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ENERGY INSTITUTE

Balancing the Benefits of Biofuels

THE ECONOMICS OF U.S. CROP-BASED
FUEL PRODUCTION

JULY 2024





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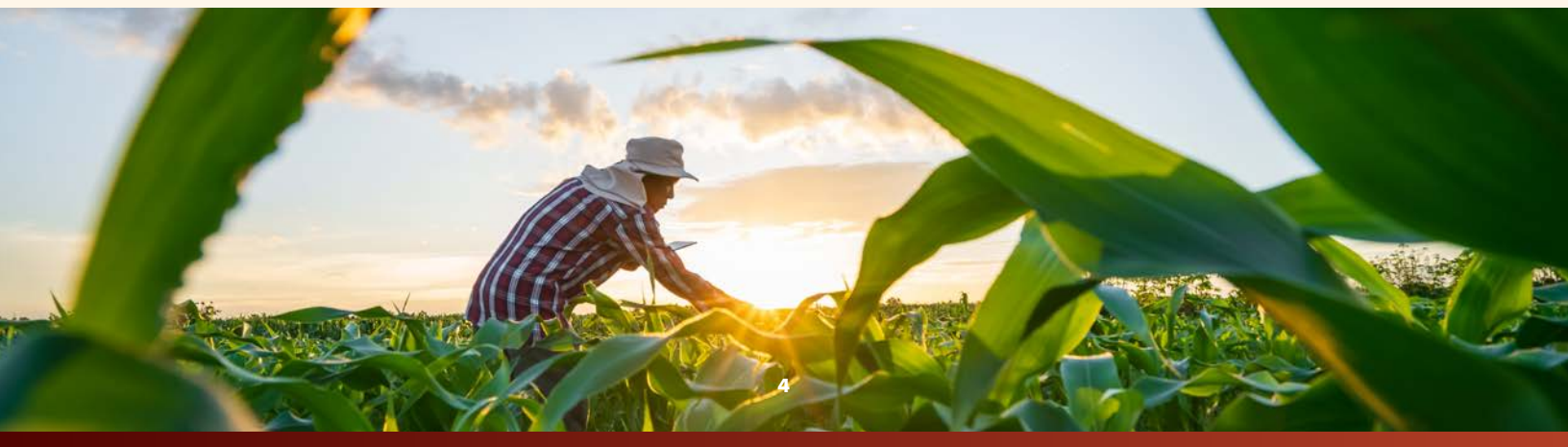
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Executive Summary

Balancing the Benefits of Biofuels: The Economics of U.S. Crop-Based Fuel Production

Biofuels possess great potential to contribute to a lower-carbon transportation sector, yet questions remain regarding the overall economic and environmental impact of the industry. While biofuels are produced from a wide range of feedstocks, those produced from crop-based feedstocks raise the most questions due to potential conflict with the use of those same crops for food and livestock feed. In this report, we evaluate the economics and impacts of crop-based biofuels production.

In **section 1**, we provide an overview of the biofuels landscape in the U.S. at present. Ethanol, biodiesel (BD), and renewable diesel (RD) combined make up more than 99% of all U.S. production; hence, this report focuses on these primary biofuels. The market for sustainable aviation fuel (SAF) is in a nascent state as of this writing. We anticipate that with sufficient policy support, SAF will grow over the coming decades and compete for the same feedstocks utilized for ethanol, BD, and RD. The magnitude of

the policy incentives and associated rate of growth in SAF production is a public policy decision that we do not attempt to forecast in this report. The specific policy enactments will impact the extent to which this results in changing the utilization of the feedstocks covered by this outlook versus simply increasing the demand for those same feedstocks. As these markets evolve, we expect the analysis laid out herein to evolve as well.

Section 2 is dedicated to explaining the current landscape of feedstock production. The primary crop-based feedstocks used to produce ethanol, BD, RD, and SAF in the U.S. are corn, soybeans, and canola. While biofuel feedstock acreage jumped sharply between 2010 (the first year of the current federal Renewable Fuel Standard [RFS] program)¹ and 2011, since then, the acreage requirement has been relatively steady, between 40 and 47 million acres per year (average 44.3 million acres). Additionally, per-acre yields of each of the primary biofuel's feedstocks have been growing steadily over time; the cumulative effect of these trends is that the supply of these feedstocks has grown more rapidly than the acreage dedicated to these crops. Key factors contributing to this steady growth in yields are regular improvements in seeds as well as adoption of improved agronomic practices by the many individual farmers growing these crops.

¹ The original RFS was established by the Energy Policy Act of 2005 (PL 109-58), enacted on August 8, 2005. The RFS was significantly expanded and modified into its current form (RFS2) by the Energy Independence and Security Act of 2007 (PL 110-140), enacted on December 19, 2007.

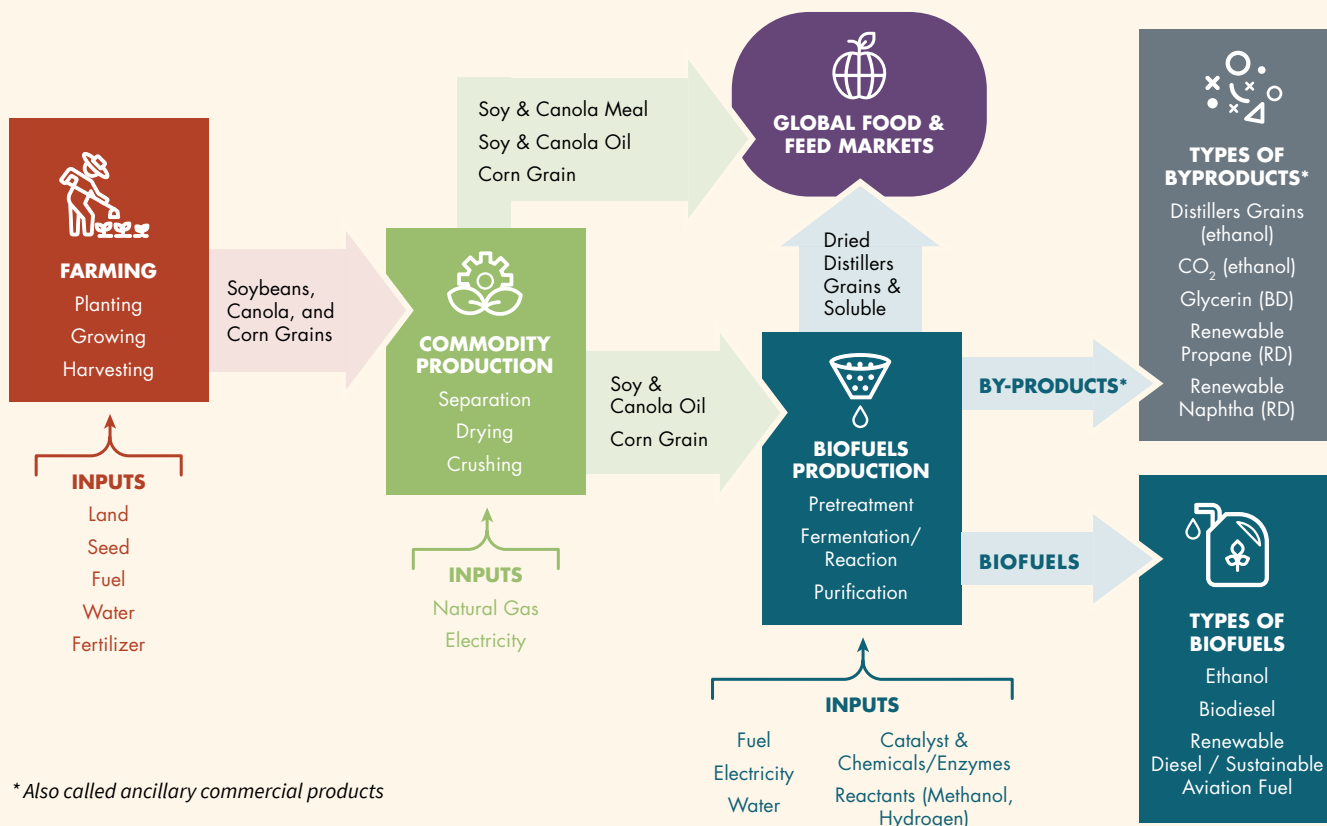
Biofuel production efficiency has also increased over the past decade. The U.S. Energy Information Administration (EIA) in their 2023 Annual Energy Outlook² expects 2024 to be the near-term peak for U.S. ethanol, BD, and RD production—and therefore also for feedstock demand—given the federal and state incentive programs in place in the fall of 2022. Considering potential regulations needed to implement the SAF Grand Challenge,³ low-carbon fuel (LCF) programs proposed in several state legislatures, and emerging international interest in decarbonizing marine transport, there is strong reason to believe that U.S. demand for biofuels could keep growing well beyond 2024.

The portion of the agriculture sector that produces feedstocks for biofuels also supplies the global food and feed market, which is much larger than the

biofuel feedstock market. [Figure ES-1](#) provides an overview of the flow of crop-based feed, food, and fuel production. Understanding the interdependent relationships of these markets is key to understanding the economics and impacts of the biofuels industry in the U.S.


In **section 3** we explain the inputs into biofuels production, broken down into two primary components: feedstock production and feedstock conversion to biofuel. Feedstock costs account for the majority of the cost of producing biofuels, while conversion costs account for most of the remainder. Costs for transporting feedstocks to production plants and biofuels to market are also a factor, but they are small relative to feedstock production and conversion to biofuels.

FIGURE ES-1. PROGRESSION OF FEED, FOOD, AND FUEL PRODUCTION FROM SOY, CANOLA, AND CORN



2 EIA | Annual Energy Outlook 2023

3 U.S. Department of Energy | Sustainable Aviation Fuel Grand Challenge



Per-acre yields of each of the primary biofuel's feedstocks have been growing steadily over time; the cumulative effect of these trends is that the supply of these feedstocks has grown more rapidly than the acreage dedicated to these crops.

In **section 4** we cover the co-products (also referred to as by-products or ancillary commercial products) of each of the biofuels conversion processes. For ethanol, the co-products are carbon dioxide, corn or grain sorghum oil, and distillers grains. The primary co-product from the BD conversion process is crude glycerol. The co-products from the only currently commercialized refining process for production of RD and SAF are renewable fuel gas, renewable propane, and renewable naphtha.

In **section 5** we delve into the production costs of biofuels; these can be broken into the feedstock production costs and feedstock conversion costs. The feedstock production costs can be viewed as the costs to produce the commodity grain or oil that is converted to biofuel. Biofuel feedstocks—commodity grains and oilseeds—are primarily produced as food and animal feed, and these food

and feed markets are the drivers for pricing of these commodities. Thus, the cost of producing the feedstocks is not directly a cost of biofuels production, as the commodity price sets the cost of feedstock to the biofuel industry.

In **section 6** we wade into the food versus fuel debate. Overall demand for food, both in the U.S. and globally, is set primarily by growth in population and secondarily by economic growth. How that overall food demand translates into demand for corn, grain sorghum,⁴ soybeans, and canola will also be dependent on trends in food preferences (e.g., preference for meat versus vegetables in the diet), which are difficult to predict and outside the scope of this report. The impact of the production of corn ethanol on food prices and indirect land use change was more significant in the early years of the RFS than in the long run. These effects were exacerbated

⁴ Grain sorghum is not typically used as human food; its dominant use is as livestock feed.

by other factors, including low crop stocks, high energy prices, and growing overseas demand for food. Agricultural supply responded to higher prices by increasing productivity, inducing more double-cropping, and changing the mix of crops; U.S. crop acres have decreased over time, but acres dedicated to corn and soy have become a larger share of the mix. The mix of livestock products demanded over time has also changed. In the long run, the demand and supply of agricultural commodities tends to be more elastic, and this has helped mitigate the food versus fuel effects.



In **section 7**, we highlight the impacts of policy on the feedstock and biofuels sectors. A combination of factors—including the RFS, tax credits, the methyl tert-butyl ether (MTBE) ban, and oil prices—have contributed to the expansion in biofuel production in the U.S., while LCF programs have resulted in increased demand for these fuels and a decrease in the carbon intensity (CI) of transportation fuel in their jurisdictions. Such policies have resulted in very large shares of corn and soybeans used in the fuel production process also yielding food and livestock feed. Several broad conclusions can be drawn from this review.

Section 8 offers a few conclusions and key findings from this analysis. We find that there is significant potential to lower the CI of corn ethanol by adopting climate-smart practices for crop production, such as increasing the efficiency of nitrogen fertilizer use, reducing use of fossil energy for crop production, and increasing soil carbon sequestration. Positive environmental opportunities could be supported if policies to address climate change could take into consideration environmental impacts across agencies and sectors, just as those factors are considered in the transportation sector. In order to incentivize continued carbon reductions in the agricultural side of the equation, for example, regulators might consider establishing a mechanism for biofuel producers to earn credit from improved feedstock production processes that will increase the climate change and environmental benefits of biofuels. Government policies that supplement existing policies could be helpful. These might include conservation programs as well as pricing carbon and nitrate emissions to create incentives for the agricultural industry to adopt new technologies that increase productivity while lowering environmental impacts. By creating consistent and growing demand, state LCF programs and the federal RFS and clean fuels provisions in the Inflation Reduction Act of 2022 can also help drive increased efficiencies in the cultivation of renewable feedstocks and in the production of renewable fuels from those feedstocks. To successfully drive renewable fuel production and adoption, however, these programs must reduce the costs of feedstock and fuel production to the point at which the market can afford their use.



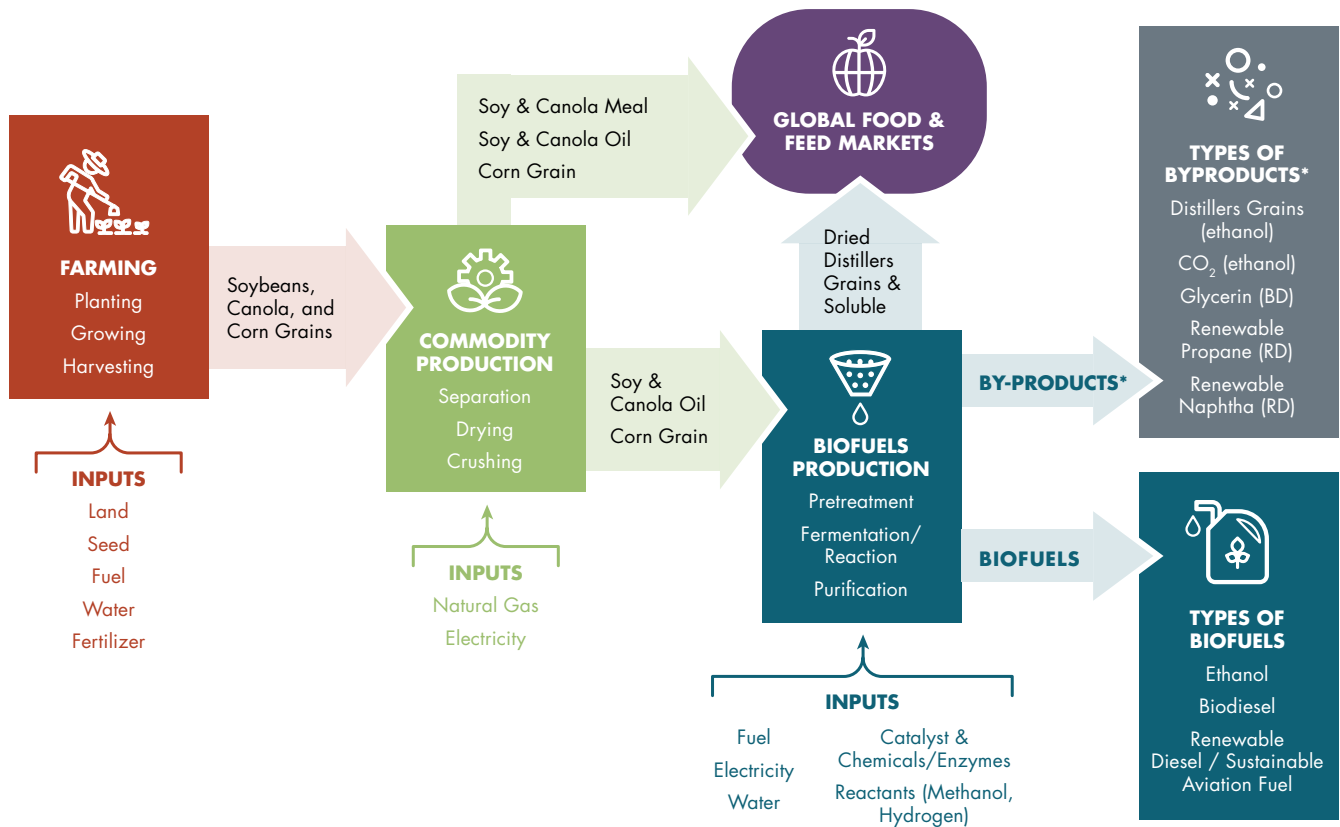
SECTION 1.

