.16 lbs of soybean oil, that process is separated from the biodiesel production process that uses soybean oil outputs from soybean crushing to produce biodiesel. Nonetheless, soybean meal is a highly marketable input in livestock feed production, and the sale of soybean meal would represent an additional stream of revenue for soybean crushing plants that are also producing biodiesel. Table C-4 presents soybean meal production, exports, and prices under the Reference and Control Cases. The increase in biodiesel production under the Control Case results in increased soybean meal production, which results in a slightly lower market equilibrium price.

C.4 Technology Change

Unlike ethanol production, we assumed no changes in the technology of biodiesel production over time that would affect the biodiesel conversion rate or processing costs. Because the cost of biodiesel feedstocks depends on market forces, increases in corn and soybean yields over time will tend to dampen potential price increases associated with increases in demand for these crops because of renewable fuels' requirements or other changing market conditions. However, we assumed no changes in technology would occur that would directly affect the cost of biodiesel production.

Table C-4. Prices, Exports, and Production of Soybean Meal, 2022

Variable	Units	Value in Reference Case (units)	Value in Control Case (units)	Percentage Change
Production	tons	43.83	45.91	4.7%
Exports	tons	15.81	16.26	2.8%
Price	$/ton	201.05	200.82	−0.1%

C.5 Agricultural Market Impacts

FASOM tracks the impacts on agricultural markets associated with changing production practices to allocate different levels of corn and soybean oils from production of food and animal feed to biodiesel production. Large-scale expansion of biodiesel production to provide feedstocks for biodiesel production will potentially have major implications for corn and soybean oil prices, as well as the production of competing food and animal feed products. Production increases must be induced through higher equilibrium market prices and will result in production shifting toward the crops that experience the greatest increase in demand and price and away from other crops. However, as land shifts out of other crops, the supply of those crops will decline and result in price increases in those markets until a new equilibrium is reached. In addition, changes in prices of animal feeds will affect livestock production. Because FASOM captures the opportunity costs of land and other resources, results reflect the changes in market equilibrium associated with introducing a renewable fuels policy that increases the market demand for certain feedstocks.

Expansion of soybean oil production for use as a biodiesel feedstock will also result in increased production of soybean meal, which can be used in livestock feed. Thus, this coproduct will help mitigate impacts on livestock producers. In the Control Case modeled in FASOM, increases in soybean meal production result in decreased soybean meal prices. Although more is being used in livestock production, the increase in demand for soybean meal as a livestock feed is more than outweighed by the increase in supply associated with expanded soybean crushing.

The use of waste oils as a feedstock in FASOM does not require any additional land because the land use is already accounted for in production of the primary product. In addition, the substitution of waste oils for soybean and corn oils used extensively in food and feed production reduces market impacts in the soybean and corn oil markets. However, based on current model assumptions regarding the quantities of these waste feedstocks produced, their costs, and biodiesel conversion rates, there are limited opportunities for competitive expansion of the use of waste oils in biodiesel production. To the extent that more efficient ways to use additional waste oils in biodiesel production can be identified, impacts of increased biodiesel production on food and feed markets could be reduced.

APPENDIX D:
MODELING CELLULOSIC ETHANOL PRODUCTION

This appendix contains an overview of the key assumptions and methods used to model cellulosic ethanol production in FASOM. Ethanol processes included in FASOM are described in Section D.1, additional detail on feedstock costs is provided in Section D.2, coproducts are described briefly in Section D.3, assumed technology change over time is discussed in Section D.4, and the types of agricultural market impacts associated with cellulosic ethanol production are discussed in Section D.5.

D.1 Process Types Included in FASOM

In FASOM, there is currently one standard size for cellulosic ethanol plants. All ethanol plants relying on cellulosic feedstocks are assumed to produce 100 million gallons per year (MGY) of ethanol using a single type of feedstock. The selection of this plant size was based on Carolan, Joshi, and Dale.[160] Plant-level production costs used within the model are calculated based on the assumption of a representative 100 MGY plant. Processing costs are based on information presented in the RIA for this rule. These costs were based on biochemical conversion using acid prehydrolysis, enzymatic hydrolysis, and fermentation, followed by distillation of ethanol and separation of coproducts. Thermochemical conversion plants, which rely on processes such as gasification, pyrolysis, and catalytic cracking to produce synthesis gas that can be converted to ethanol, are not included within FASOM.

The quantity of feedstock required per plant varies by feedstock type based on moisture content; energy density; and available technology for feedstock conversion to ethanol, which changes over time. Table D-1 lists the categories of cellulosic feedstocks currently included in FASOM as well as the assumed ethanol yield for 2022 and the corresponding number of dry tons of each feedstock required per plant to produce 100 MGY. Section D.2 provides additional information on the underlying sources of the initial assumptions on ethanol yield and moisture content, and Section D.4 discusses assumed technology changes over time.

[160] Carolan, J., S. Joshi, and B. Dale. 2007. "Technical and Financial Feasibility Analysis of Distributed Bioprocessing Using Regional Biomass Pre-Processing Centers." *Journal of Agricultural & Food Industrial Organization* 5(2), Article 10. Available at http://www.bepress.com/jafio/vol5/iss2/art10.

Table D-1. Cellulosic Feedstocks Included in FASOM and Annual Quantity Requirements for a 100 MGY Ethanol Plant, 2022

Feedstock	Ethanol Yield (gallons/dry ton)	Quantity Required per Plant (dry tons)
Crop Residues		
Barley crop residues	92.30	1,083,424
Corn crop residues	92.30	1,083,424
Oat crop residues	92.30	1,083,424
Rice crop residues	92.30	1,083,424
Sorghum crop residues	92.30	1,083,424
Wheat crop residues	92.30	1,083,424
Energy Crops		
Hybrid poplar	101.50	985,222
Switchgrass	92.30	1,083,424
Willow	101.50	985,222
Logging Residues		
Hardwood logging residues	101.50	985,222
Softwood logging residues	92.30	1,083,424
Processing Residues		
Bagasse	92.30	1,083,424
Hardwood milling residues	101.50	985,222
Softwood milling residues	92.30	1,083,424
Sweet sorghum pulp	92.30	1,083,424

Note: Ethanol yields are based on Tao, L. and A. Aden, *Technoeconomic Modeling to Support the EPA Notice of Proposed Rulemaking (NOPR)*, November 2008.

FASOM simulates the supply of cellulosic ethanol by feedstock over time in response to the demand for cellulosic ethanol to meet the proposed renewable fuel volumes and provides estimates of total cellulosic ethanol production, and the number of cellulosic ethanol plants located in each of the 11 FASOM market regions over time.

D.2 Feedstock Costs

Costs of using cellulosic feedstocks for ethanol production include the cost of the feedstock, which must cover the costs of harvesting as well as opportunity costs associated with residue removal (e.g., need for additional fertilizer due to nutrient removal), the cost of hauling the feedstock from the roadside at the farm to the ethanol production plant, and handling costs associated with storage and grinding. This section discusses the costs of purchasing sufficient feedstock inputs to produce a given level of cellulosic ethanol, which depends on feedstock energy content (i.e., tons of feedstock required to produce a given amount of ethanol vary across feedstocks because they have different moisture levels and energy contents). The quantity of feedstock required also affects hauling and handling costs, as described in Section D.3.

Plant-level feedstock costs reflect the cost per unit of feedstock multiplied by the number of units required to provide enough feedstock to produce 100 million gallons of ethanol. Although the unit of quantity varies by feedstock for grain ethanol, all cellulosic ethanol feedstocks are measured in U.S. short tons (1 short ton is equal to 2,000 pounds). For a plant using a given feedstock type, the plant-level quantity requirements are multiplied by the regional farm-level market price for that feedstock generated by FASOM to calculate the total plant-level feedstock costs.

The regional farm-level market price for a crop residue feedstock reflects the fact that farmers require compensation for additional costs associated with residue removal, including assumed harvesting and handling costs of $13.14 per wet ton (2007$)[161] and increased fertilization requirements due to nutrient removal that vary by crop. The farm-level feedstock price must be at least high enough to cover these costs before farmers will be willing to supply any residues to the market.[162]

For energy crops, land opportunity costs and production costs must be covered by the market price available for the feedstock in order for farmers to be willing to move land into energy crop production. In addition, some processing residues are already used in applications other than cellulosic ethanol production, and an opportunity cost is associated with diverting those residues to cellulosic ethanol production.

D.2.1 Crop Residues

For crop residues, there is a limit to how much residue can be removed before negatively affecting soil erosion. In addition, opportunity costs are associated with loss of nutrients from removing residues. This section describes the calculation of the total quantity of residue, the

[161]Because this value is specified as a constant cost per wet ton, costs of residue harvesting and handling per dry ton will clearly increase with feedstock moisture content. However, because the assumed moisture content is relatively similar across the crop residues included, the cost per dry ton varies only from $14.42 per dry ton for wheat residue to $15.46 per dry ton for rice residue.

[162]The farm-level price that processing plants are willing to pay for each feedstock depends on the hauling and handling costs and ethanol yield associated with that feedstock. In the FASOM model solution, ethanol processing plants are located in the regions where production of EISA-required volumes can be achieved at the lowest cost.

portion that is sustainably removable, feedstock density, moisture content, energy content, ethanol yields, and other factors affecting the potential ethanol production from crop residues.