Biofuels Overview

The primary biofuels produced in the U.S. are ethanol, biodiesel (BD), renewable diesel (RD), renewable natural gas, renewable jet fuel (also known as sustainable aviation fuel [SAF]), and renewable naphtha (RN).⁵ Of these, ethanol, BD, and RD combined make up more than 99% of all U.S. production; hence, this report focuses on those primary biofuels. The feedstocks and production process for current commercial SAF production closely parallel those required for RD; therefore, most observations about RD production herein can also be applied to SAF.

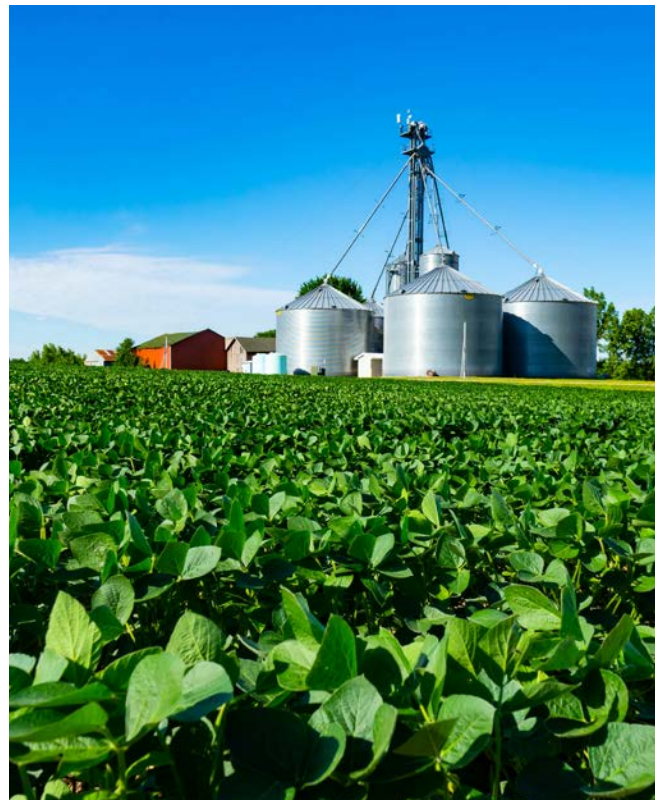
⁵ EIA | Biofuels Explained

FIGURE 1. PROGRESSION OF FEED, FOOD, AND FUEL PRODUCTION FROM SOY, CANOLA, AND CORN



* Also called ancillary commercial products

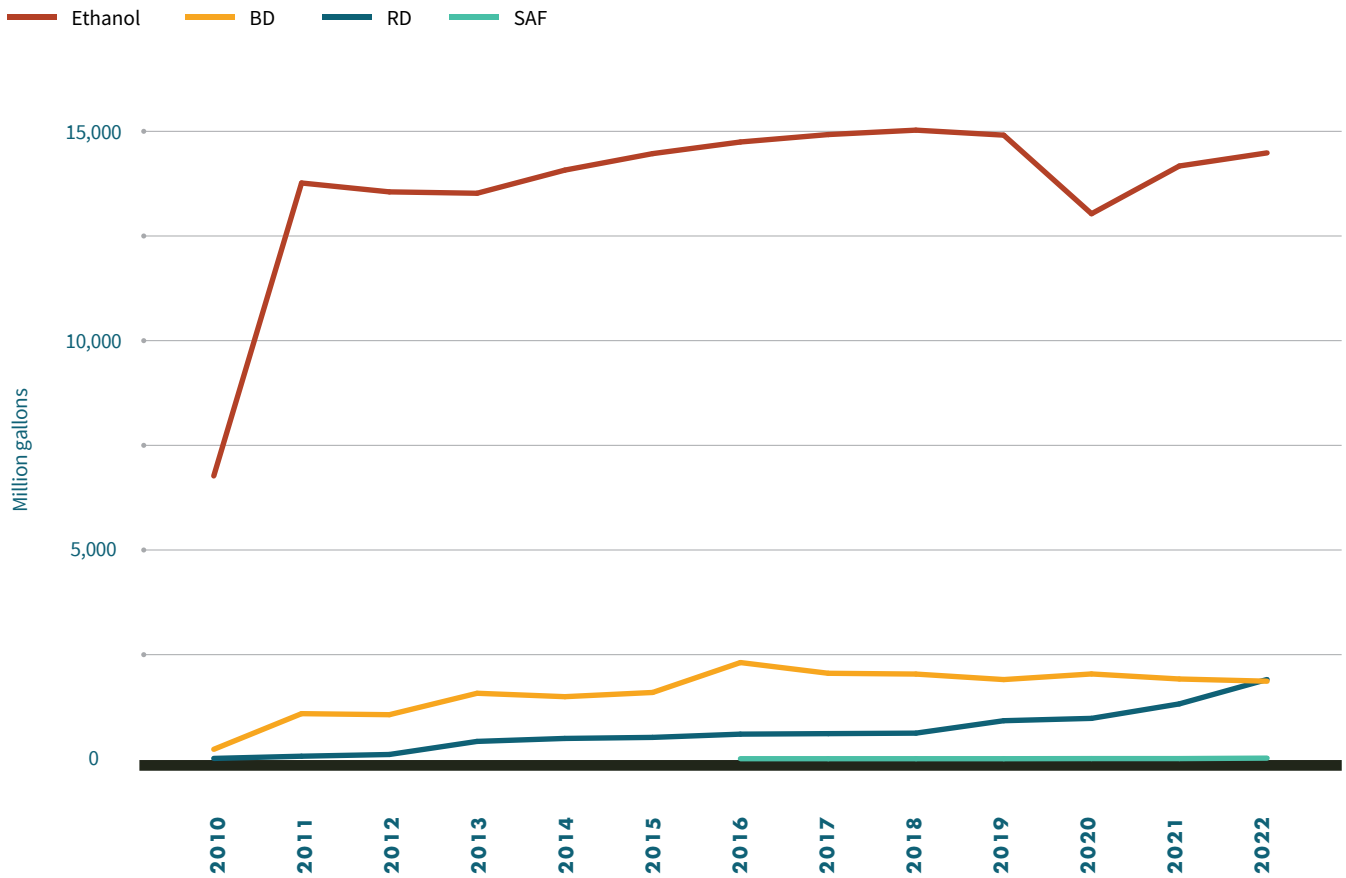
The primary crop-based feedstocks used to produce ethanol, BD, and RD in the U.S. are corn to produce ethanol, and soybeans and canola for BD and RD. In addition to soybean and canola oil, fats, oils, and greases (FOG)—including tallow, used cooking oils, and white and yellow greases—are used as feedstock for BD and RD. Feedstocks for RD production are predominately FOG and inedible corn oil from ethanol production. The portion of the agriculture sector that produces feedstocks for biofuels also supplies the global food and feed market, which is much larger than the biofuel feedstock market. Figure 1 provides an overview of the flow of crop-based feed, food, and fuel production. Understanding the interdependent relationships of these markets is key to understanding the economics and impacts of the biofuels industry in the U.S. We will expand upon the concepts presented in [Figure 1](#) in each of the sections that follow.



1.1 TYPES AND VOLUMES OF BIOFUELS PRODUCED

Based on information supplied by the U.S. Department of Agriculture (USDA), [Figure 2](#) displays the volumes of biofuels and SAF used to comply with the federal Renewable Fuel Standard (RFS). Ethanol makes up over 79% of the volume in 2022, while BD and RD are each slightly over 10%. SAF is only about 0.1% of the volume produced. In the incomplete 2023 data not graphed, ethanol, BD, and RD made up about 75%, 11%, and 14% of the volume, respectively, indicating the continued growth in RD production.

FIGURE 2. U.S. BIOFUELS PRODUCTION (2010–2022)



Source: USDA | Quick Stats

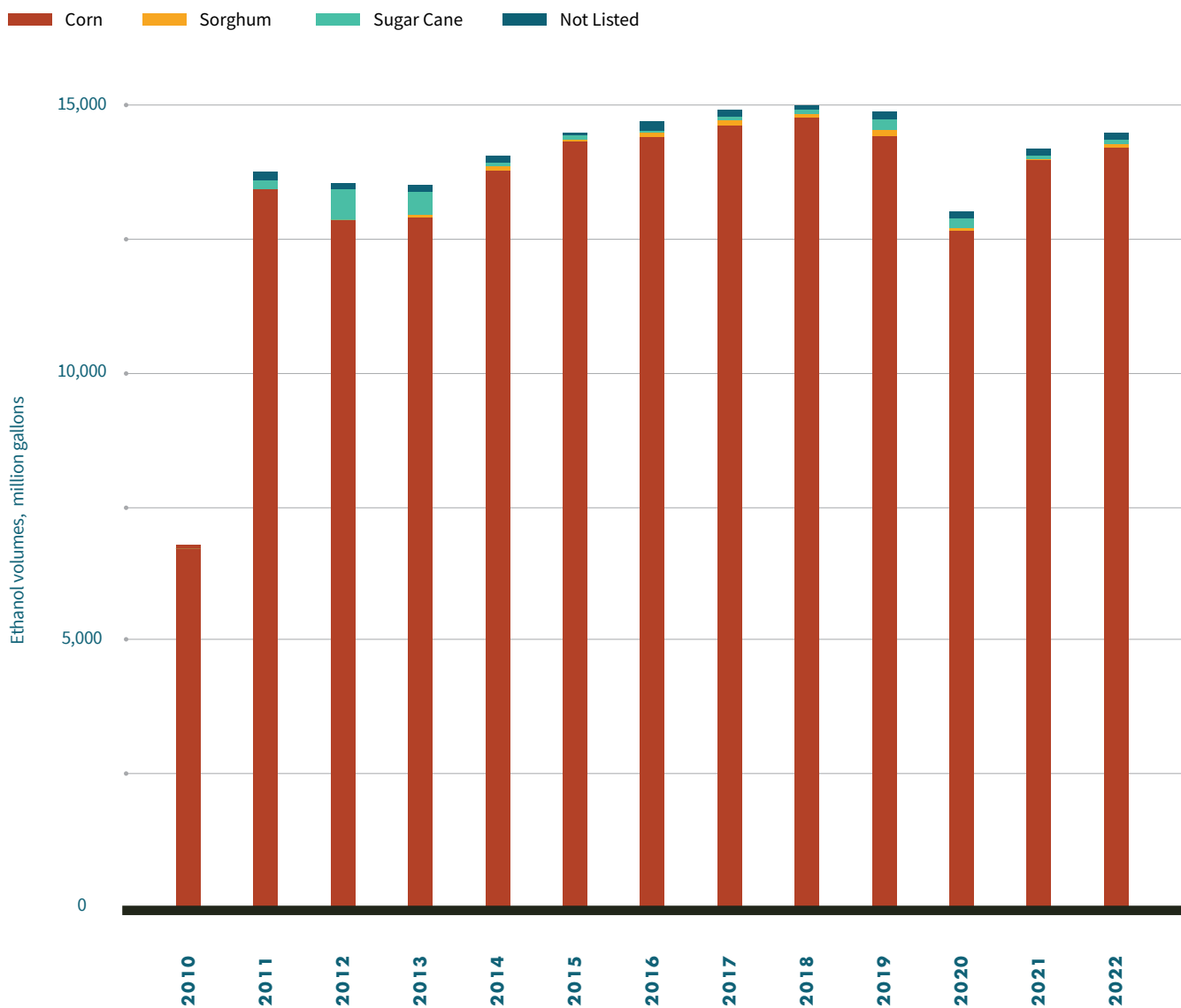


1.2 TYPES OF FEEDSTOCK UTILIZED

The amounts of feedstocks used to produce these biofuels are depicted in Figures 3, 4, and 5. As can be seen, the three primary crop-based feedstocks are corn for ethanol, and soybeans and canola for BD and RD.

Figure 3 shows ethanol production volume by feedstock between 2010 and 2022. Over the past 12 years, corn has been the feedstock used to produce about 98% of all ethanol in the U.S. A decade ago, sugarcane ethanol from Brazil made up 3%–4% of ethanol used in the U.S., but in recent years sugarcane and sorghum combined have been used for less than 1% of ethanol production.

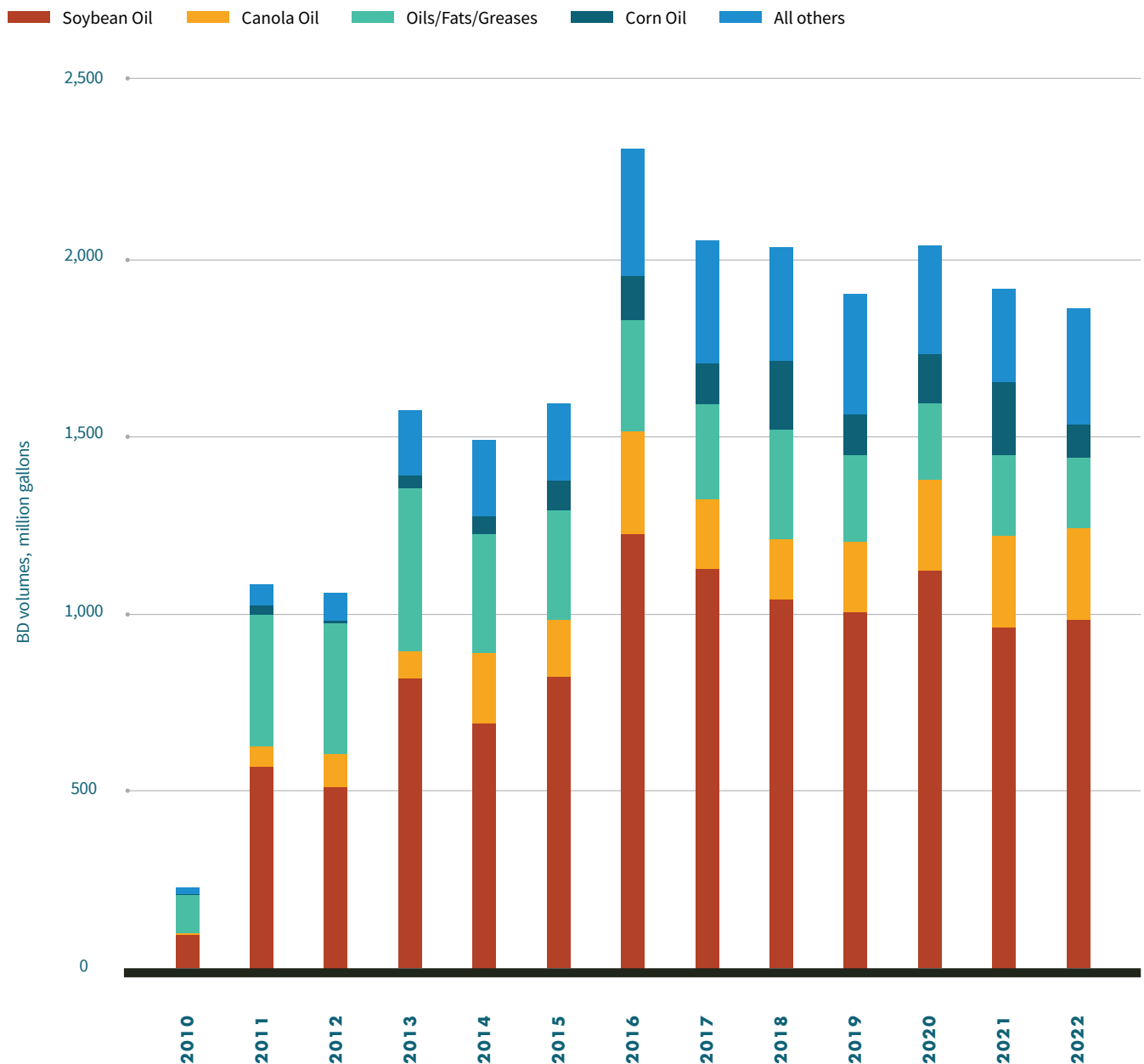
FIGURE 3. U.S. ETHANOL PRODUCTION VOLUMES BY FEEDSTOCK (2010–2022)



Source: USDA | Quick Stats

Figure 4 shows BD production volume by feedstock between 2010 and 2022. Soybean oil has consistently been the most common feedstock used, accounting for more than 50% of BD production since 2016. FOG⁶ made up the largest fraction of BD feedstocks used in 2010, but its volume peaked in 2013, after which RD facilities began attracting increased FOG volumes. By 2022, FOG made up just 8.5% of the feedstock used in BD production in the U.S. Canola oil is now the second largest feedstock used for BD production, at just under 14% of the total in 2022, and corn oil was used to produce 5% of the BD in that same year. Other common types of feedstocks used include cottonseed and palm oils.

FIGURE 4. U.S. BD PRODUCTION VOLUMES BY FEEDSTOCK (2010–2022)

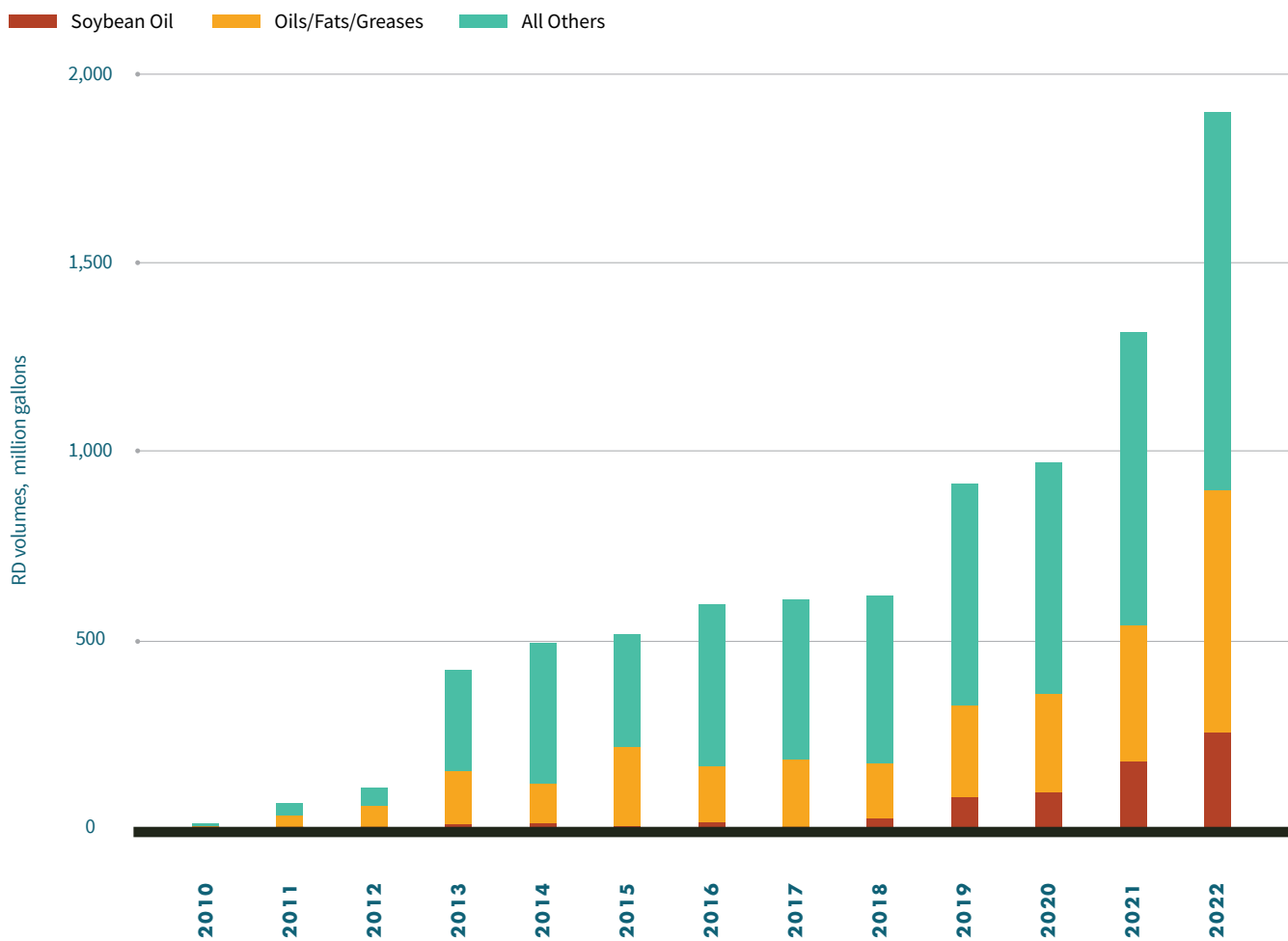


Source: USDA | Quick Stats

⁶ Per EIA, FOG includes animal fats from meat processing plants, used/recycled cooking oil, and yellow grease from restaurants.

Figure 5 shows RD production volume by feedstock between 2010 and 2022. As can be seen, RD production growth has been strong over the past decade and has accelerated since 2019. Unlike BD, RD meets the ASTM D975 specification for petroleum diesel (i.e., the two fuels are both predominantly hydrocarbons with similar bulk properties), so it is considered a drop-in fuel and can be blended, transported, and even co-processed with petroleum diesel. RD’s drop-in status enables much larger volumes to be blended in markets such as California that provide greater incentives to blend renewable fuels to reduce greenhouse gas (GHG) emissions from transportation fuels. The increase in RD production facilities has resulted in competition with BD producers for feedstocks, which has caused BD production to decline since 2016 (Figure 4). FOG is the most common feedstock used to produce RD due to its low lifecycle carbon intensity (CI) as assessed under low-carbon fuel (LCF) programs in California, Oregon, and Washington; this low CI score increases the value of the RD. The “all others” feedstocks lumped together in Figure 5 include canola, corn, cottonseed, and palm oils.⁷ With the growth in RD production, these other feedstocks are used to fill the new production facilities when FOG supply falls short. This trend will continue as additional RD facilities come online over the next year.

FIGURE 5. U.S. RD PRODUCTION VOLUMES BY FEEDSTOCK (2010-2022)



Source: USDA | Quick Stats

⁷ Palm oil-derived fuels are specifically excluded from Inflation Reduction Act of 2022 incentive programs. State LCF programs do not prohibit palm but assign it a CI high enough to strongly discourage its use. The RFS does not prohibit palm, but palm BD only qualifies for D6 renewable identification numbers. Additionally, the less-favorable cold-flow properties of palm-based BD and RD make it a technically less-desirable feedstock, particularly in colder weather.

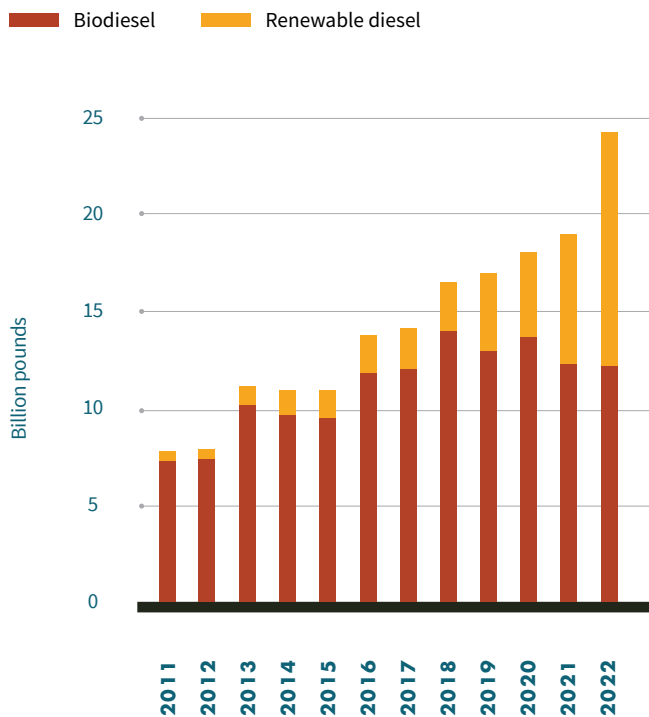
1.3 VOLUMES OF FEEDSTOCK UTILIZED

Feedstock usage in the production of ethanol is explained using USDA statistics.⁸ In 2022, U.S. production of ethanol was 15.3 billion gallons from 5.15 billion bushels of corn, which means that 2.95 gallons of ethanol were produced per bushel of corn (approximately 105 gallons per ton). These data also show that 37.6% of the corn produced in the U.S. was used to produce ethanol, and ethanol made up 10.2% of all fuel used in gasoline vehicles in 2022.

The other most common sources of ethanol production are various feedstocks from the production of sugar. One ton of molasses (a by-product of sugarcane and sugar beet processing) yields about 69.4 gallons of ethanol, one ton of raw sugar yields 135.4 gallons, and one ton of refined sugar yields about 141 gallons of ethanol.⁹

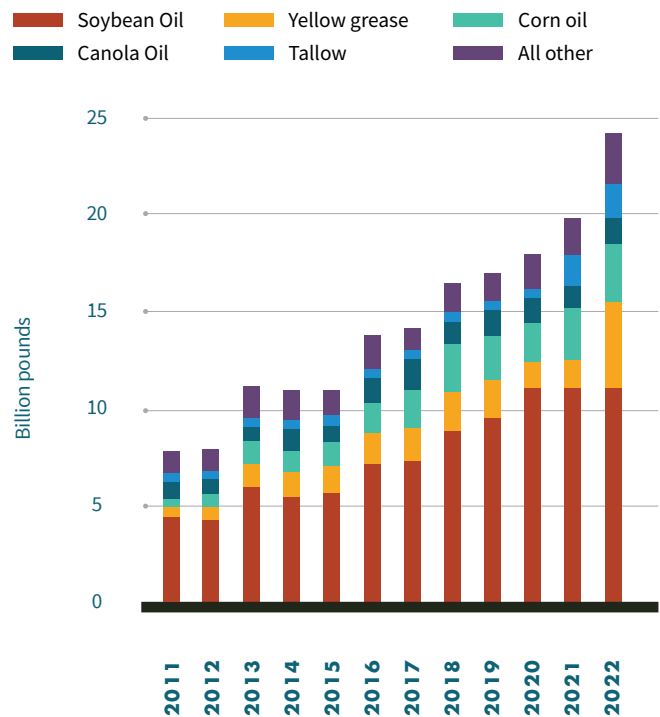
Feedstock consumption in the production of BD and RD is detailed by FarmDoc Daily.¹⁰ For BD, 7.55 pounds of soybean oil or 7.5 pounds of trap grease is used to produce one gallon (approximately 265–267 gallons per ton). For RD, an average of 8.125 pounds of feedstock is used to produce one gallon (approximately 246 gallons per ton). [Figure 6](#) presents annual estimates of implied total feedstock usage from 2011 through 2022 for RD and BD production, and [Figure 7](#) shows the quantity of feedstocks used to produce BD and RD over the same time frame. As can be seen, there is a notable increase in the use of two of the lowest-carbon feedstocks (yellow grease and tallow) in 2021 and 2022; these feedstocks were diverted from other uses because of the value added to the products by California’s Low Carbon Fuel Standard (LCFS) program.

FIGURE 6. IMPLIED FEEDSTOCK USAGE TO PRODUCE U.S. RD AND BD (2011–2022)



Source: EIA

FIGURE 7. FEEDSTOCK USED TO PRODUCE U.S. RD AND BD (2011–2022)



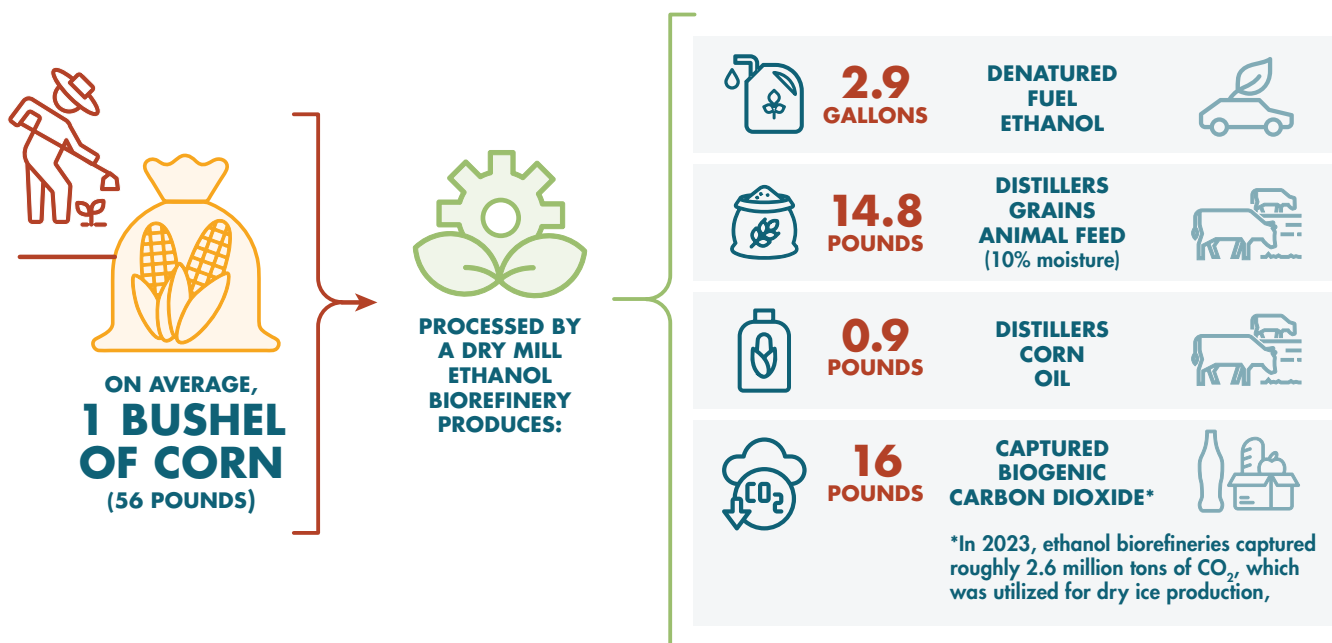
Source: EIA

⁸ USDA | U.S. Bioenergy Statistics, July 2023

⁹ Maria Gerverni et al. | Renewable diesel and biodiesel feedstock trends over 2011–2022

¹⁰ Maria Gerverni et al. | Renewable diesel and biodiesel feedstock trends over 2011–2022

FIGURE 8. CO-PRODUCTS FROM ETHANOL PRODUCTION



Source: Renewable Fuels Association | Ethanol Co-Products

*Approximately 30% of U.S. dry mills capture CO₂ from fermentation.