D.2.1.1 Sustainable Crop Residue Production

The quantity of crop residue produced after harvest (measured in wet tons) is calculated as

$$\text{Residue} = \text{Crop Yield} * \text{Straw-to-Grain Ratio} * \text{Weight Conversion Factor}, \qquad \text{(D.1)}$$

where crop yield is the value for grain yield from FASOM crop budgets and varies by crop, region, irrigation status, tillage, and rate of fertilizer application; straw-to-grain ratio is the average quantity of residue produced for every unit of grain production, which varies by crop[163,164]; and weight conversion factor is a factor used to convert from crop harvest units (e.g., bushel [bu], hundredweight [cwt]) to the common metric of tons of residue and which varies by crop.

Because crop yields are assumed to increase over time due to continued technical progress in crop production (see Table B-3), the amount of residue being produced per acre and the sustainably removable levels of residue will also increase over time. Currently, it is assumed that both crop residue yield and grain yield change at the same average annual rate. However, FASOM includes an adjustment factor that can be applied to allow residue yield adjustments that differ from grain yield adjustments, if appropriate. In addition, there is an option to specify a maximum quantity of residue removal per acre within FASOM.

Table D-2 presents the assumed straw-to-grain ratio and weight conversion factor for each of the six crops (these values were assumed to be the same for all varieties of wheat modeled). These values are constant across regions and remain constant over time.

Based on the values presented in Tables B-3 and D-2, we can calculate residue production per acre. For instance, average corn residue production per acre in the Corn Belt in 2022 is equal to 197.2 bu grain/acre * 1 bu residue/bu grain * 0.028 tons/bu = 5.52 wet tons of corn residue/acre. Corn residue is assumed to have a moisture content of 12%, so 5.522 wet tons of corn residue/acre correspond to 4.85 dry tons of corn residue/acre after removing the 12% of

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[163]Tyner, W., M. Abdallah, C. Bottum, O. Doering, B.A. McCarl, W.L. Miller, B. Liljedahl, R. Peart, C. Richey, S. Barber, and V. Lechtenberg. 1979. “The Potential of Producing Energy from Agriculture.” Report to the Office of Technology Assessment. W. Lafayette, IN: Purdue University School of Agriculture.

[164]Lal, R. 2005. “World Crop Residues Production and Implications of Its Use as a Biofuel.” *Environment International* 31(4):575-584.

Table D-2. Straw-to-Grain Ratio and Weight Conversion Factor

Crop	Straw to Grain Ratio	Weight Conversion Factor
Barley	1.5 : 1	0.024 tons/bu
Corn	1.0 : 1	0.028 tons/bu
Oats	1.0 : 1	0.024 tons/bu
Rice	1.0 : 1	0.050 tons/cwt
Sorghum	1.0 : 1	0.050 tons/cwt
Wheat	1.5 : 1	0.030 tons/bu

corn residue that is water. For hard red winter wheat in the Great Plains, average residue production per acre in 2022 is 85.4 bu grain/acre * 1.5 bu residue/bu grain * 0.030 tons/bu = 3.84 wet tons of wheat residue/acre. Moisture content for wheat is assumed to be 8.9%. Thus, 3.84 wet tons of wheat residue/acre is equivalent to 3.50 dry tons of wheat residue/acre. However, removing all residue production is not consistent with good management practices and is not sustainable.

A number of site-specific factors affect the maximum amount of crop residue that can be sustainably removed, including crop type, soil type, soil fertility, slope, tillage, and climate. As a general rule, though, USDA National Resources Conservation Service recommends that about 30% residue cover is adequate to control soil erosion.[165] Removable residue values used in FASOM were calculated by adjusting the residue production per acre based on the harvestable percentages provided in Graham et al.[166] and Perlack et al.,[167] which consider the effects of erosion and runoff. This approach uses a maximum percentage removal of residues.[168] These percentages vary by crop and tillage, as shown in Table D-3. Another potential measure of sustainable residue availability is the minimum quantity of residues per acre that must be

[165] Maung, T.A. 2007. "Economics of Biomass Fuels for Electricity Generation: A Case Study with Crop Residues." Draft unpublished dissertation. College Station, TX: Texas A&M University.

[166] Graham, R.L., R. Nelson, J. Sheehan, R.D. Perlack, and L.L. Wright. 2007. "Current and Potential U.S. Corn Stover Supplies." *Agronomy Journal* 99:1-11.

[167] Perlack, R.D., L.L. Wright, A.F. Turhollow, R.L. Graham, B.J. Stokes, and D.C. Erbach. 2005. *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply*. Report prepared for the U.S. Department of Energy and the U.S. Department of Agriculture. Available at http://feedstockreview.ornl.gov/pdf/billion_ton_vision.pdf.

[168] Many site specific factors associated with the sustainable removal of residue (e.g., crop type, soil type, soil fertility, slope, and climate) affect which geographic regions are suitable for crop residue removal. Detailed modeling of these factors was beyond the scope of this analysis.

Table D-3. Sustainably Harvestable Residue Percentages

Crop	Conventional Tillage	Conservation Tillage	Zero Tillage
Barley	0%	24.7%	35.3%
Corn	0%	35.0%	50.0%
Oats	0%	24.7%	35.3%
Rice	0%	24.7%	35.3%
Sorghum	0%	24.7%	35.3%
Wheat	0%	24.7%	35.3%

retained on the land to prevent erosion and maintain soil carbon levels.[169] However, insufficient data on minimum sustainable residues per acre were available for use in this analysis. In addition, other than corn, removal rates for all crops in FASOM with potential residue use were assumed to be equal because there is limited residue-specific information available.[170,171]

Table D-4 presents average removable residue per acre in 2022, reflecting adjustments to regional residue production per acre to account for the sustainably removable percentages. These values change over time with changes in crop yields and tillage practices. However, corn provides the greatest volume of sustainably removable crop residue per acre in all years in almost every region (the exception is hard red winter wheat residue in the Northeast region).[172]

D.2.1.2 Ethanol Production from Crop Residues

Available sustainably removable crop residues that are removed from fields under equilibrium market conditions in FASOM can then either be converted to ethanol or used in bioelectricity production. Baseline ethanol conversion rates used in FASOM to produce ethanol from crop residue feedstocks are based on several different sources. These baseline values are

169 Wilhelm, W.W., J.M.F. Johnson, D.L. Karlen, and D.T. Lightle. 2007. "Corn Stover to Sustain Soil Organic Carbon Further Constrains Biomass Supply." *Agronomy Journal* 99:1665-1667.

170 Kerstetter J.D., and J.K. Lyons. 2001. "Logging and Agricultural Residue Supply Curves for the Pacific Northwest." Washington State University Energy Publication.

171 Banowetz, G.M., A. Boateng, J.J. Steiner, S.M. Griffith, V. Sethi, and H. El-Nashaar. 2008. "Assessment of Straw Biomass Feedstock Resources in the Pacific Northwest." *Biomass and Bioenergy* 32(7):629-634.

172 Having the highest sustainably removal residue per acre does not necessarily mean that corn residues will be the preferred crop residue feedstock in a given region, however. The choice of feedstock by cellulosic ethanol processing plant depends on the relative cost of feedstocks per unit of ethanol produced. Thus, other factors such as crop density and energy content will also influence optimal feedstock selection.

Table D-4. Regional Average Sustainably Removable Crop Residue (Dry Tons per Acre), 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Barley residue	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.6	0.7	0.4
Corn residue	1.8	1.7	1.6	1.3	1.9	1.7	1.2	1.7	1.6	1.3
Oats residue	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.4	0.3
Rice residue	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Sorghum residue	1.2	0.9	NA	1.0	NA	0.5	0.5	1.0	0.8	0.6
Wheat, Durham	NA	0.5	0.5	NA	NA	1.1	0.7	NA	NA	NA
Wheat, hard red spring	NA	0.6	0.6	NA	0.8	NA	0.6	NA	NA	NA
Wheat, hard red winter	1.4	0.9	1.3	1.4	NA	1.2	0.9	1.2	1.3	0.8
Wheat, soft white	NA	NA	NA	NA	1.0	NA	0.9	NA	NA	NA

Note: CB = Corn Belt; GP = Great Plains; LS = Lake States; NE = Northeast; PNWE = Pacific Northwest—East side (agriculture only); PSW = Pacific Southwest; RM = Rocky Mountains; SC = South Central; SE = Southeast; SW = Southwest (agriculture only). Values are only presented for an individual crop for regions where that crop can be produced with residue collection in FASOM. Although it is theoretically possible that residues could be collected from rice production, all rice production in FASOM is assumed to use conventional tillage.[173] Thus, rice in FASOM has 0% sustainably removable residues as shown in Table D-3.

then increased over time based on assumed rates of technical progress, reaching the levels shown in Table D-5 by 2022. To place feedstocks with varying moisture contents on a more readily comparable basis, the ethanol conversion rate is often reported in terms of gallons of ethanol per dry ton, and the quantities of feedstocks that can be sustainably removed are converted to dry tons by adjusting for their average moisture content (i.e., quantity in wet tons * [1 – proportion of feedstock that is moisture]). Thus, ethanol conversion rates are provided in terms of both gallons per wet ton and gallons per dry ton in Table D-5.

Using these conversion rates, the required supply for a 100 MGY plant was calculated for each feedstock (see Table D-1). For instance, an ethanol plant using corn residue as a feedstock in 2022 would need 100 million gallons of ethanol per year/92.3 gallons per dry ton of corn residue = 1,083,424 dry tons of corn residue per year (1,231,163 wet tons). With increases in the

[173] Historically, there was very little U.S. rice production utilizing reduced tillage, but this practice has become more common in recent years.

Table D-5. Ethanol Conversion Rates for Crop Residues, 2022

Crop Residue	Moisture (%)	Ethanol Conversion Rate (gallons/wet ton)	Ethanol Conversion Rate (gallons/dry ton)
Barley	10.3%	82.79	92.30
Corn	12.0%	81.22	92.30
Oats	10.3%	82.79	92.30
Rice	15.0%	78.46	92.30
Sorghum	10.0%	83.07	92.30
Wheat	8.9%	84.08	92.30

Source for ethanol conversion rate (gallons/dry ton): NREL (2008)

ethanol conversion rate over time, the quantity of feedstock required by an ethanol plant of a given output level declines commensurately.

D.2.1.3 Crop Residue Feedstock Costs

The cost of acquiring crop residues for cellulosic ethanol production (excluding hauling and handling) is determined in FASOM by calculating the market price of each alternative feedstock. These prices will vary by scenario but must be high enough to provide farmers with compensation for additional costs associated with residue removal. In addition to the on-farm harvesting and handling costs described above, there are increased fertilization requirements due to nutrient removal that vary by crop. FASOM assumes that there is an increase in fertilization requirement relative to baseline fertilizer use for each ton of residue removed from an acre of cropland.[174] In the Reference Case, there is essentially no market for cellulosic feedstocks. Thus, the market prices of crop residues are zero. Under the Control Case or other scenarios requiring cellulosic ethanol production, a market for cellulosic feedstocks is created, and residue prices rise to positive market-clearing levels under the new market conditions.

Table D-6 summarizes the market prices for crop residues in FASOM in the Control Case in 2022. The only crop residues that are being traded in the market in the Control Case equilibrium are corn residues in the Corn Belt, Great Plains, and Lake States and wheat residues in the Great Plains, Rocky Mountains, and Pacific Northwest-East regions.

[174] Additional fertilizer application amounts are based on the GREET defaults, as described in the November 7, 2006 report by M Wu, M. Wang, and H. Huo, “Fuel-Cycle Assessment of Selected Bioethanol Production Pathways in the United States”(ANL/ESD/06-7).

Table D-6. FASOM National Average Farm Gate Prices for Crop Residues (2007$/dry ton) in Control Case, 2022

Feedstock	Price (2007$/dry ton)
Corn crop residues	$39.19
Wheat crop residues	$36.25

D.2.2 Energy Crops

Because there is little field experience with energy crops, more assumptions are involved in generating estimates of feedstock availability and costs than for crop residues. This section outlines assumptions underlying the use of energy crops for ethanol production in FASOM. In order for energy crops to be adopted widely, they need to provide high enough returns to farmers to induce them to switch from alternative land uses to energy crops.

For energy crops, assumed baseline yields per acre are based on Thomson et al.[175] for switchgrass and Walsh et al. for willow and hybrid poplar.[176] Switchgrass yields are assumed to increase over time at a rate of 2.04% per year, while yields for willow and hybrid poplar increase at a rate of 0.75% per year. It was assumed that switchgrass could potentially be produced in eight of the FASOM regions (Corn Belt, Great Plains, Lake States, Northeast, Rocky Mountains, South Central, Southeast, Southwest); willow could be produced in four regions (Corn Belt, Lake States, Northeast, Southeast); and hybrid poplar could be produced in eight regions, matching up with the regions for switchgrass except for the exclusion of the Rocky Mountains region and addition of the Pacific Northwest—East side region. Although it is technically possible for energy crops to be produced in each of these regions, they will only enter the market solution if they are competitive with alternative land uses available in those regions.[177]

Table D-7 presents regional average energy crop yields for the year 2022 for the three energy crops included in FASOM. Other things being equal, the higher the energy crop yield in a region, the more likely that energy crop will offer competitive returns to landowners. In all regions where switchgrass is included in FASOM as a production possibility, switchgrass has the

[175] Thomson, A.M., R.C. Izarrualde, T.O. West, D.J. Parrish, D.D. Tyler, and J.R. Williams. 2009. *Simulating Potential Switchgrass Production in the United States*. PNNL-19072. College Park, MD: Pacific Northwest National Laboratory.

[176] Walsh, M.E., D.G. de la Torre Ugarte, H. Shapouri, and S.P. Slinsky. 2003. "Bioenergy Crop Production in the United States: Potential Quantities, Land Use Changes, and Economic Impacts on the Agricultural Sector." *Environmental and Resource Economics* 24:313-333.

[177] To reflect constraints on land conversion that may not be fully captured within FASOM, energy crop penetration was limited to a maximum of 12.5% of cropland in each region.

highest potential yield among the energy crops included in the model. However, it is important to keep in mind that regions with high yields available for energy crops will also tend to have relatively high yields for competing crops. Thus, it is not necessarily the case that regions with the highest potential energy crop yields will be the regions that produce those crops in the model solution.

Unlike crop residues, where only a portion of the residues is removed based on the sustainably removable fractions described earlier, the entire yield of energy crops presented in Table D-8 can be harvested and used for cellulosic ethanol production.

Table D-7. Regional Average Energy Crop Yields (Dry Tons per Acre), 2022

Crop	CB	GP	LS	NE	PNWE	PSW	RM	SC	SE	SW
Hybrid poplar	3.7	3.0	3.5	3.1	4.6	NA	NA	3.3	3.2	3.0
Switchgrass	9.9	6.1	7.7	5.5	NA	NA	3.4	9.3	7.7	8.6
Willow	3.6	NA	3.6	3.7	NA	NA	NA	NA	3.5	NA

Note: CB = Corn Belt; GP = Great Plains; LS = Lake States; NE = Northeast; PNWE = Pacific Northwest—East side (agriculture only); PSW = Pacific Southwest; RM = Rocky Mountains; SC = South Central; SE = Southeast; SW = Southwest (agriculture only).

Table D-8. Ethanol Conversion Rates for Energy Crops, 2022

Energy Crop	Moisture (%)	Ethanol Conversion Rate (gallons/wet ton)	Ethanol Conversion Rate (gallons/dry ton)
Hybrid poplar	31.03%	70.00	101.50
Switchgrass	11.99%	81.23	92.30
Willow	33.33%	67.67	101.50

Source for ethanol conversion rate (gallons/dry ton): NREL (2008)

D.2.2.1 Ethanol Production from Energy Crops

Biomass from energy crops is converted to ethanol in FASOM using conversion rates that increase over time as discussed in Section D.4. Table D-8 summarizes the ethanol conversion values used for 2022. Using these conversion rates, the required supply for a 100 MGY plant was calculated for each feedstock (see Table D-1). For instance, an ethanol plant using switchgrass as a feedstock in 2022 would need 100 million gallons of ethanol per year divided by 92.3 gallons per dry ton of switchgrass = 1,083,424 dry tons of switchgrass per year (1,231,024 wet tons). With increases in the ethanol conversion rate over time, the quantity of feedstock required by an ethanol plant of a given output level declines commensurately.

D.2.2.2 Costs of Using Energy Crop Feedstocks

Similar to crop residues, the cost of acquiring energy crops as a feedstock (excluding hauling and off-farm handling) is determined by the market-clearing farm-level price for each energy crop commodity as estimated by FASOM. It is important to note that opportunity costs associated with energy crop production include not only the cost of harvesting the feedstock, but also crop production costs and the opportunity cost of land because it is a dedicated crop rather than residues associated with other crop production. Ethanol feedstock yields per acre are generally much higher for these crops than for residues, however. Thus, if feedstock prices reach high enough levels, energy crops become competitive with alternative land uses in some regions.

As is the case for crop residues, there is almost no market for energy crops in the Reference Case, but when a market is created under the Control Case, prices of these feedstocks increase substantially. Table D-9 summarizes the market prices for energy crops in FASOM under the Control Case in 2022. The only energy crop that enters the market solution under the Control Case is switchgrass, which is produced principally in the Southwest but also in the Northeast and Southeast. Although the ethanol conversion rate (gallons per dry ton) of switchgrass is lower than that of hybrid poplar or willow, switchgrass is assumed to have a higher crop density, higher crop yield per acre, and contains less moisture than hybrid poplar or willow (all of which tend to reduce hauling costs), which may help explain the market focus on switchgrass in the model.[178]

Table D-9. FASOM National Average Prices for Energy Crops (2007$/Dry Ton) in Control Case, 2022

Feedstock	Price (2007$/dry ton)
Switchgrass	$46.42

D.2.3 Logging and Processing Residues

Finally, FASOM also includes logging and processing residues as potential feedstocks for cellulosic ethanol production. This section outlines assumptions underlying the use of these residues for cellulosic ethanol production.

[178] Note that although switchgrass has a lower ethanol conversion rate per dry ton than the other energy crops considered, its ethanol conversion rate per wet ton is higher because moisture content of switchgrass is much less than that of hybrid poplar or willow.