1.4 CO-PRODUCTS OF BIOFUELS PRODUCTION

The production of biofuels results in co-products—also referred to as by-products or ancillary commercial products—that can be used in other applications. The primary co-products from ethanol production include distillers grains,¹¹ oil, and carbon dioxide (CO₂), each of which can be captured as listed in Figure 8. The non-food-grade corn oil produced at dry mill ethanol plants is primarily utilized as a feedstock for BD and RD production.

Most distillers grains are consumed by cattle (74%), while the rest is fed to swine (18%) and poultry (7%). In addition to distillers grains, corn gluten feed and corn gluten meal¹² are other co-products sold into the meat production industry. The quantities of these co-products since 2000 are shown in Figure 9.¹³ In the absence of corn ethanol production, replacing the protein contributed by the 35.1 million metric tons of dried distillers grains with solubles (DDGS) demand in the U.S. in 2022¹⁴ would require growing 15 million additional acres of soybeans and 5 million additional acres of corn (based on average U.S. soybean yields of 49.5 bushels per acre and corn yields of 173.3 bushels per acre in 2022).¹⁵

11 Distillers grains contain all the protein and fiber content of the corn kernel that remain after the cornstarch is converted to ethanol and the oil is separated out as a separately marketed product. As a concentrated source of protein and fiber, distillers grains represent a high-value feedstock, particularly for ruminant species such as cattle.

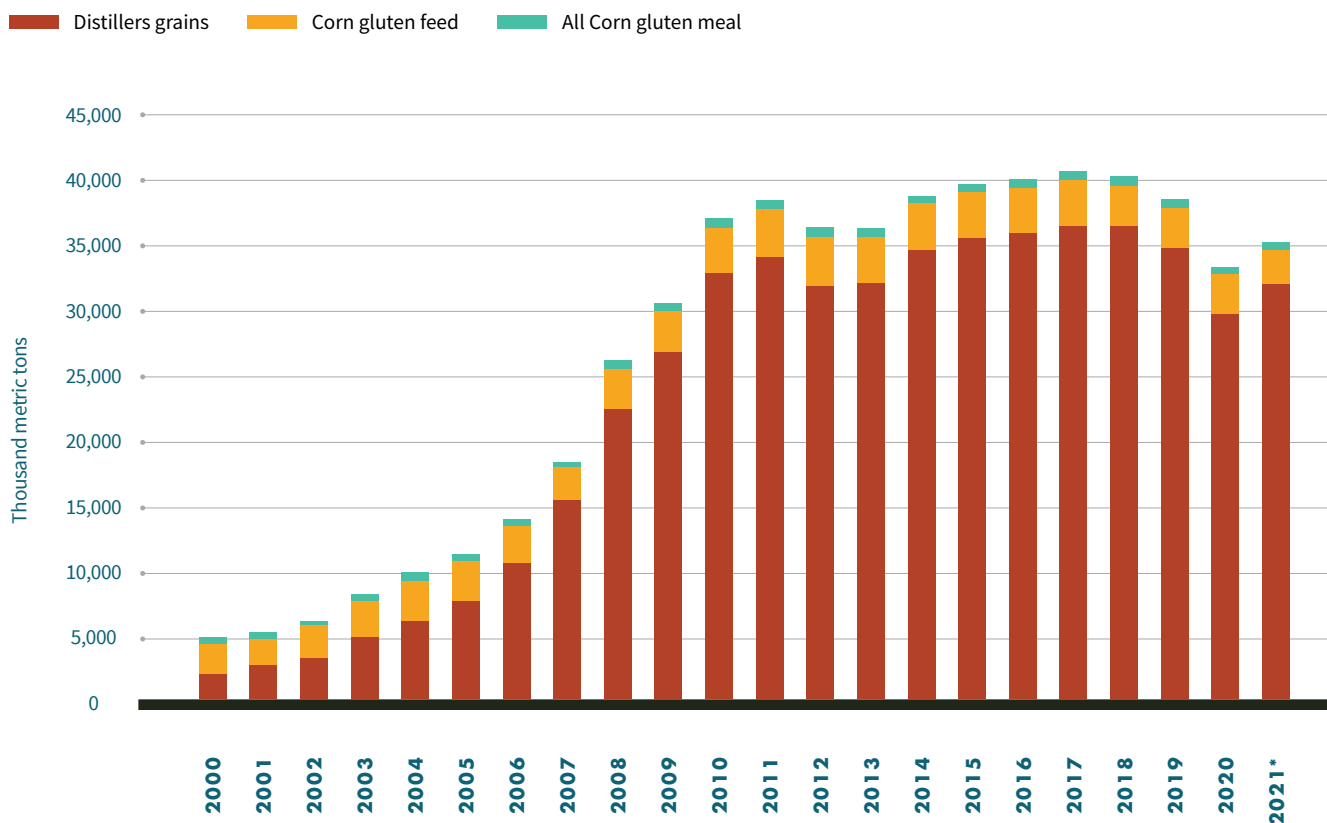
12 Corn gluten feed and corn gluten meal are co-products produced at wet mill ethanol plants. Similar to dried distillers grains with solubles, they concentrate the protein and fiber from the corn kernel, while the starch is converted to ethanol and the oil is recovered for food use.

13 Renewable Fuels Association | Ethanol Co-products

14 USDA | U.S. Bioenergy Statistics, January 2024

15 USDA | Quick Stats

FIGURE 9. ANIMAL FEEDSTOCK CO-PRODUCTS FROM U.S. ETHANOL PRODUCTION (2000–2021)



Source: Renewable Fuels Association; USDA

Note: All co-products converted to 10 percent moisture basis.

*Estimated

The primary co-product from BD production is glycerin, of which about 10 pounds is produced for every 100 pounds (or 13.6 gallons) of BD. Glycerin is a sugar commonly used in the manufacture of pharmaceuticals and cosmetics.¹⁶

RD can be produced by many different technologies, but by far the most prominent is the traditional hydrotreating process used in petroleum refineries. The predominant co-products from RD production are renewable propane, renewable butane, RN, and SAF. When these co-products are used for transportation in locations that have LCF programs, they generate credits with significant value. However, with the exception of SAF, not many vehicles can operate on these fuels; hence, RD producers often use these co-products for energy in the production plant to lower the CI of their primary RD product.¹⁷ SAF can remain in the finished RD product but can also be separated from it via fractionation so that it can be used to fuel jet airplanes. Most SAF today is not separated from RD because it has more value replacing diesel than jet fuel, but this is beginning to change as some jurisdictions are implementing substantial tax credits to support the decarbonization of air travel.

16 U.S. Department of Energy, Alternative Fuels Data Center | Biodiesel Production and Distribution

17 Per the Alternative Fuels Data Center, other SAF production pathways include several via Fischer-Tropsch processes, microbial conversion processes, and conversion of alcohols.



SECTION 2.

Feedstock Production

2.1 ACREAGE USED FOR PRODUCTION OF BIOFUEL FEEDSTOCKS IN THE U.S.

A large share of biofuels produced in the U.S. use agricultural crops—primarily corn (used for ethanol) and soybeans and canola (both used for BD, RD, and SAF)—as feedstocks. For this report, the quantities of each of these feedstocks is estimated from U.S. Environmental Protection Agency (EPA) Moderated Transaction System data on the annual generation of RFS credits (known as renewable identification

numbers, or RINs) by feedstock¹⁸ and USDA data on annual ethanol yields from corn.¹⁹ The acreage required to produce these crops is estimated based on annual yield data as published by USDA.²⁰ Each of these feedstocks has unique attributes, summarized in the subsections that follow.

As the crop acreage allocations covered in this report rely on EPA's data on RIN generation, we first compare that data for BD and RD with USDA's data on annual supply (production plus imports) of these fuels.²¹

18 EPA | RINs Generated Transactions, Feedstock Summary Report

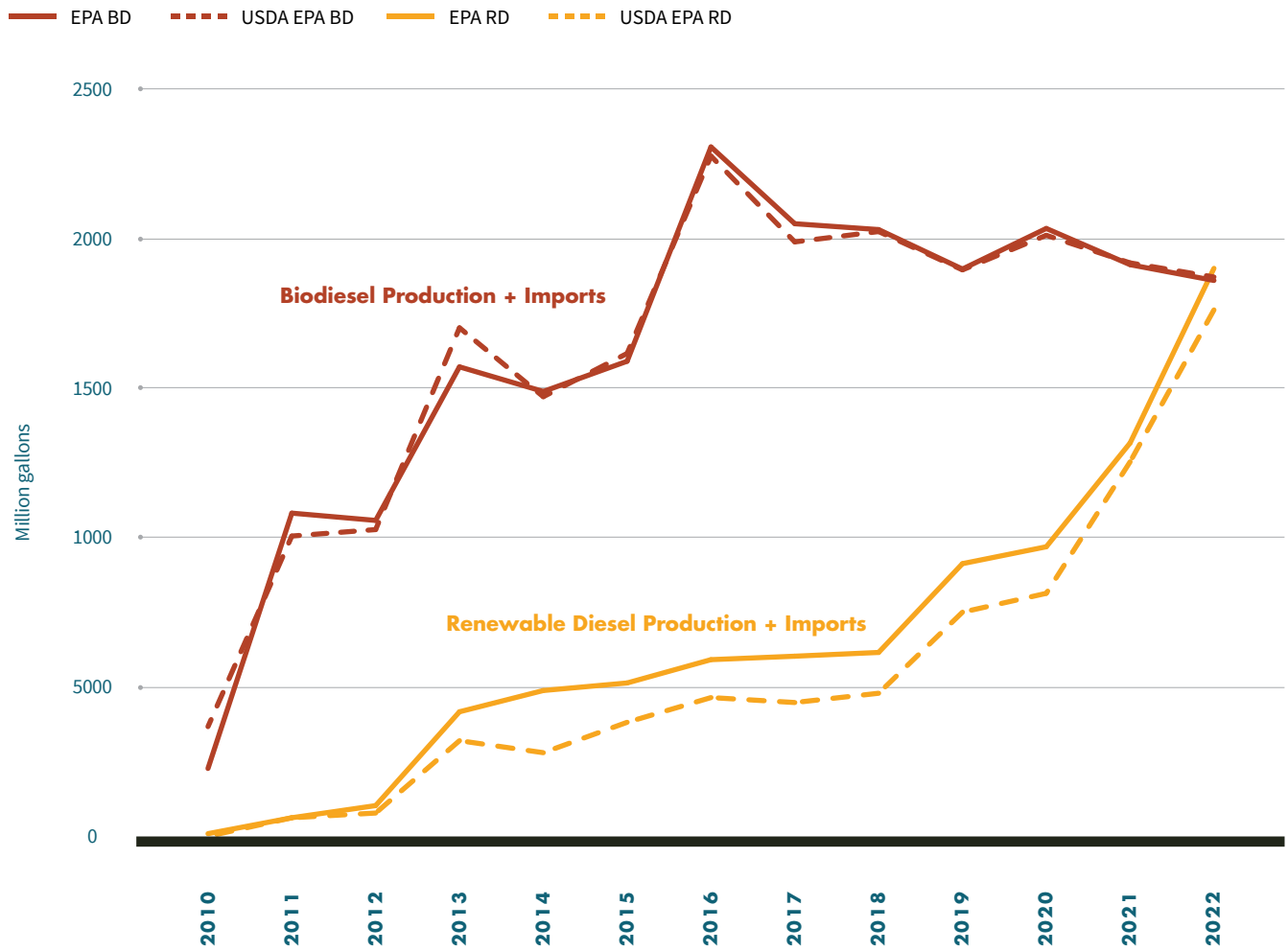
19 Calculated from U.S. Bioenergy Statistics, published quarterly by USDA Economic Research Service.

20 USDA | Quick Stats

21 These data, obtained from the January 2024 edition of USDA's quarterly U.S. Bioenergy Statistics report, rely on data from the U.S. Energy Information Administration.

Figure 10 compares these two data sources. For BD data, the two sources appear to track very well, especially since 2014. For RD data, however, the EPA data consistently shows larger volumes than the USDA data; this difference appears to have narrowed since 2020. Stillwater believes that the EPA data represents an accurate (potentially conservative for RD) source for estimating crop acreage requirements for production of these fuels.

FIGURE 10. COMPARISON OF EPA AND USDA DATA FOR U.S. SUPPLY OF BD AND RD (2010-2022)



Sources: USDA; EPA; Stillwater analysis

2.1.1 CORN

About 98% of all U.S. fuel-grade ethanol production is derived from corn grain. Growth in overall U.S. corn acreage has been slower than implied by the growth in U.S. ethanol production. Growing demand for U.S. corn has led to steady improvements in agricultural practices and seeds; as a result, per-acre yields of corn have grown steadily, from 152.6 bushels²² per acre in 2010 to 173.3 bushels per acre in 2022; similarly, the yield of ethanol per bushel of corn has grown from 2.76 gallons per bushel in 2010 to 2.96 gallons per bushel in 2023. In addition, the distillers grains co-product of corn ethanol, amounting to about 19 pounds for every 56-pound bushel of corn used for ethanol production, is utilized as a high-protein animal feed, displacing

corn, soybean meal, and other grains in livestock feed rations. Corn acreage required to supply fuel-grade ethanol production in the U.S. has increased from 15.9 million acres in 2010 to 27.8 million acres in 2022; even with this large increase in corn demand for ethanol, corn production available for all other uses declined by only 4.4% over this period.