D.2.3.1 Logging and Processing Residues Production

For logging residues, yields are generated by applying assumed logging residue percentages to FASOM data on round wood yields. Yields were averaged by FASOM market region using the FASOM forestry inventory data as weights. Two-thirds of the logging residue was assumed to be harvestable based on Helynen, Hakkila, and Nousiainen.[179] Logging residue yields in 1,000 cu ft per acre were then converted to tons per acre using 27.5 lbs per cu ft for softwood and 33.0 lbs per cu ft for hardwood based on Carpenter.[180]

Bagasse, milling residues, and sweet sorghum pulp are produced as coproducts of sugar, wood products, and sweet sorghum production in FASOM and depend on production of these products by region. Bagasse and milling residues are currently used on site for energy production in the sugar refining and the wood product and paper industries, so use of these products for ethanol production competes with those alternative uses.

D.2.3.2 Ethanol Production from Logging and Processing Residues

FASOM assumes improvements in conversion technology take place over time, as discussed in Section D.4. Biomass from logging and processing residues can be converted to ethanol in FASOM in the year 2022 using the conversion rates shown in Table D-10.

Table D-10. Ethanol Conversion Rates for Logging and Processing Residues, 2022

Residue	Moisture (%)	Ethanol Conversion Rate (gallons/wet ton)	Ethanol Conversion Rate (gallons/dry ton)
HW logging residue	33.33%	67.67	101.50
SW logging residue	33.33%	61.54	92.30
Bagasse	31.03%	63.66	92.30
HW milling residue	33.33%	67.67	101.50
SW milling residue	33.33%	61.54	92.30
Sweet sorghum pulp	35.00%	60.00	92.30

HW = Hardwood, SW = Soft Wood
Source for ethanol conversion rate (gallons/dry ton): NREL (2008)

Using these conversion rates, the required supply for a 100 MGY plant was calculated for each feedstock (see Table D-1). As with all of the other feedstocks, increases in ethanol

179 Helynen, S., P. Hakkila, and I. Nousiainen. 2000. "Wood Energy 1999-2003: A New National Technology Programme in Finland." *New Zealand Journal of Forestry Science* 1-2:46-53.

180 Carpenter, E.M. 1980. *Wood Fuel Potential from Harvested Areas in the Eastern United States*. U.S. Department of Agriculture Forest Service, Resource Bulletin NC-51, 14 p. St. Paul, MN: U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station.

conversion rates over time result in a reduction in the quantity of feedstock needed by an ethanol plant. This lowers hauling costs because the smaller quantity of feedstock required can be collected from a smaller area.

D.2.3.3 Costs of Using Logging and Processing Residues as Ethanol Feedstocks

The cost of acquiring logging and processing residues for ethanol production (excluding hauling and handling costs) includes opportunity costs associated with diverting processing residues from heat and power production to ethanol production. Unlike most of the other cellulosic feedstocks, the Reference Case includes markets for selected processing residues (bagasse and sweet sorghum pulp). However, the increase in demand associated with the Control Case results in large increases in prices.

Table D-11 summarizes the market prices for logging and processing residues in FASOM under the Reference and Control Cases in 2022.

Table D-11. FASOM National Average Prices for Processing Residues (2007$/Dry Ton) in the Reference and Control Cases, 2022

Feedstock	Reference Case Price (2007$/dry ton)	Control Case Price (2007$/dry ton)
HW logging residue	$0	$34.83
SW logging residue	$0	$27.55
Bagasse	$9.32	$43.06
Sweet sorghum pulp	$79.26	$115.45

Note: Prices are only included for those feedstocks and cases where the feedstock is used in ethanol production in the model solution.

D.3 Coproducts

The only coproduct of cellulosic ethanol production that is tracked within FASOM is lignin, which is calculated as a proportion of feedstock use that varies across feedstock types. For switchgrass, 26.4% of switchgrass volume is lignin; hybrid poplar 20.7%; willow, softwood, hardwood 20%; bagasse 28.5%; corn residue 22.2%; wheat residue 27.3%; sorghum and barley residue 27.0%; rice residue 25.5%; and sweet sorghum pulp 12.7%. Lignin production levels were derived from data in Kadam et al.[181] and Kadam[182]. Lignin can be used as a fuel for generating heat or could potentially be used for electricity generation.

[181]Kadam, K.L., V.J. Camobreco, B.E. Glazebrook, L.H. Forrest, W.A. Jacobson, D.C. Simeroth, W.J. Blackburn, and K.C. Nehoda. 1999. *Environmental Life Cycle Implications of Fuel Oxygenate Production from California*

FASOM includes electricity production using lignin as a production possibility. In FASOM budgets, 384,151 tons of lignin from crops, 329,567 tons of lignin from hardwoods, and 308,642 tons of lignin from softwoods are required by the standard 100 megawatt (MW) electricity generation plant included in FASOM. In addition, there are production possibilities in FASOM for co-firing with lignin at levels ranging from 5% to 20%.

D.4 Technology Change

One of the vital issues affecting the potential future large-scale adoption of cellulosic ethanol as a transportation fuel is the rate of technical change. Currently, cellulosic ethanol production is not cost competitive, but increases in ethanol conversion rates and feedstock yields could potentially help to make large-scale cellulosic ethanol production competitive with other fuels. The cost of feedstock per unit over time will depend on market forces, but the quantity required to produce a given amount of ethanol is expected to decline over time with improvements in ethanol conversion technology, which will tend to reduce feedstock costs per gallon. The reduction in the quantity of feedstock needed to meet the EISA volume requirement over time (due to increasing cellulosic ethanol yields) will tend to reduce the demand for these feedstocks and is expected to contribute to lower feedstock prices farther into the future, other things being equal. As less feedstock is required per gallon of ethanol, hauling and handling costs will also tend to decline because less feedstock needs to be hauled and handled. In addition, the plant can acquire the necessary quantity of feedstock from fewer acres so average hauling distance declines. The assumed increase in feedstock yields over time also contributes to these cost reductions by reducing average hauling distance and cost. Finally, the cost of processing delivered feedstock into ethanol at the plant was also assumed to decrease over time based on data presented in the RIA for this rule.

Baseline values for ethanol yield for all feedstocks were based on data from a study conducted by NREL.[183] These yields were then increased over time until reaching the maximum feasible ethanol conversion rates assumed for each feedstock based on the work at NREL. After reaching that maximum yield, yields are assumed to remain constant at that level in subsequent

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Biomass. Golden, CO: National Renewable Energy Laboratory. Available at http://www.nrel.gov/docs/fy99osti/25688.pdf.

[182] Kadam, K.L. 2000. *Environmental Life Cycle Implications of Using Bagasse Derived Ethanol as a Gasoline Oxygenate in Mumbai*. NREL/TP-580-28705. U.S. Department of Energy, National Renewable Energy Laboratory.

[183] Tao, L. and A. Aden, *Technoeconomic Modeling to Support the EPA Notice of Proposed Rulemaking (NOPR),* November 2008.

years. The rates at which ethanol yields for different feedstocks are assumed to progress towards their maximum levels were assumed to be the same for all feedstocks.

Figures D-1 and D-2 show the ethanol yield per dry ton and corresponding feedstock quantity requirements for crop residues over time. Figures D-3 and D-4 present analogous yield and feedstock quantity information for energy crops, and Figures D-5 and D-6 provide this information for logging and processing residues. As described above, the time frame at which the yield from a particular feedstock is assumed to reach its maximum is the same across all feedstocks considered, with each cellulosic feedstock reaching its maximum level in the 2022 FASOM model period. The magnitude of reductions in feedstock quantity required over time are an important factor affecting the costs of cellulosic ethanol production in FASOM over time.

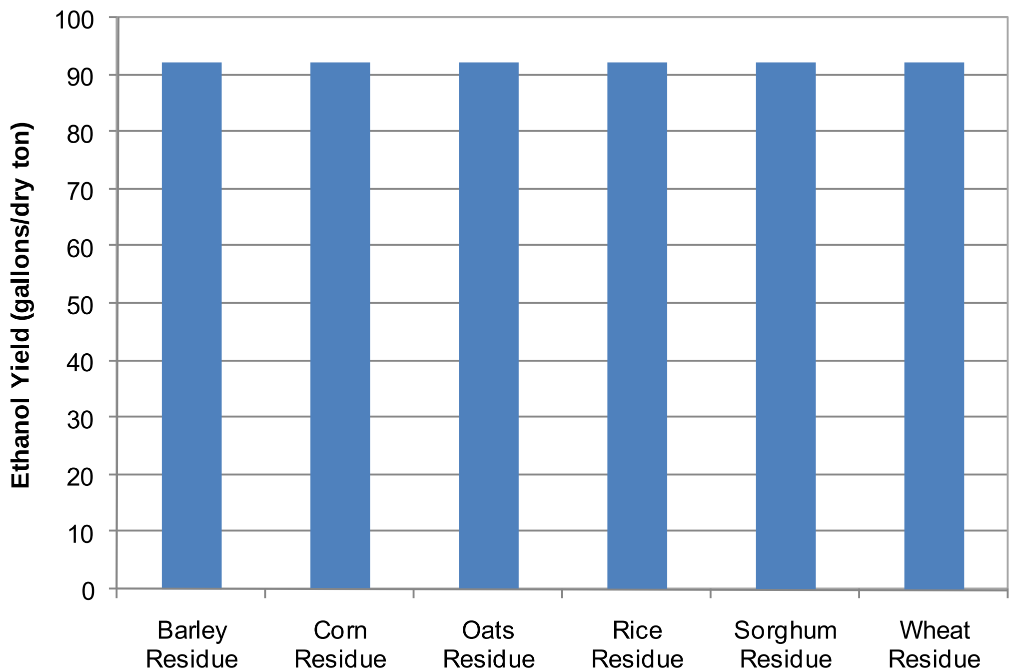

Figure D-1. Ethanol Yield per Dry Ton from Crop Residues, 2022

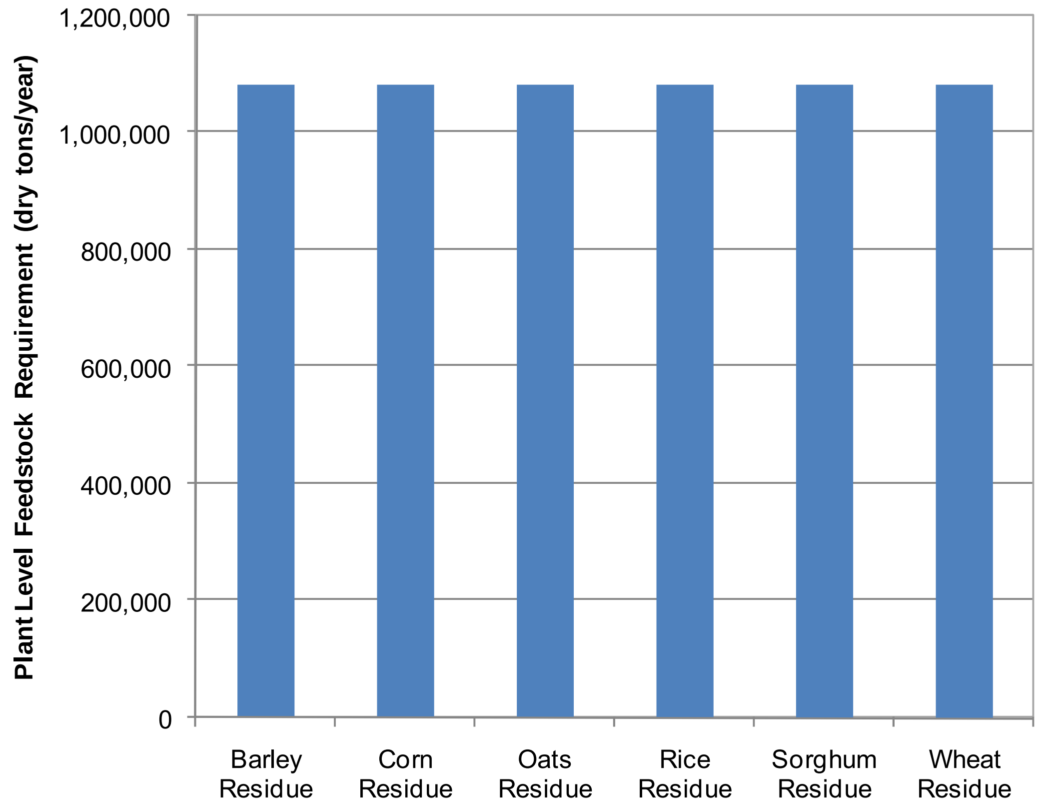

Figure D-2. Dry Tons of Crop Residue Feedstocks Required for a 100 MGY Ethanol Production Plant, 2022

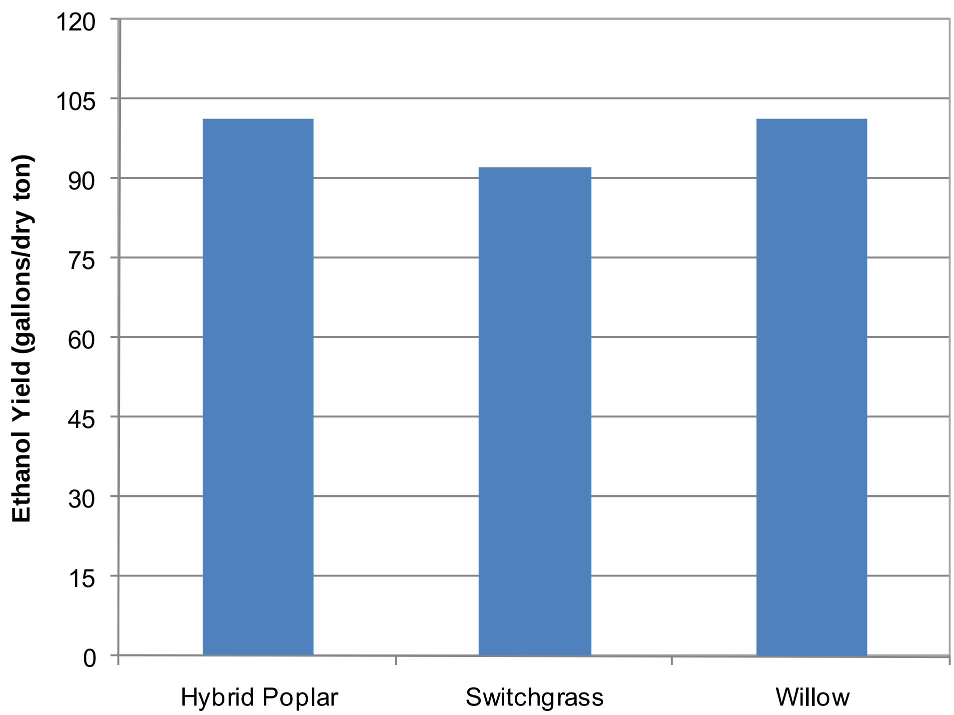

Figure D-3. Ethanol Yield per Dry Ton from Energy Crops, 2022

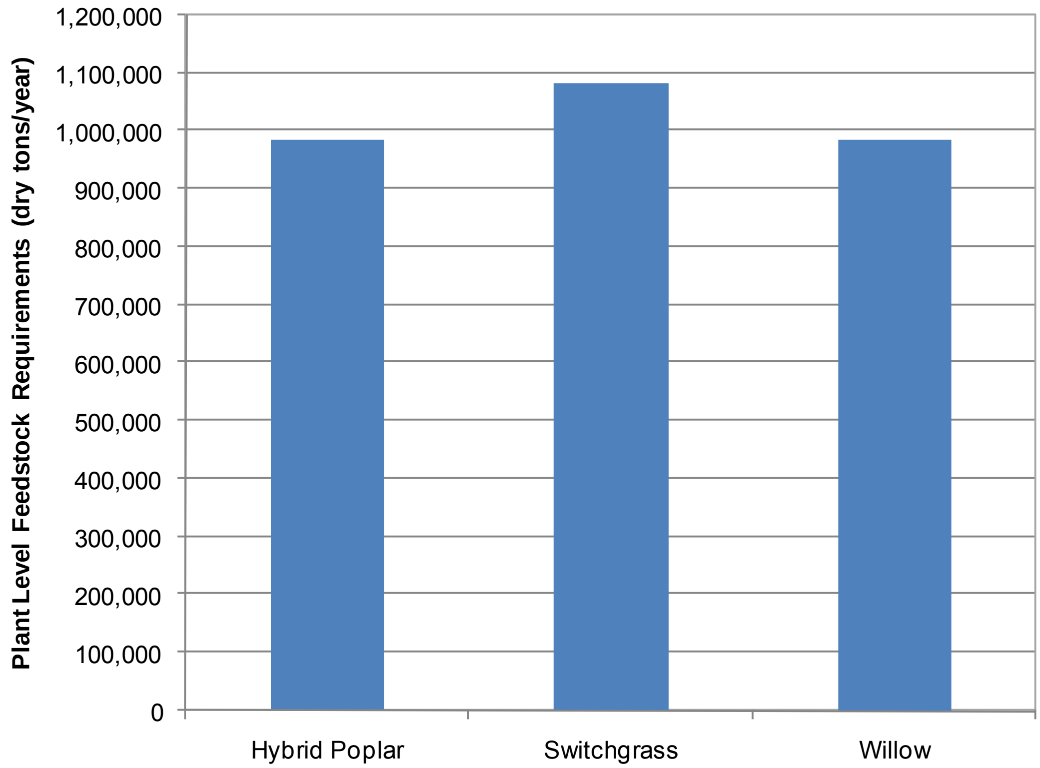

Figure D-4. Dry Tons of Energy Crop Feedstocks Required for a 100 MGY Ethanol Production Plant, 2022