2.1.2 SOYBEANS

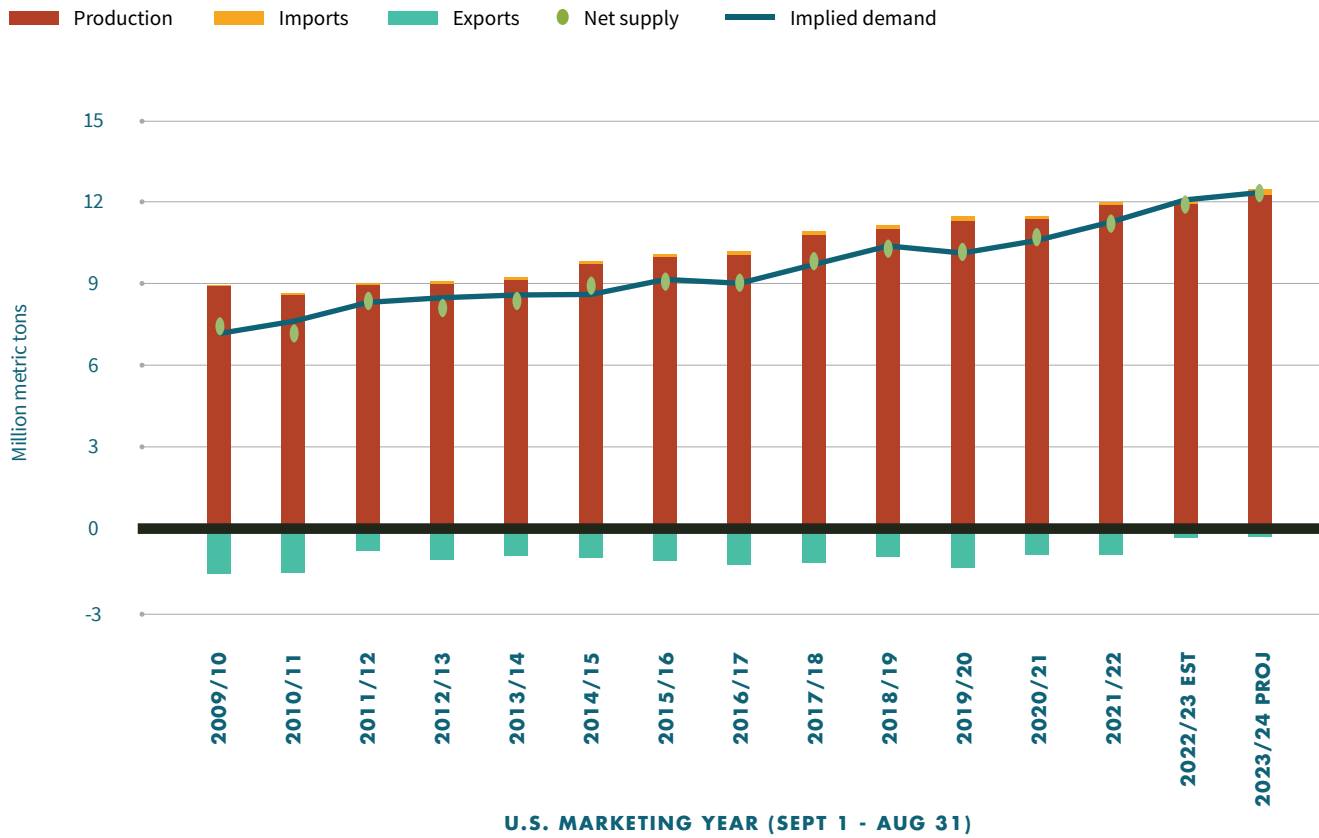
Soybean oil, derived from crushing whole soybeans to produce about 20% soybean oil and 80% soybean meal, is the largest single feedstock utilized for BD and RD production and represents about 35%–40% of total U.S. production of these fuels.²³ Per-acre yields of soybeans have steadily grown from 43.5

²² One bushel of corn is 56 pounds.

²³ Other major BD feedstocks are canola oil, tallow, distillers corn oil, and used cooking oil.



FIGURE 11. ANNUAL U.S. SOYBEAN OIL SUPPLY-DEMAND BALANCE



Source: USDA WASDE; Stillwater analysis

bushels per acre in 2010 to 49.5 bushels per acre in 2022.²⁴The soybean meal co-product is a major source of high-protein animal feed and, historically, has been the primary source of value for growing soybeans. Soybean acreage required to supply the soybean oil used for U.S. BD and RD production has increased from 1.3 million acres in 2010 to 15.9 million acres in 2022. Over this period, all non-biofuel uses of U.S. soybean oil production also increased by 2.3%; about 75% of this overall demand increase was supplied by increased U.S. soybean oil production, with the remainder coming from reduced U.S. soybean oil exports.

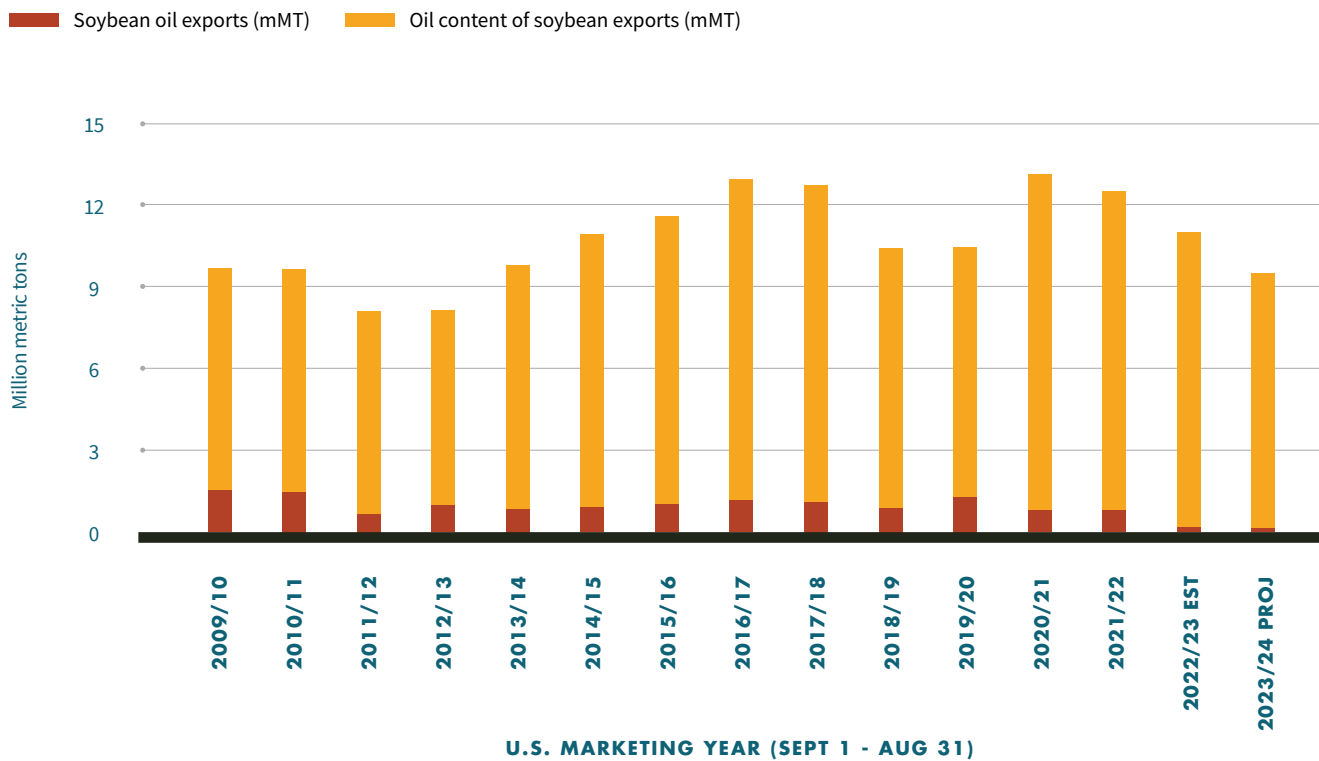
One often-cited concern with the growth of U.S. biofuel demand is that it would divert soybean oil from export markets, thereby resulting in the need

to increase soybean cultivation in other markets, driving undesirable changes in land use. While nearly all soybean oil demand in the U.S. is supplied from domestic production, the most recent estimates from USDA for the 2023/24 marketing year project the U.S. to be a small net importer of soybean oil. [Figure 11](#) shows the annual U.S. soybean oil supply and demand balance since the 2009/10 marketing year. It can be seen that U.S. exports (the downward green bars) decreased in the 2011/12 marketing year, held relatively stable through the 2021/22 marketing year, and are now expected to nearly disappear in 2022/23 and 2023/24. This trend occurs even as U.S. soybean oil production has grown by an average 2.3% per year over the same time period.

²⁴ One bushel of soybeans is 60 pounds.

A more complete picture of U.S. soybean oil exports, however, also requires consideration of U.S. exports of whole soybeans, because the purchasers of those soybeans, like their U.S. counterparts, go on to crush nearly all those soybeans to produce soybean meal and soybean oil. [Figure 12](#) places this into perspective, comparing annual U.S. soybean oil exports to the oil content (20% by weight) of U.S. exports of whole soybeans. It can be seen that far more soybean oil is derived from U.S. exports of whole soybeans than from U.S. exports of soybean oil and that the growth in U.S. whole soybean exports roughly compensates for reduced U.S. soybean oil exports since the start of the RFS.

FIGURE 12. U.S. MARKETING YEAR EXPORTS OF SOYBEAN OIL AND THE OIL CONTENT OF EXPORTED WHOLE SOYBEANS



Source: USDA WASDE; Stillwater analysis

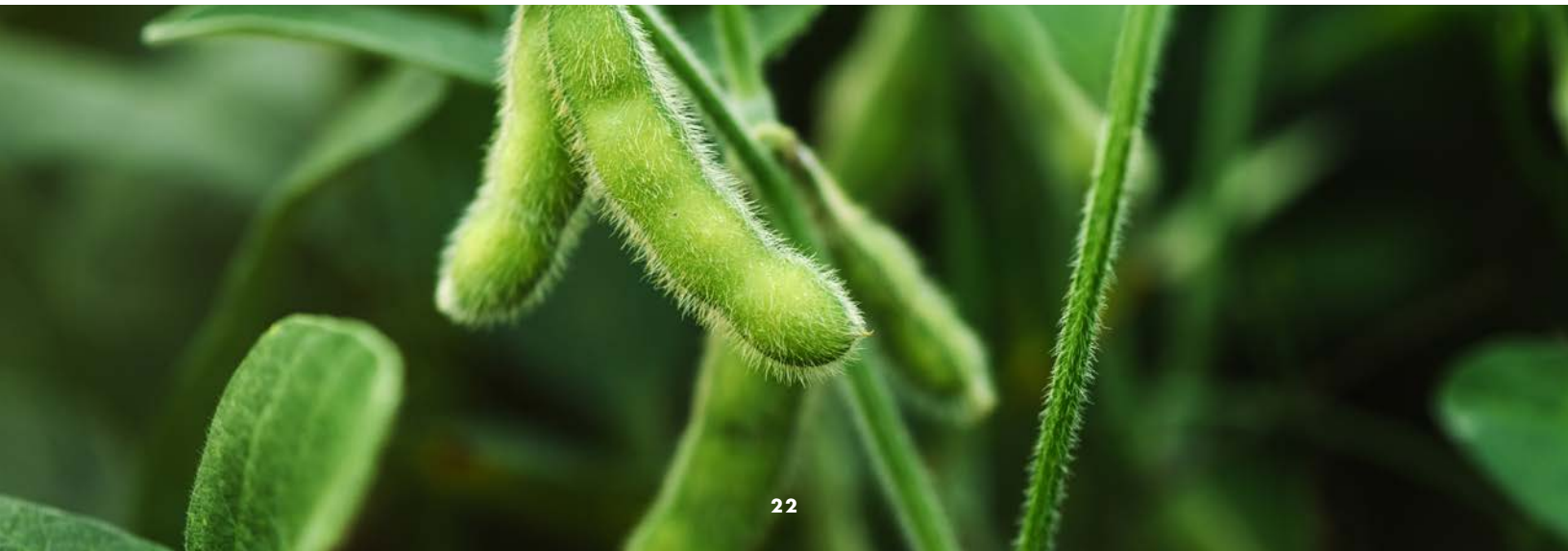
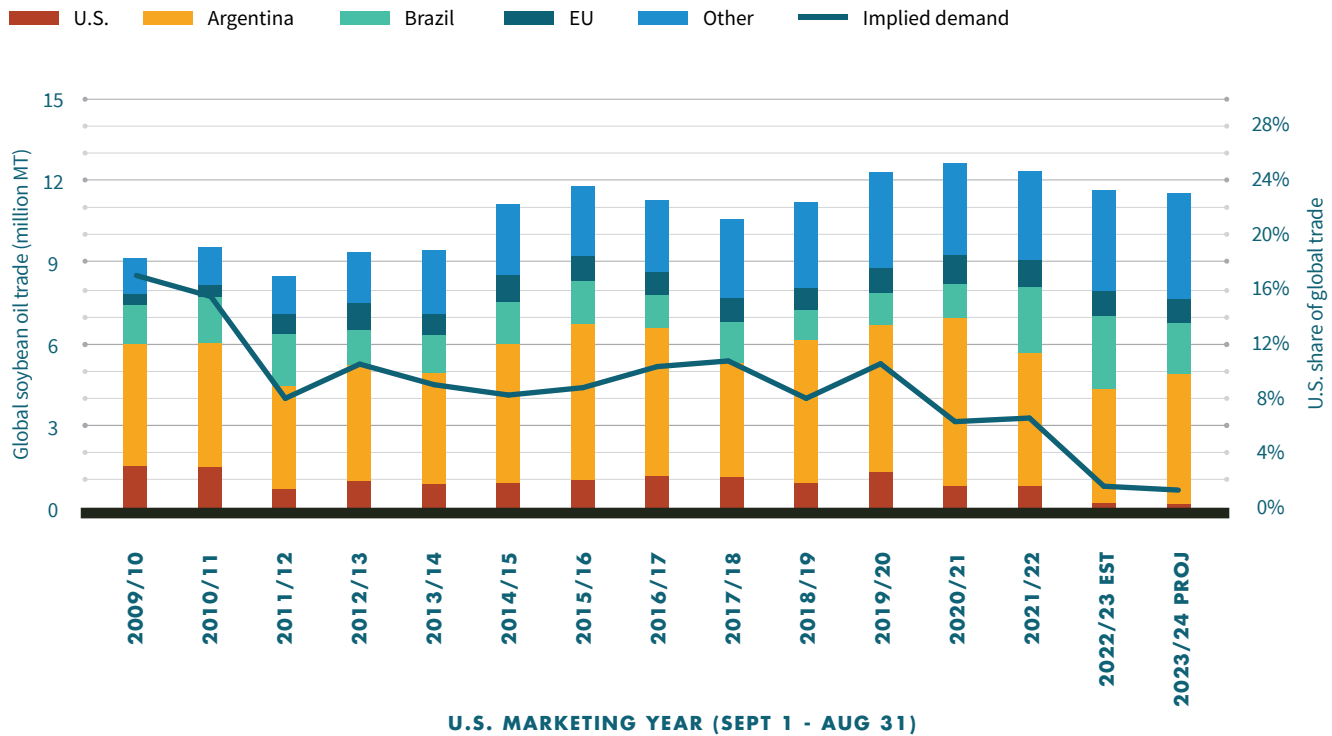


FIGURE 13. MAJOR GLOBAL SOYBEAN OIL EXPORTERS AND U.S. MARKET SHARE



Source: USDA WASDE; Stillwater analysis

Additional perspective on U.S. soybean oil exports is provided by looking at overall global trade in soybean oil, which has grown by an average of 1.7% per year since the 2009/10 marketing year. As can be seen in [Figure 13](#), the U.S. share of this growing trade has diminished as other exporters—notably Brazil and the EU—have rapidly grown their soybean oil exports, and Argentina continues to account for 40%–50% of annual global trade.

The implications of reduced U.S. soybean oil exports are further complicated by the fact that soybean oil is just one of the major vegetable oils (together with canola/rapeseed oil, sunflower oil, palm oil, and several other lower-volume oils) used in the human food supply. These different oils are near substitutes for many food applications and, thus, a full understanding of supply and demand factors needs to encompass all these oils, a task beyond the scope of this report. Importantly, all these vegetable oils, with the exception of palm oil, are by-products

of crops grown primarily for their high-protein meals. As oil palms are grown exclusively for their oil, they are the default crop for closing any global supply-demand imbalances. The largest producers of palm oil are Malaysia and Indonesia, and a major environmental concern is that growth in palm oil production requires cultivation of rainforest and peat lands in those countries, a conversion that is seen as releasing large volumes of sequestered carbon and placing endangered species at risk of habitat loss. Accordingly, diversion of soybean oil from food to biofuel usage raises concerns about that soybean oil being replaced in the food supply by increased production of palm oil. The main counterpoint to that concern is that, to date, diversion of U.S. soybean oil production to biofuels applications has been largely addressed by the expanding productivity of global soybean growers, largely on existing croplands.

2.1.3 GRAIN SORGHUM

Grain sorghum (also known as milo) is used as feedstock for less than 1% of all U.S. fuel-grade ethanol production; the amount varies from year to year depending on the relative economics of processing grain sorghum as an alternative to corn at ethanol plants located in sorghum-growing regions of the U.S.²⁵ This usage represents about 10%–20% of the grain sorghum crop, with the remainder of the crop being primarily used as livestock feed in the U.S. and export markets. As is the case with corn ethanol, production of sorghum ethanol produces a high-protein distillers grains product that is a valuable livestock feed, offsetting demand for corn, soybean meal, and other grains.

2.1.4 CANOLA

Canola oil, derived from crushing whole canola seeds to produce about 44% canola oil and 56% canola meal, is the second largest crop-based feedstock utilized for BD and RD production but represents only about 6%–9% of total U.S. production of these fuels.²⁶ Per-acre yields of canola have grown from 1,711 pounds (28.5 bushels)²⁷ per acre in 2010 to 1,762 pounds (29.4 bushels) per acre in 2022. The canola meal co-product is a significant source of high-protein animal feed. Acreage required to supply the canola oil used for U.S. BD and RD production has increased from 52 thousand acres in 2010 to 2.5 million acres in 2022. While EPA has approved the use of canola oil as a feedstock for BD for some time, its use as a feedstock for RD was only approved in December 2022.²⁸ With this new approval, canola oil is expected to find increasing use in the rapidly growing RD segment.



²⁵ U.S. grain ethanol plants typically draw all their feedstocks from within a 25- to 50-mile radius of the plant. In 2023, grain sorghum was grown in Colorado, Kansas, Nebraska, Oklahoma, South Dakota, and Texas.

²⁶ Other major BD feedstocks are canola oil, tallow, distillers corn oil, and used cooking oil.

²⁷ One bushel of canola is 60 pounds.

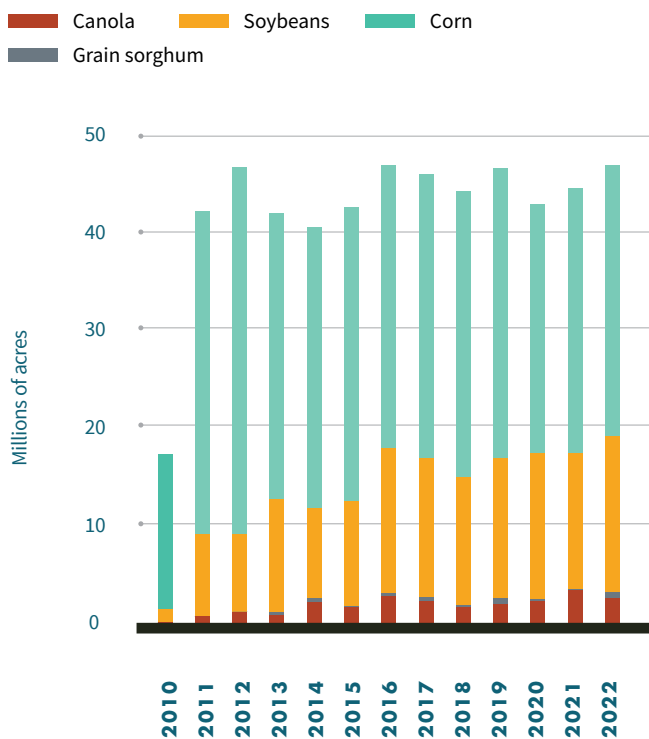
²⁸ EPA | [Canola Oil Pathways Final Rulemaking](#)

2.1.5 SUMMARY

The annual gross estimated acres of these four crops (prior to adjustment for co-production of distillers grains from corn and grain sorghum and of meal from soybeans and canola) required to supply U.S. biofuels production since 2010 is presented in [Figure 14](#). While it may be observed that biofuel feedstock acreage jumped sharply between 2010 (the first year of the RFS2²⁹ program) and 2011, since then, the acreage requirement has been relatively steady, between 40 and 47 million acres per year (average 44.3 million acres).

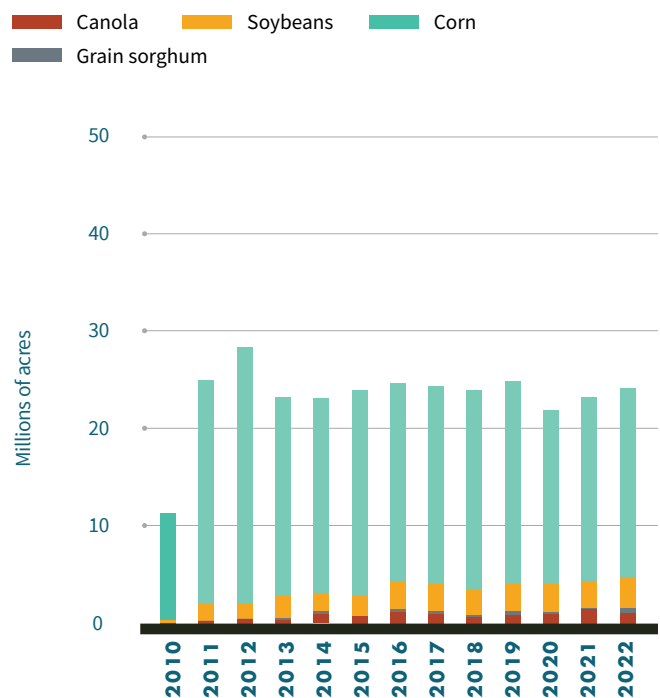
As a large portion of these gross feedstock volumes are returned to feed markets as meal (soybean and canola) or distillers grains (corn and grain sorghum), [Figure 15](#) adjusts the volumes in Figure 14 to reflect the net acreage attributable to actual biofuel production. Importantly, this net acreage calculation shows that acreage dedicated to biofuel production peaked at 28 million acres in 2012 and has held relatively steady between 22 and 25 million acres since then.

FIGURE 14. U.S. CROP GROSS ACREAGE USED FOR BIOFUEL PRODUCTION (2010-2022)



Sources: USDA; Stillwater analysis

FIGURE 15. U.S. CROP NET ACREAGE USED FOR BIOFUEL PRODUCTION (2010-2022)



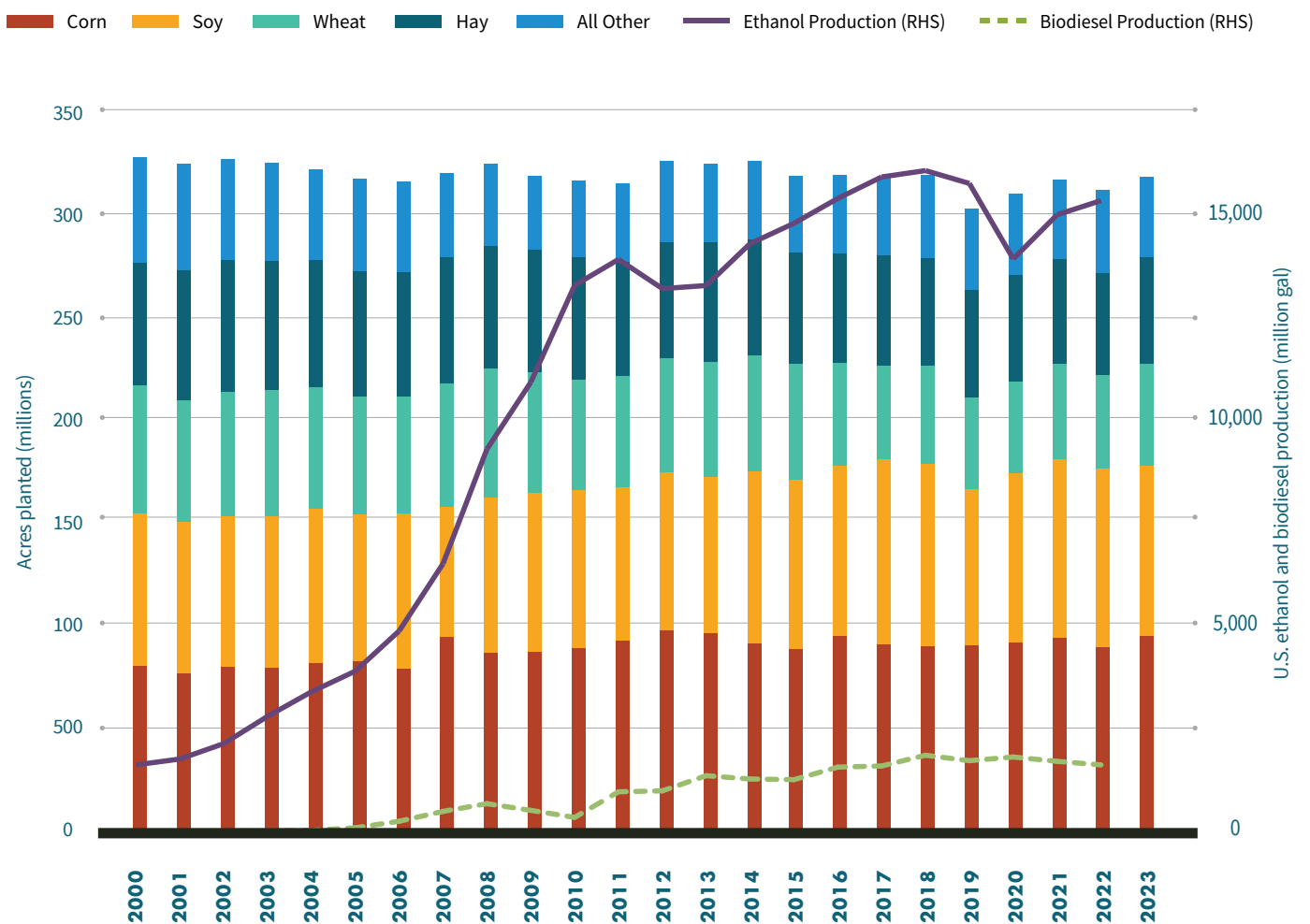
Sources: USDA; Stillwater analysis

29 The original RFS program was established by the Energy Policy Act of 2005. It was extensively amended and expanded by the Energy Independence and Security Act of 2007 to establish what is often referred to as RFS2. Colloquially, the term “RFS” is used to refer to both the original and the expanded programs.

2.2 TOTAL U.S. AGRICULTURAL CROP ACRES

USDA reports U.S. crop acreage by crop with a report issued annually in June.³⁰ For purposes of this analysis we review USDA’s annual acreage reports from June 2000 through June 2023; this time frame can be divided into the pre-RFS period (2000–2007) and the RFS period (2008–2023).³¹ These data for the three major row crops (wheat, corn, and soybeans), hay, and all other crops are presented as stacked columns in [Figure 16](#), with U.S. Energy Information Administration (EIA) data on U.S. annual fuel-grade ethanol production³² overlaid as a black line. Data on the disposition of U.S. crops is obtained from USDA’s World Agricultural Supply and Demand Estimates (WASDE) report, published monthly.³³

FIGURE 16. ANNUAL U.S. CROP ACREAGE AND FUEL-GRADE ETHANOL PRODUCTION (2000–2023)



Source: USDA WASDE; Stillwater analysis

30 USDA | Acreage Report, June 30, 2023

31 The legislation establishing the RFS2 program was enacted in December 2007, so the crops planted in the spring of 2008 represent the first annual cycle during which farmers were considering RFS2 demands in their planting decisions.

32 EIA | Petroleum & Other Liquids Report, Oxygenate Production

33 USDA | World Agricultural Supply and Demand Estimates

Some key observations concerning these data:

- It is necessary to look at long-term trends in crop acreage, as there is significant year-to-year variation due to factors such as inventory levels, weather, and anticipated domestic and international market demands.
- Total U.S. crop acreage has generally been on a decline, largely due to steadily increasing per-acre yields of key crops. The largest acreage between 2000 and 2023 was 328 million acres planted in 2000, with a low of 303 million acres planted in 2019. The average over these years is 319 million acres, with the pre-RFS2 years averaging 322 million acres and the post-RFS2 years averaging 318 million acres.
- While total acreage has been declining, the mix of agricultural demand is dynamic, with some acres being permanently removed from agriculture each year due to development for other uses and some new acreage coming into agriculture each year. Importantly, RFS regulations limit crop-based feedstocks to those grown on existing agricultural land as of December 19, 2007.³⁴ As this period has seen increases in domestic non-biofuel demands and increased exports of agricultural products, the conversion of new acres to crop production cannot simply be attributed to biofuel feedstock demands alone.³⁵
- Since 2007, the U.S. government has reduced crop land in the Conservation Reserve Program (CRP) by approximately 14 million acres. Much of this land has been put back into production for a variety of crops, including biofuel feedstocks.
- Corn acreage has increased since the start of RFS2, from an average of 81 million acres for 2000–2007 to an average of nearly 91 million acres since 2008. Notably, this increase of nearly 10 million acres is less than the 12 million acres required to support increased ethanol production while growing U.S. corn exports and holding corn grain availability constant.
- Soybean acreage has also increased since the start of RFS2, from an average of nearly 73 million acres for 2000–2007 to an average of slightly less than 82 million acres since 2008. More than half of this increase has been used to supply a doubling of U.S. soybean exports since 2000, while domestic crushing of soybeans for soybean oil production has grown by over 50%, with all the increase utilized as biofuel feedstock, while other uses, including use as food, has remained nearly flat.
- About 60% of the increase in corn and soybean acreage came from reduced wheat acreage, with domestic use and exports of U.S. wheat production declining slightly. The other 40% of the increase in corn and soybean acreage came from reduced hay acreage, as growing production of distillers grains and soybean meal was increasingly used in domestic and export livestock feed markets.
- U.S. fuel-grade ethanol production grew rapidly from 6.2 billion gallons in 2007 to 13.9 billion gallons in 2011, before growth began to slow with saturation of the U.S. gasoline market. Production continued to grow at a slower pace to a record of 16.2 billion gallons in 2018, largely driven by growing demand in export markets. Production was 15.4 billion gallons in 2022.