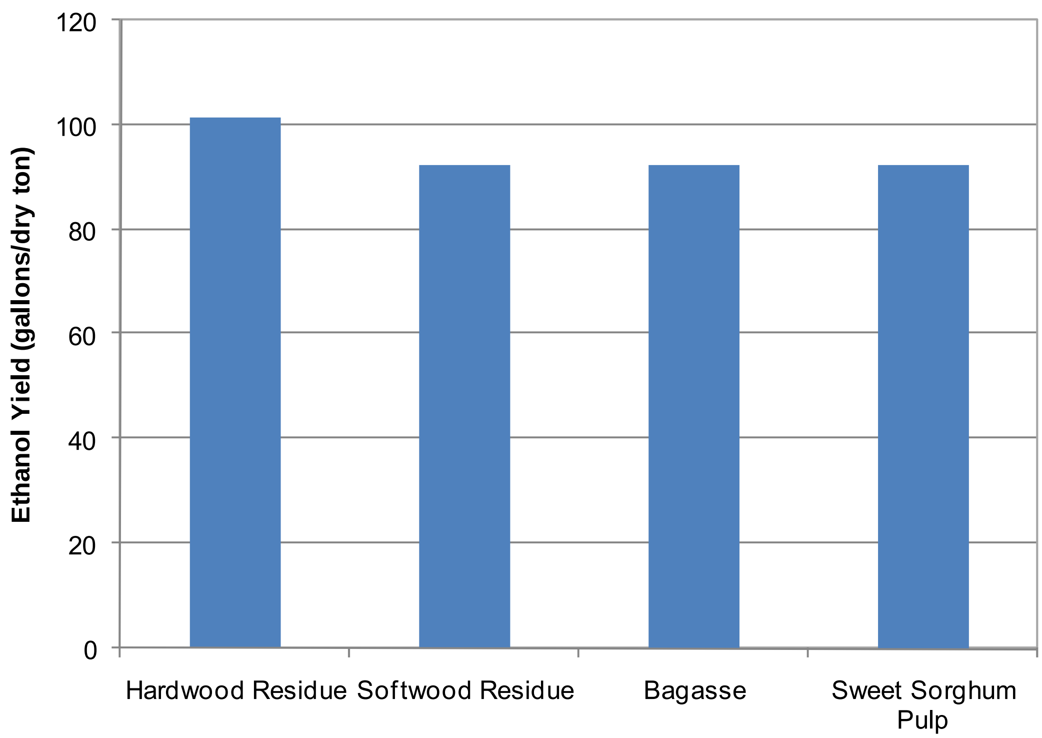

Figure D-5. Ethanol Yield per Dry Ton from Logging and Processing Residues, 2022

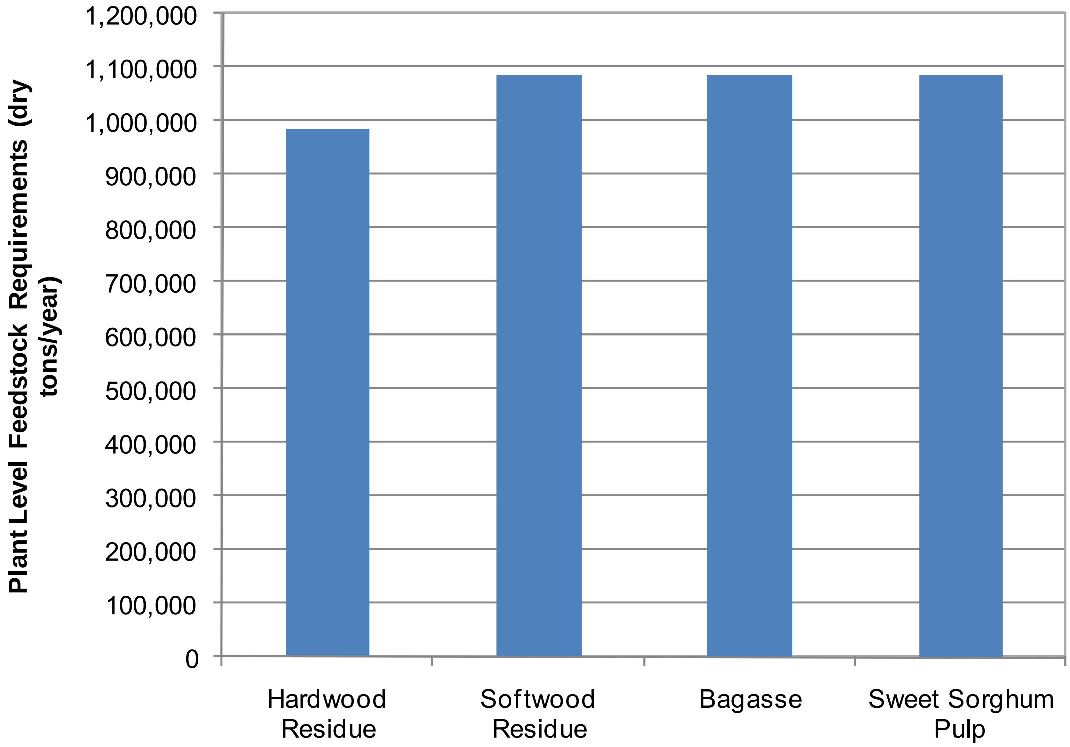

Figure D-6. Dry Tons of Logging and Processing Residue Feedstocks Required for a 100 MGY Ethanol Production Plant, 2022

Increases in feedstock yields also contribute to reductions in production costs. Table D-12 summarizes changes in yield over time for cellulosic feedstocks. Changes are presented as an index relative to the year 2002. Although initial yields differ across FASOM regions, the percentage change in yield for a given crop is assumed to be the same in each region.

In addition to these productivity increases putting downward pressure on cellulosic ethanol production costs, the assumed costs of converting delivered feedstock to ethanol are decreasing over time between 2007 and 2022, then remain constant at the 2022 level in later years.

Table D-12. Cellulosic Feedstock Yield Index (Change in Tons of Feedstock per Acre), 2022 (2002 = 100)

Feedstock	2022
Crop Residues	
Barley crop residues	101.9
Corn crop residues	138.0
Oat crop residues	100.3
Rice crop residues	130.3
Sorghum crop residues	101.8
Wheat crop residues	129.7
Energy Crops	
Hybrid poplar	116.0
Switchgrass	149.8
Willow	116.0
Logging Residues	
Hardwood logging residues	138.0
Softwood logging residues	138.0
Processing Residues	
Bagasse	100.1
Hardwood milling residues	138.0
Softwood milling residues	138.0
Sweet sorghum pulp	101.8

D.5 Agricultural Market Impacts

FASOM tracks the impacts on agricultural markets associated with changing production practices to collect crop residues, produce energy crops, collect logging residues, and to begin using or diverting processing residues from production of heat and power to ethanol. The large-scale production of energy crops could have substantial implications for land use and production of food products, but returns to those crops must exceed the opportunity costs of land for producers to switch to production of energy crops. When the alternative feedstock source involves collecting residues on land that can be used for primary production of grains, energy crop production is generally less attractive unless these crops could be grown at high density around ethanol plants in regions where the opportunity costs of land are low.

Crop residues could potentially be used for grazing in cow-calf operations or as livestock bedding and provide some value as a fertilizer due to potash, potassium, and nitrogen content. However, the opportunity cost of retaining these residues in other uses is relatively low. In FASOM, there are crop budgets both with and without residue collection for barley, corn, oats, rice, sorghum, and wheat. As described earlier, the primary difference between the budgets with and without residue collection is that additional fertilizer is required if residues are removed. Using the baseline FASOM fertilizer prices of $0.293 per pound for nitrogen fertilizer and $0.309 per pound for phosphorus fertilizer,[184] the additional fertilizer costs for these nutrients would be about $3.16 per ton of residues removed. In addition, there are costs of harvesting, baling, and moving the residue to the roadside at the farm. Crop yields and other input uses are assumed to be the same with and without residue collection. Thus, as long as the market prices for crop residues are equal to or higher than the sum of these opportunity costs, farmers in FASOM will choose to switch from production without residue collection to production with residue collection.

For cellulosic ethanol production in FASOM, all feedstocks have the same processing costs per gallon to convert delivered feedstock to ethanol. In addition, handling costs per wet ton are assumed to be equal across all crop residues and energy crops. Because there are some differences in energy content per wet ton, feedstocks with higher energy content per ton have lower handling costs per gallon of ethanol produced, but these costs tend to be fairly close across feedstocks. Thus, the allocation between feedstocks purchased by an ethanol plant rests largely on the differences in feedstock costs and biomass hauling costs. As noted above, residue removal from land where traditional crops can be produced as well will tend to have lower opportunity costs than devoting land to energy crops. Regions where there are few attractive alternative crops and energy crops can be grown at very high density surrounding an ethanol production plant would provide the greatest potential for energy crop production. Otherwise, ethanol production will tend to be concentrated in the regions where large quantities of crop residues are available at high density. In FASOM, the density of energy crops is assumed to be 10% for all regions where production of those crops is feasible (and adjusted density is lower for hybrid poplar and willow because of the multiple-year harvesting cycle). Consistent with these expectations, FASOM results for the Control Case show the majority of cellulosic ethanol feedstocks coming from corn residues in the Corn Belt, Great Plains, and Lake States regions and switchgrass in the Southcentral, Southwest, and Southeast regions as well as Kansas and Missouri.

[184] See: http://www.ers.usda.gov/Data/FertilizerUse/Tables/Table7.xls (values have been adjusted to 2007$).

Because there is such a large quantity of residue available at relatively low cost, a large amount of land in FASOM is reallocated from crop production without residue collection to crop production with residue collection, especially in the Corn Belt, Great Plains, and Lake States regions. Because more residue can be removed from no-till acres, if the price of residues is high enough, it could induce switching from conventional tillage to conservation tillage or no-till. However, there is relatively little change in tillage in FASOM model results for the Control Case. The switch from production without residue collection to crop production with residue collection in FASOM is much more pronounced. This implies that in the regions where ethanol production from crop residues is concentrated, many farmers begin collecting residues where they did not under baseline conditions, potentially with little change in other aspects of their production practices (e.g., tillage, irrigation).