³⁴ 40 CFR § 80.1401

³⁵ For purposes of enforcement, EPA requires that U.S. crops used as biofuel feedstock be grown on compliant land. For the retrospective analyses done for the [Third Triennial Report to Congress](#) covering the environmental impacts of biofuels, EPA determined that 56% of the increase in corn and soy acres came from land previously used for other crops, 13% from pastureland, 20% from noncultivated cropland, and 11% from Conservation Reserve Program acres. The report does not attempt to attribute increased corn and soy acres to biofuels use versus other demands. In making these determinations, EPA relied on data from USDA and the U.S. Geological Survey.



The largest acreage between 2000 and 2023 was 328 million acres planted in 2000, with a low of 303 million acres planted in 2019.

The average over these years is 319 million acres, with the pre-RFS2 years averaging 322 million acres and the post-RFS2 years averaging 318 million acres.

2.3 FEEDSTOCK YIELDS

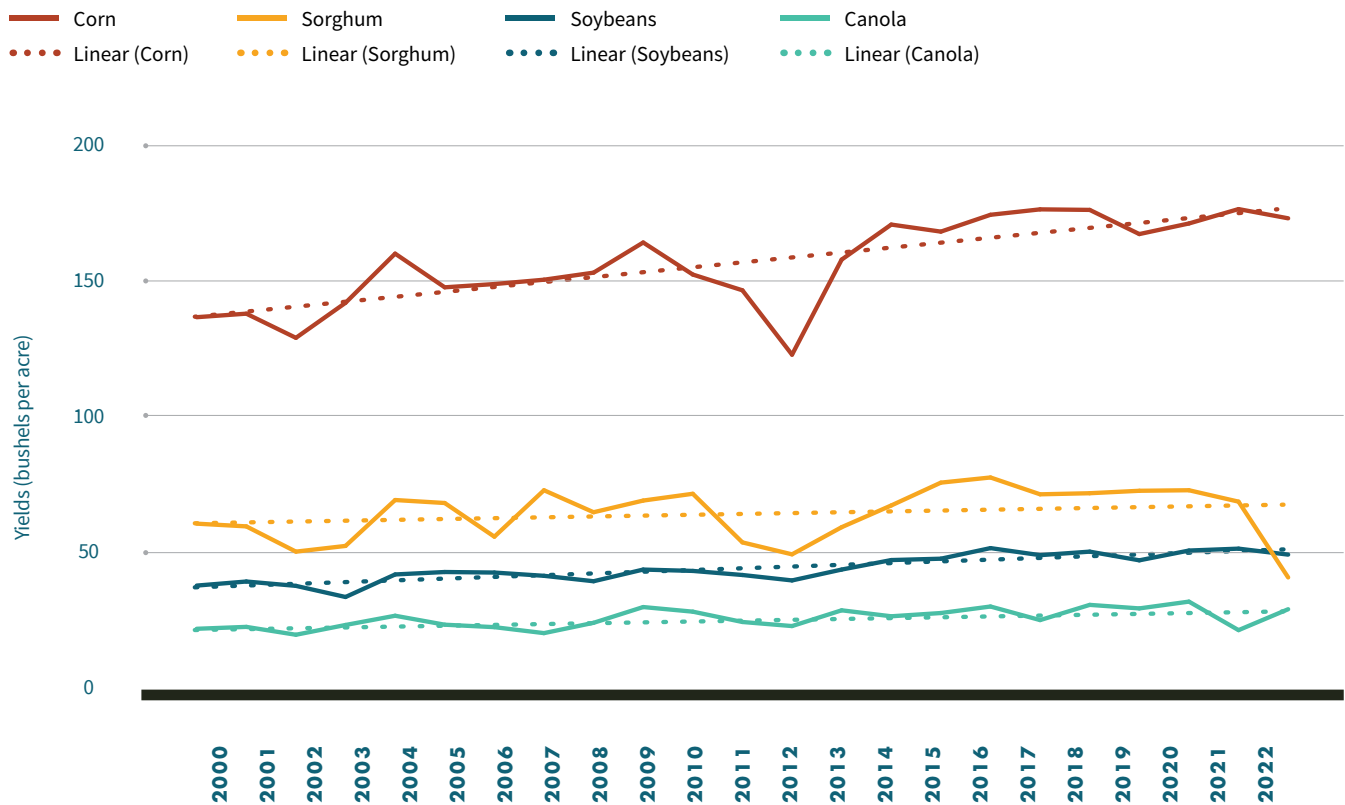
The per-acre yields of each of the four biofuel feedstocks covered in section 2.1 have been growing steadily over time; the cumulative effect of these trends is that the supply of these feedstocks has grown more rapidly than the acreage dedicated to these crops. Key factors contributing to this steady growth in yields are regular improvements in seeds as well as adoption of improved agronomic practices by the many individual farmers growing these crops.

While the underlying trend in yields for each of these crops is upward, the annual data, as shown in [Figure 17](#), varies significantly from year to year. In [Figure 17](#) the solid lines with markers are the annual yields reported by USDA,³⁶ and the dashed lines represent the long-term yield trend for each crop. These data are also tabulated in [Table 1](#).

The yearly yield variability is due to weather conditions (variation in temperature and rainfall patterns from year to year and storm events) and differences in the geographic mix of the land used to grow these crops. An additional factor can be changes in the cost of fertilizers and other inputs, which, in combination with anticipated crop prices, may influence the extent to which these treatments are used to enhance yields. Importantly, planting of sorghum and canola is much more geographically concentrated than that of corn and soybeans; as a result, local weather conditions result in greater variability in the yield trends for sorghum and canola.

[Figures 18–21](#) present production by county for corn, sorghum, and soybeans in 2022 and for canola in 2018 as reported by USDA.

FIGURE 17. ANNUAL YIELDS FOR MAJOR U.S. BIOFUEL FEEDSTOCKS (2000–2022)



Sources: USDA; Stillwater analysis

TABLE 1. ANNUAL YIELDS FOR MAJOR U.S. BIOFUEL FEEDSTOCKS (2000–2022)

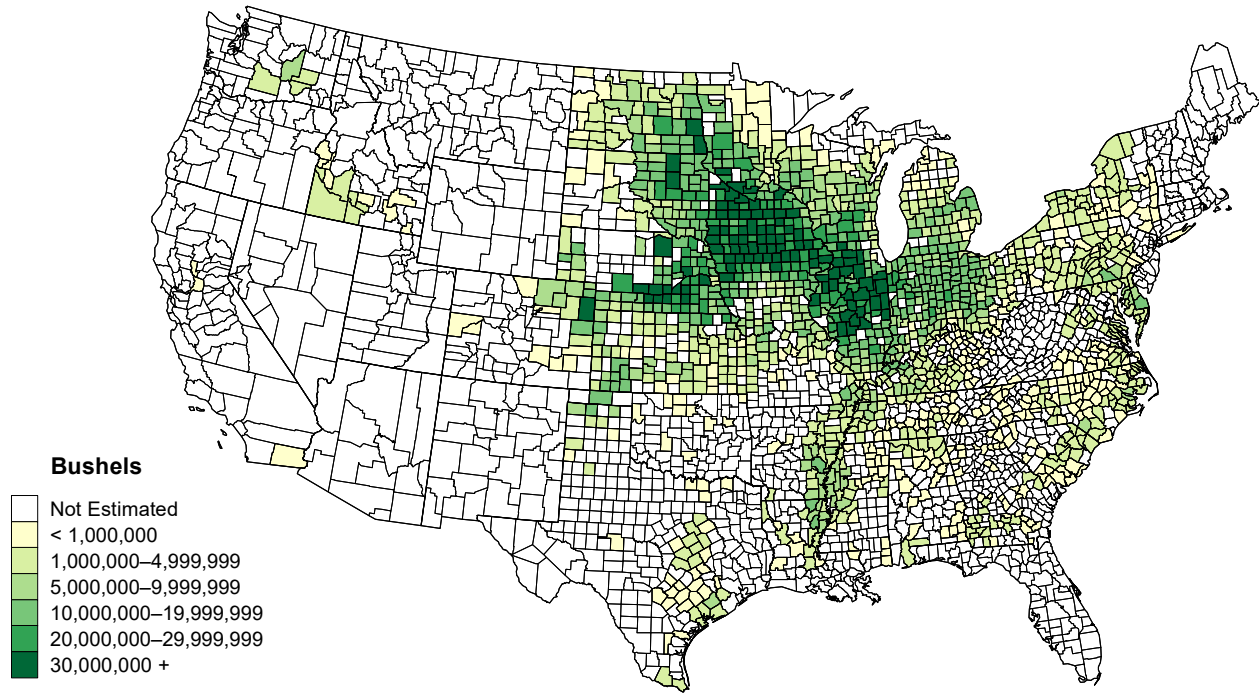
YEAR	CORN (bu/ac)	GRAIN SORGHUM (bu/ac)	SOYBEANS (bu/ac)	CANOLA (bu/ac)
2000	136.9	60.9	38.1	22.2
2001	138.2	59.9	39.6	22.9
2002	129.3	50.6	38.0	20.0
2003	142.2	52.7	33.9	23.6
2004	160.3	69.6	42.2	27.0
2005	147.9	68.5	43.1	23.7
2006	149.1	56.1	42.9	22.8
2007	150.7	73.2	41.7	20.6
2008	153.3	65.1	39.7	24.4
2009	164.4	69.4	44.0	30.2
2010	152.6	71.9	43.5	28.5
2011	146.8	54.0	42.0	24.7
2012	123.1	49.6	40.0	23.2
2013	158.1	59.6	44.0	29.0
2014	171.0	67.6	47.5	26.8
2015	168.4	76.0	48.0	28.0
2016	174.6	77.9	51.9	30.4
2017	176.6	71.7	49.3	25.4
2018	176.4	72.1	50.6	31.0
2019	167.5	73.0	47.4	29.7
2020	171.4	73.2	51.0	32.2
2021	176.7	69.0	51.7	21.7
2022	173.3	41.1	49.5	29.4

Sources: USDA; Stillwater analysis

Units: bushels/acre (bu/ac)

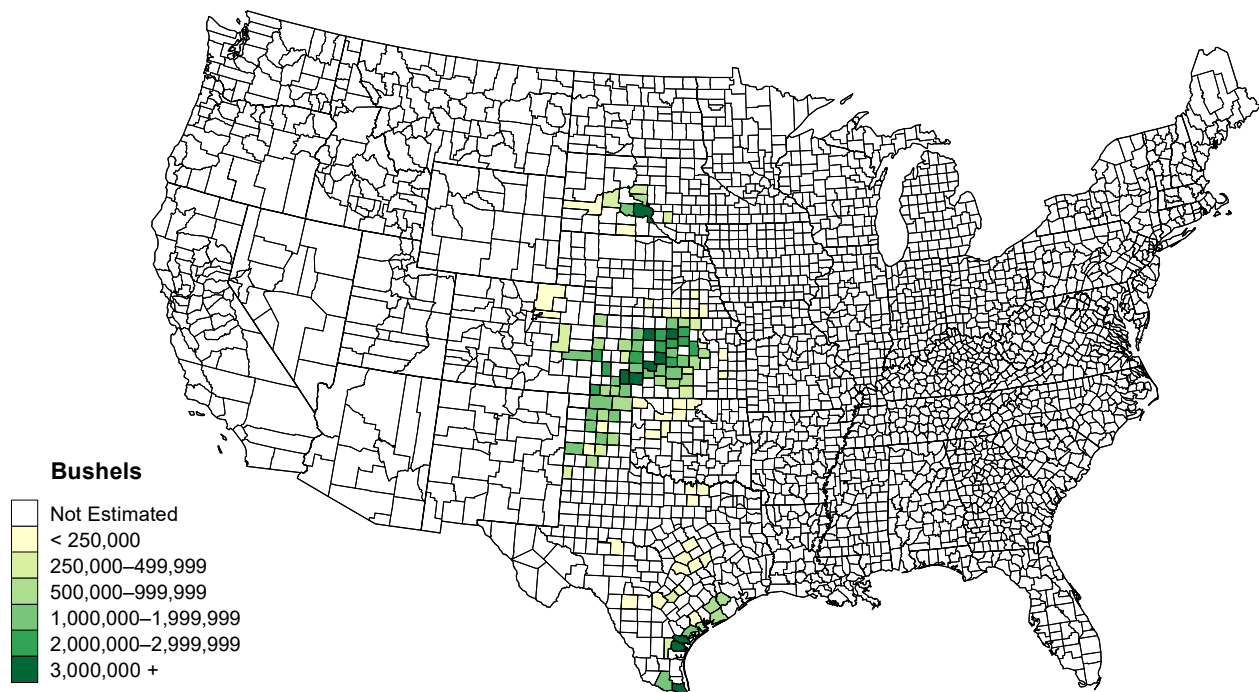


FIGURE 18. U.S. CORN PRODUCTION BY COUNTY (2022)



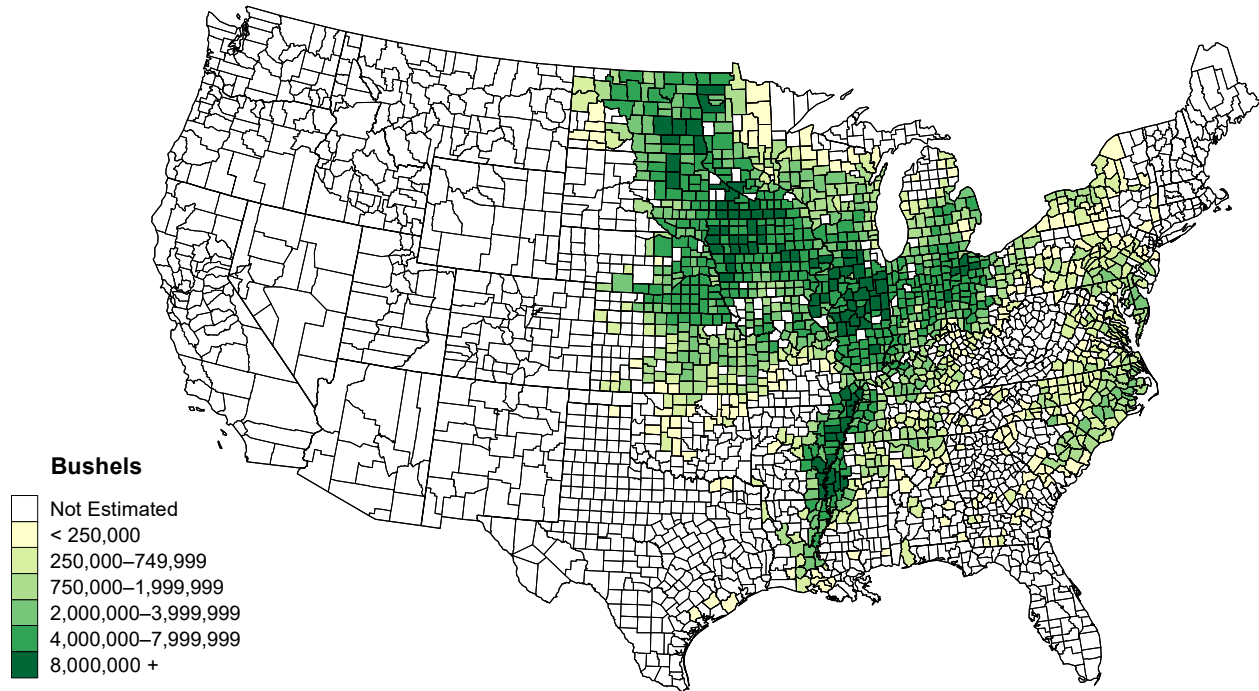
Source: USDA, National Agricultural Statistics Service