Because FASOM assumes there are no effects on crop yields or input uses other than fertilizer associated with residue collection in the Control Case, agricultural market impacts of cellulosic ethanol production from crop residues are relatively small. There may be sizable impacts on sectors such as the custom baling and transportation sectors associated with introducing a large-scale market for collecting and transporting crop residues to ethanol production plants. However, these sectors are not included within the FASOM model. The sizable production from switchgrass has larger market effects, resulting in a reallocation of land toward switchgrass production and contributing to an increase in land values and commodity prices.

APPENDIX E:
HIGH YIELD SENSITIVITY SCENARIO

One important assumption influencing the amount of land required to produce sufficient feedstocks to meet the required EISA renewable fuels volumes is the rate of increase in crop yields over time. The greater the rate of increase in crop yields, the less land that will required over time to provide the feedstock necessary to meet the volume requirements. In addition to analyzing the impacts of the Control Case relative to the Reference Case under a primary set of key assumptions, FASOM was used to analyze the effects of increasing the rates of increase for two key crops, corn and soybeans. In this appendix, we present selected key 2022 results for the High Yield Sensitivity Scenario. Our comparisons focus on the impacts on U.S. harvested acres by crop; prices for corn, soybeans, and switchgrass; and corn and soybean exports across scenarios. This sensitivity analysis enables examination of the implications of higher crop yields for the modeled impacts of the renewable fuel volumes required by EISA.

E.1 Specification of High-Yield Sensitivity Scenario

For the High Yield Sensitivity Scenario, the yields of both corn and soybeans were assumed to increase at faster rates than assumed in Section 2. These higher yield growth rates were applied to both the Reference Case and Control Case, with the impacts associated with EISA requirements for a particular scenario based on the differences between those cases. Therefore, the impacts being measured in this scenario are the incremental effects of EISA if corn yields grow at a faster rate than assumed in the Base Reference and Control Scenarios described in Section 2. The reason that corn yields are increased in both the Reference and Control Cases is that we are not assuming in this sensitivity analysis that EISA would lead to faster increases in corn productivity, but that the impacts may differ if corn yields were to increase more rapidly over time than assumed in the Base Scenario presented in Section 2.

This increase in the technological rate of progress begins in the 2012 model period in the FASOM model (the next future time period). By 2012, national average corn yields in the U.S. are 7.9 percent higher in the High Yield Control Case than in the Base Yield Control Case. By 2017, they are 16.2 percent higher, and by 2022 they are 24.6 percent higher. Similarly, soybean yields in the U.S. are 10.1 percent higher in 2012, 21.0 percent higher in 2017, and 32.6 percent higher in 2022 in the High Yield Control Case than in the Base Yield Control Case.[1] Similar

[1] Corn yields in individual FASOM regions are all increased by 7%, 17%, and 27% in 2012, 2017, and 2022, respectively. Similarly, soybean yields in individual FASOM regions are all increased by 7%, 19%, and 30% in 2012, 2017, and 2022, respectively. However, because some regions have higher yields than others and the

increases in technological rates of progress for corn and soybeans were applied to the export supply functions for non-U.S. corn and soybean exporters. Table E-1 summarizes the differences in average corn and soybean yields at the national level.

Table E-1. U.S. Average Yields (Bushels per Acre) for Corn and Soybeans for the Control Case under the Base and High Yield Sensitivity Scenarios, 2022

Crop	Base Scenario	High Yield Sensitivity Scenario	Change	Percentage Change
Corn	185.1	232.9	47.8	25.8%
Soybeans	45.4	60.2	14.8	32.6%

In the following subsection, we present comparisons of the FASOM results generated for the High Yield Sensitivity Scenario to those from the Base Scenario, focusing on impacts on crop acreage, commodity prices, and exports.

E.2 Comparison of Acreage, Prices, and Exports

Although the assumptions employed in the Base Scenario were selected as reasonable estimates of future conditions, a number of uncertainties are associated with projecting values far into the future. Increases in yield over time can mitigate competition for land and increases in agricultural commodity prices because more output is being produced per acre of land. To the extent that corn yields increase at a faster rate than assumed in the Base Scenario, there will be less future competition for land and a reduction in the upward pressure on agricultural commodity prices.

E.2.1 Sensitivity Analysis Results for Harvested Acreage

Figure E-1 summarizes the harvested area for U.S. crops in the Reference Case under the Base and High Yield Sensitivity Scenarios. The biggest differences between the Scenarios considered are the reductions in corn and soybean acreage as their yields increase and fewer acres are required to meet market demand for these commodities.

regional allocation of production across regions changes under this scenario, the weighted average national yields do not increase at exactly the same rate as the increases applied to each individual region.

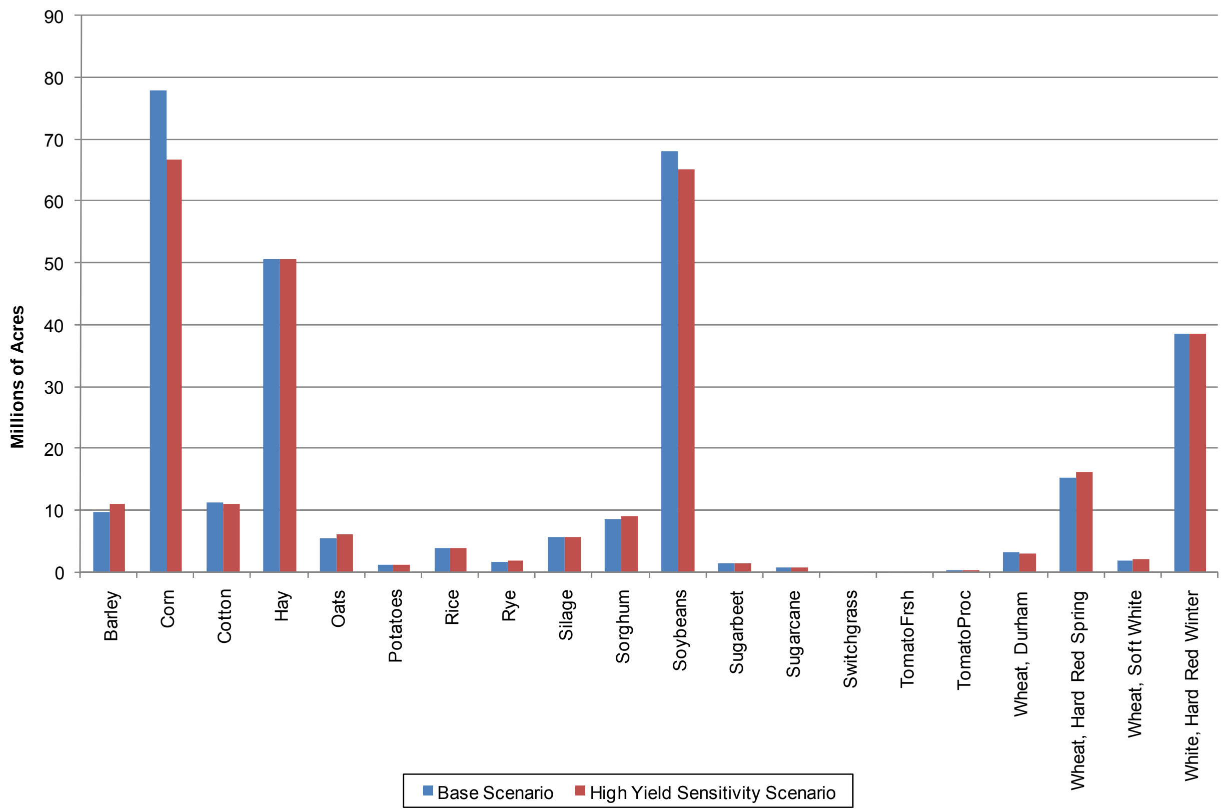

Figure E-1. U.S. Harvested Acreage by Crop for the Reference Case under the Base and High Yield Sensitivity Scenarios, 2022

Figure E-2 shows the change between the Reference and Control Cases for 2022 harvested acreage for U.S. crops simulated using FASOM under both Base and High Yield Sensitivity Scenario assumptions. The biggest difference is that the increase in switchgrass acres for the High Yield Sensitivity Scenario is less than half the increase experienced under the Base Scenario. In addition, corn acreage increases more and soybean acreage decreases less under the High Yield Sensitivity Scenario. At higher corn yields, there is also greater production of corn stover per acre. As a result, the use of corn residues as a cellulosic ethanol feedstock almost doubles in the High Yield Sensitivity Scenario, while the use of switchgrass declines by nearly 60%. In general, there are smaller declines in acreage for crops other than corn and soybeans under the High Yield Sensitivity Scenario because less land is required for renewable fuels feedstock production with higher yields.

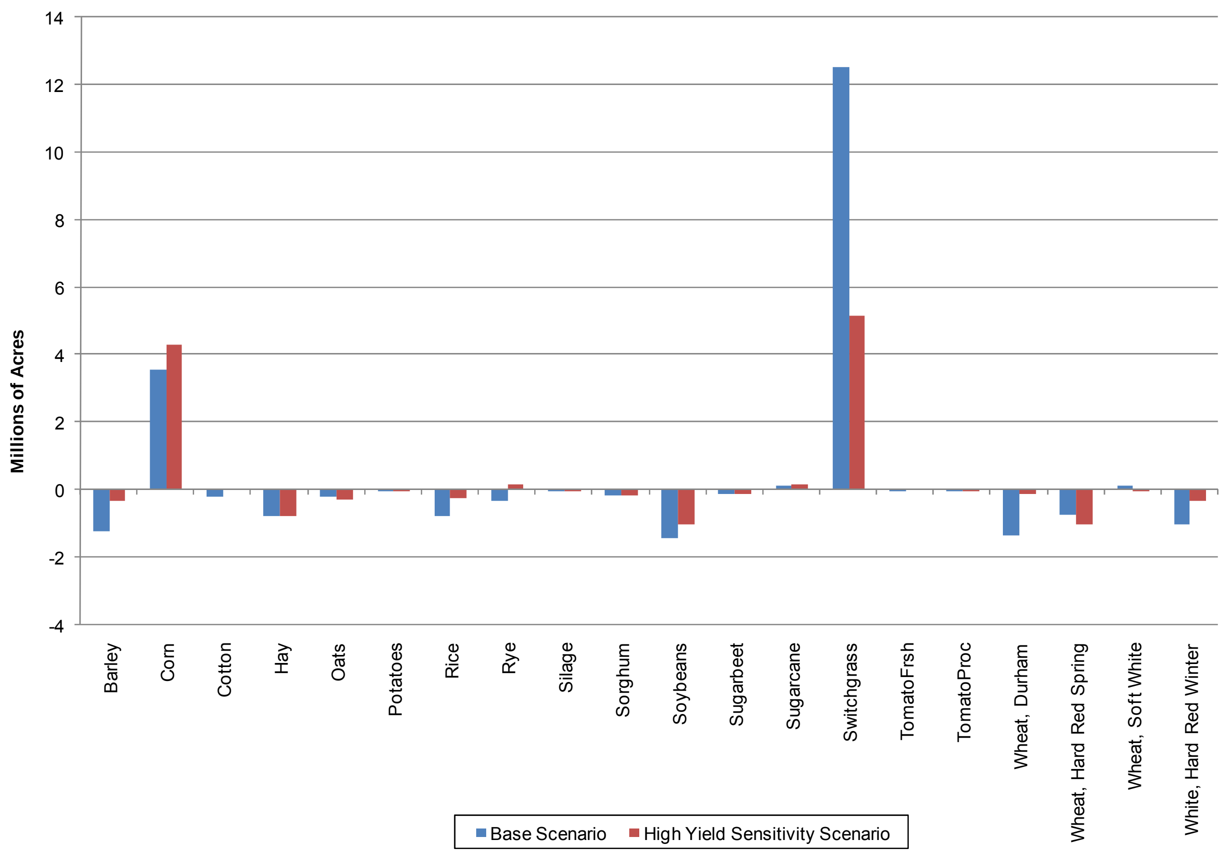

Figure E-2. Change in U.S. Harvested Acreage between the Reference Case and the Control Case for the Base and High Yield Sensitivity Scenarios, 2022

Similarly, there is less land conversion from pasture and forest under the High Yield Sensitivity Scenario. As shown in Table E-2, total harvested cropland in 2022 under the Reference Case is reduced by about 11 million acres in the High Yield Sensitivity Scenario. In addition, meeting the EISA renewable fuels volume targets requires an increase in harvested cropland that is 2.7 million acres less under the High Yield Sensitivity Scenario, resulting in a total of 13.7 million acres less harvested cropland under the Control Case for the High Yield Sensitivity Scenario than the Base Scenario.

As expected, there are substantial differences in U.S. land allocation if the yields for corn and soybeans are increased at a substantially higher rate. Not only are corn and soybeans two of the most important U.S. crops, but they also provide key feedstocks for renewable fuels production. When corn and soybeans have higher yields, the market equilibrium simulated in FASOM has less acreage in these crops, other things being equal. There are competing effects in this case because a higher rate of technical progress increases corn and soybean production per

Table E-2. Total Harvested Cropland under the Base and High Yield Sensitivity Scenarios, 2022

	Reference Case	Control Case	Change	Percentage Change
Base Scenario	306,279	314,385	8,106	2.6%
High Yield Sensitivity Scenario	295,243	300,678	5,435	1.8%
Difference between High Yield and Base Scenarios	−11,036	−13,707	−2,671	
Percentage Change	−3.6%	−4.4%	−33.0%	

acre, which would tend to increase the returns to production and draw more acreage into these crops. However, increased production per acre will reduce the number of acres needed to meet the demand for corn, and prices fall until corn and soybean acreage have decreased sufficiently to equilibrate supply and demand. In this case, we see that the net effect of higher yields is to reduce equilibrium harvested acreage.

E.2.2 Sensitivity Analysis Results for Prices of Key Renewable Fuels Feedstocks

In Table E-3, we present a comparison of FASOM model results for equilibrium U.S. corn, corn residues, soybean, and switchgrass prices (largest sources of feedstocks for renewable fuels) under the Reference Case and Control Case simulated for both the Base and High Yield Sensitivity Scenarios. The prices of these commodities increase when EISA requirements are introduced in every case with the exception of corn prices under the High Yield Sensitivity Scenario. Given the increase in demand for these feedstocks associated with EISA in order to increase ethanol production, increasing prices are entirely consistent with expectations. For corn under the High Yield Sensitivity Scenario, with less land in crops and lower commodity prices, the development of a market for corn stover increases the returns for planting corn relative to alternative crops sufficiently that corn acreage and production actually increase enough relative to the increased demand for corn due to EISA that equilibrium corn prices fall by 4.2%.

As expected, equilibrium prices are lower in the Reference Case under the High Yield Sensitivity Scenario. In addition, price increases required to induce sufficient feedstock production to meet EISA volume requirements are smaller under the High Yield Sensitivity Scenario. In fact, we observe that corn acreage and production will increase enough to meet demand even with a decrease in corn price. Under this scenario, substantially higher yields for corn and soybeans result in lower agricultural commodity prices and land values in the Reference Case. With these market conditions, the development of a market for corn residues in the

Table E-3. Changes in Simulated Market Prices for Corn, Soybeans, and Switchgrass between the Reference and Control Cases under the Base and High Yield Sensitivity Scenarios, 2022 (2007$)

	Reference Case	Control Case	Change	Percentage Change
Base Scenario				
Corn ($/bu)	$3.32	$3.60	$0.27	8.2%
Corn residues ($/dry ton)	NA	$34.49	$34.49	NA
Soybeans ($/bu)	$9.85	$10.87	$1.02	10.3%
Switchgrass ($/dry ton)	NA	$37.22	$37.22	NA
High Yield Sensitivity Scenario				
Corn ($/bu)	$2.74	$2.62	−$0.12	−4.2%
Corn residues ($/dry ton)	NA	$21.34	$21.34	NA
Soybeans ($/bu)	$7.69	$8.44	$0.24	2.9%
Switchgrass ($/dry ton)	NA	$32.66	$32.66	NA

Control Case increases the returns to corn production (and the corn residue coproduct) relative to alternative crops enough to make corn production relatively more attractive than alternative crops even though the expanded production leads to a decline in the price of corn. With higher yields, less additional corn acreage is needed to produce enough feedstock to meet the renewable fuels volume requirements of EISA, but the increase in corn acreage is larger in the High Yield Sensitivity Scenario than the Base Scenario. The supply of corn increases more than the demand for corn under the High Yield Sensitivity Scenario as the value of corn residues provides enough net income to induce greater switching towards corn in this scenario with lower commodity prices, resulting in a decrease in the equilibrium price of corn. Not surprisingly, one of the implications of this sensitivity analysis is that the faster corn productivity increases over time, the smaller the adjustments required to meet the increased demand for corn under EISA.

E.2.3 Sensitivity Analysis Results for Selected Exports

Table E-4 compares model results for exports of key commodities most directly affected by expanded volume requirements for renewable fuels. With higher yields for corn and soybeans, the model results show an increase in corn exports under the High Yield Sensitivity Scenario. Exports of soybeans are lower as domestic soybean processing expands even more than soybean production, resulting in a large increase in domestic soybean oil production and

Table E-4. Changes in Simulated Exports for Corn, Soybeans, and Soybean Oil between the Reference and Control Cases under the Base and High Yield Sensitivity Scenarios, 2022

	Reference Case	Control Case	Change	Percentage Change
Base Scenario				
Corn (million bu)	2,281.4	2,093.4	−187.9	−8.2%
Soybeans (million bu)	993.2	858.5	−134.7	−13.6%
Soybean oil (million tons)	2.3	1.1	−1.2	−51.2%
High Yield Sensitivity Scenario				
Corn (million bu)	2,690.9	2,812.9	122.0	4.5%
Soybeans (million bu)	896.1	839.0	−57.2	−6.4%
Soybean oil (million tons)	7.0	5.0	−2.1	−29.6%

soybean oil exports that are more than three times as high in the High Yield Sensitivity Scenario under the Reference Case.

As described above, the High Yield Sensitivity Scenario leads to a greater expansion in corn acreage and production than the Base Scenario because land values and commodity prices are substantially lower and the relative impact of revenue from corn residues is higher. As a result, the development of a market for corn residues increases the returns to corn production to the point that corn supply increases more than the increase in domestic demand associated with EISA renewable fuels volume requirements and exports of corn increase. Soybeans do not have a similar coproduct used for cellulosic ethanol production. Thus, exports of soybeans and soybean oil decline as the domestic demand for soybean oil for use in biodiesel production increases more than the increase in domestic production of soybeans and soybean oil. However, the percentage decline in exports is much smaller under the High Yield Sensitivity Scenario.