FIGURE 19. U.S. SORGHUM PRODUCTION BY COUNTY (2022)



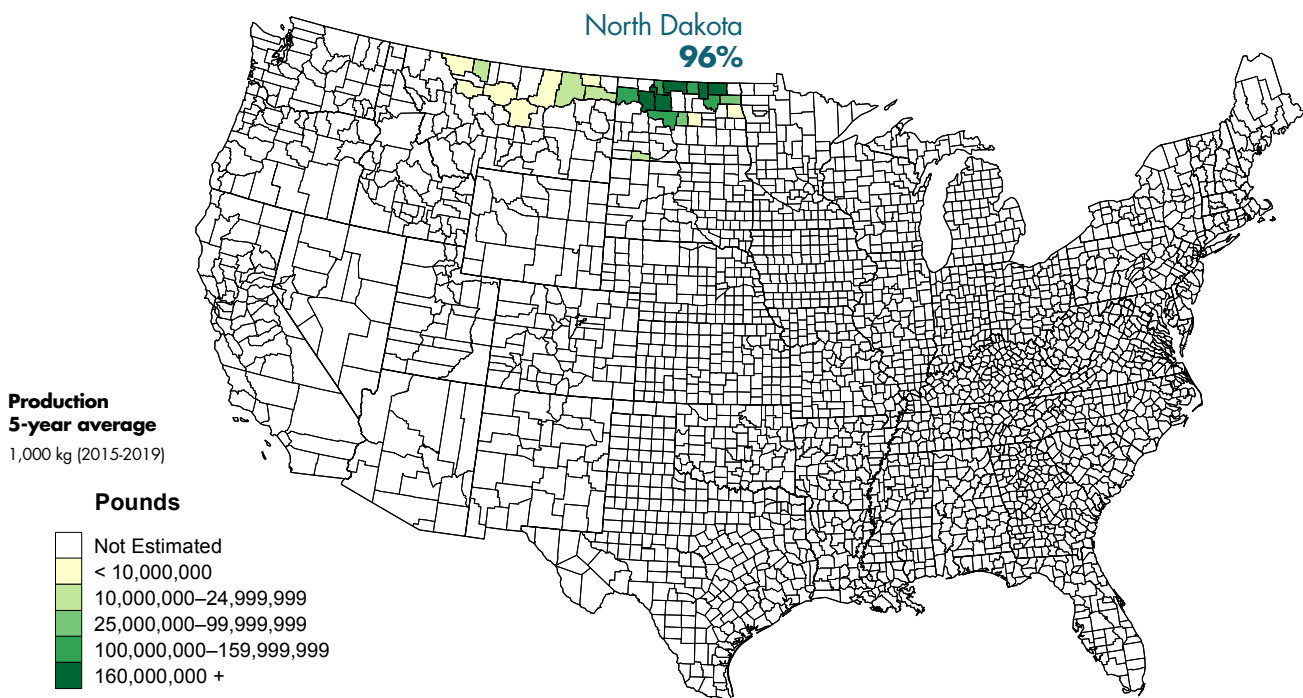
Source: USDA, National Agricultural Statistics Service

FIGURE 20. U.S. SOYBEAN PRODUCTION BY COUNTY (2022)



Source: USDA, National Agricultural Statistics Service

FIGURE 21. U.S. CANOLA PRODUCTION BY COUNTY (2018)



Source: USDA, National Agricultural Statistics Service
% Percentage value indicates percent of national production.

2.4 BIOFUEL YIELDS FROM FEEDSTOCKS

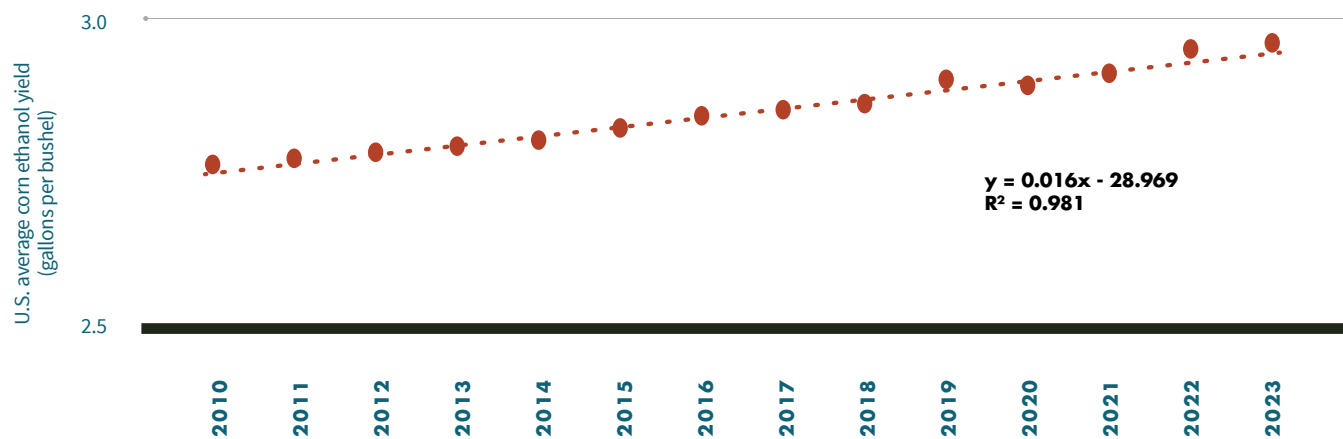
Based on USDA data, the efficiency of U.S. ethanol plants at converting corn into ethanol has increased steadily since at least 2010. These increases are attributable to improvements in ethanol plant designs and operating practices developed through experience as well as regular improvements in the efficiency of the enzymes used to access the starch contained in the corn feedstock and convert it to fermentable sugars. As seen in [Figure 22](#), the observed yields at U.S. corn ethanol plants have grown from 2.76 gallons of ethanol per bushel of corn in 2010 to 2.96 gallons per bushel in 2023. This steady rate of improvement, 0.016 gallons per bushel per year as indicated by the dashed line, directly improves the CI of ethanol, as fewer inputs are required for each gallon produced. This trend shows no sign of leveling off but will ultimately be constrained by a theoretical maximum of about 3.0 gallons per bushel set by the starch content of the corn.³⁷

As BD production employs a diverse mix of feedstocks including soybean oil, canola oil, distillers



corn oil, inedible tallow, and used cooking oil (UCO), and this mix varies depending on competing supply-demand and economic factors, there is not a comparable historical dataset on the evolution of BD yields and conversion efficiencies. Iowa State University (ISU) maintains a historical model for soybean oil BD production via the continuous flow process used at larger-scale plants and estimates an average yield of 1 gallon of BD (and 1.04 pounds of glycerin) produced from 7.6 pounds of soybean oil.³⁸ The 2022 Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model estimates that Honeywell UOP’s RD process yields 1 pound of RD for every 1.26 pounds of vegetable oil feed.

FIGURE 22. AVERAGE ETHANOL YIELD AT U.S. CORN ETHANOL PLANTS (2010–2023)

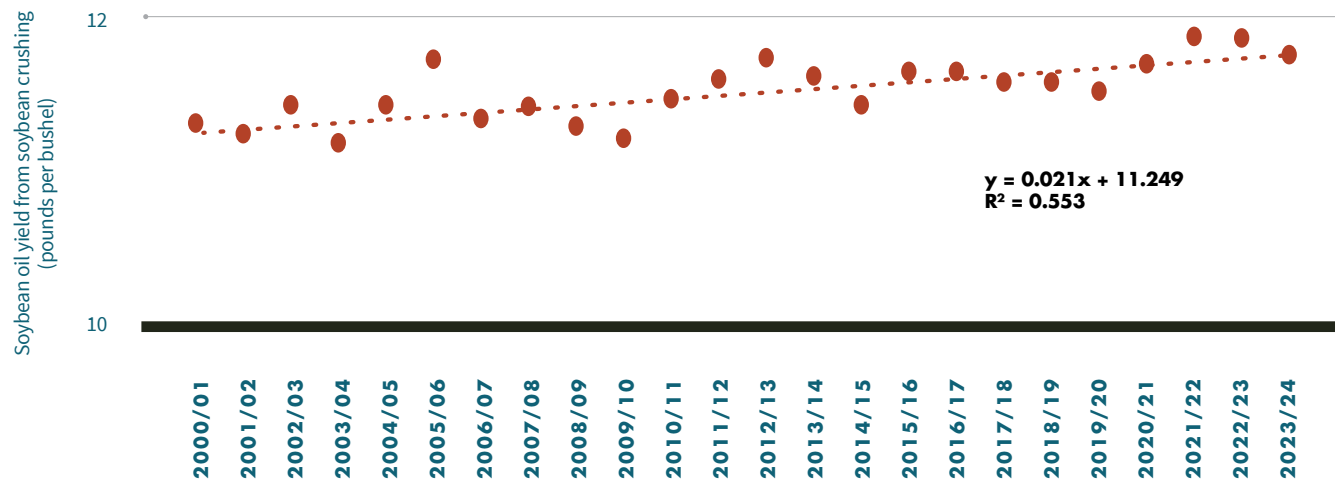


Sources: USDA; Stillwater analysis

³⁷ Based on 56 pounds per bushel of corn and a 62% by weight starch content (Penn State | [Composition of Corn and Yield of Ethanol from Corn](#)). This limit does not consider the ability to produce incremental ethanol from conversion of the corn kernel fiber, a technology which is slowly gaining use in the U.S.

³⁸ ISU | [Historical Biofuel Operating Margins](#)

FIGURE 23. AVERAGE SOYBEAN OIL YIELDS FROM U.S. SOYBEAN CRUSHING (2000/01-2023/24 PROJ)



Sources: USDA; Stillwater analysis

USDA tracks the yield of soybean oil from soybeans crushed in the U.S. on a market-year basis. As shown in [Figure 23](#), recovery of soybean oil from soybeans has generally grown from 11.30 pounds per bushel in the 2000/01 market year to a projected 11.75 pounds per bushel in the 2023/24 market year to date. While the trend line shows yield increasing by an average of 0.021 pounds per bushel per year, there is substantial year-to-year variation; this is attributable to the oil content of seeds varying somewhat based on growing conditions that can vary each year. While soybeans have historically been grown for the meal, with the oil being a lower-value by-product,³⁹ the strong growth in biofuels demand has started to shift the balance to an extent that the soybean oil is becoming the more valuable product; as this trend continues, seed companies will continue to focus on developing soybean varieties with higher oil contents. In addition to increasing oil yield through genetics, farmers and industry are actively seeking to increase biomass availability through the growth and harvest of winter annual oilseeds. These crops, which are generally from the Brassicaceae family, include pennycress, camelina, carinata, and winter

canola. Each of these four crops has the potential to yield a significant additional amount of oil per acre when grown over winter between traditional corn and soybeans. Each of these crops is at its own stage of commercialization and will likely be targeted in different regions of the country. As of this writing, these volumes are negligible.

RD has not been produced at scale via hydrogenation of oils for as long as ethanol and BD, so advances in the technology continue to be developed. These advances seek to increase yields of valuable products—RD and SAF—while shifting production away from less valuable co-products—renewable propane, renewable butane, and RN. Since changing operating conditions to maximize SAF production over RD production generally increases the output of these lighter co-products, new catalysts are being developed to reduce this tendency. The data on these new technologies are generally kept confidential by their providers. For this report, we utilize yields of RD based on the Honeywell UOP process as reported in the 2022 GREET model.

39 In fact, the biodiesel industry was initially developed in order to create an outlet for excess soybean oil.



TABLE 2. GALLON PER ACRE YIELDS OF ETHANOL, BD, AND RD (2022)

PRODUCT	FEEDSTOCK	Pounds of Feedstock per Gallon of Product	2022 Yield, Bushels per Acre	Gallons of Fuel per Acre
Ethanol	Corn	19.0	173.3	510.7
Ethanol	Sorghum	19.0	41.1	121.1
Biodiesel	Soybeans	38.6	49.5	76.9
Biodiesel	Canola	17.3	29.4	102.0
Renewable Diesel	Soybeans	41.6	49.5	71.3
Renewable Diesel	Canola	18.6	29.4	94.7

Sources: USDA; GREET 2022; Stillwater analysis

To enable comparison of the acreage requirements to produce ethanol (from corn and grain sorghum) and BD and RD (from soybeans and canola), the gallons of fuel produced from each acre of crop, based on 2022 yields as reported by USDA, are summarized in [Table 2](#).

2.5 FUTURE DEMANDS FOR FEEDSTOCKS AND ACREAGE

Our assessment of future demands for biofuel feedstocks and acreage is derived from the domestic production outlooks for ethanol, BD, and RD contained in the Reference case of the EIA’s 2023 Annual Energy Outlook (AEO).⁴⁰ This assessment is based on enacted laws and regulations as of the fall of 2022, when EIA’s analysis was done. It includes a preliminary view of the impacts of the IRA;⁴¹ it does not include proposed light-duty and heavy-duty vehicle GHG emission and fuel economy standards proposed by the Biden administration in 2023. The projected decline in BD and RD volumes between 2027 and 2028 is due to the expiration of the clean fuel production credit (CFPC, also known as the 45Z credit for the relevant section of the U.S. tax code); if Congress extends this credit (as was repeatedly done for the biomass-based diesel blender’s tax credit [BTC] throughout its history), this drop-off would be postponed or potentially eliminated. Those impacts, and a more refined view of the IRA incorporating evolving guidance from the Internal Revenue Service (IRS), will be factors in the 2025 AEO, which is expected to be published in March 2025.⁴² [Table 3](#) summarizes EIA’s outlook for domestic production of ethanol, BD, and RD.

Table 3 shows that EIA expects 2024 to be the peak for U.S. ethanol, BD, and RD production given the current federal and state incentive programs. Unless new programs can rapidly increase the demand for ethanol via E85 and E15, the increase of new gasoline fuel economy standards and the decrease in the production of flex-fueled vehicles (FFVs) will result in the gradual reduction in the U.S. demand for ethanol. As U.S. production of corn and ethanol becomes more efficient, less corn grown on fewer acres will be required to satisfy domestic demand for current ethanol applications. The longer-term outlook for U.S. ethanol production depends on whether or not demand for ethanol as a feedstock for production of SAF via the Alcohol-to-Jet process becomes material. This, together with competing demands for U.S. crop acreage will determine overall U.S. corn production and export levels.

The situation for BD and RD will be similar to ethanol, with a gradual reduction in the demand for both through 2035. Since BD and RD use the same feedstocks, and there is no surplus in feedstock availability, state LCF regulations will play a large role in determining how these feedstocks are divided between the two alternative diesel fuels.

TABLE 3. EIA OUTLOOK FOR DOMESTIC BIOFUELS PRODUCTION, MILLION GALLONS (2022–2035)

FUEL	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Ethanol	15,008	14,724	15,776	15,664	15,627	15,606	15,699	15,592	15,511	15,442	15,421	15,355	15,352	15,461
Biodiesel	1,640	1,445	1,599	1,470	1,443	1,467	1,092	1,161	1,228	1,267	1,260	1,281	1,258	1,232
Renewable Diesel	2,081	2,486	2,533	2,446	2,451	2,454	2,050	2,036	2,053	2,084	2,161	2,171	2,218	2,269
Biodiesel	17.3	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	29.4	102.0

Sources: EIA; Stillwater analysis

40 EIA | Annual Energy Outlook (AEO) Table 11: Petroleum and Other Liquids Supply and Disposition

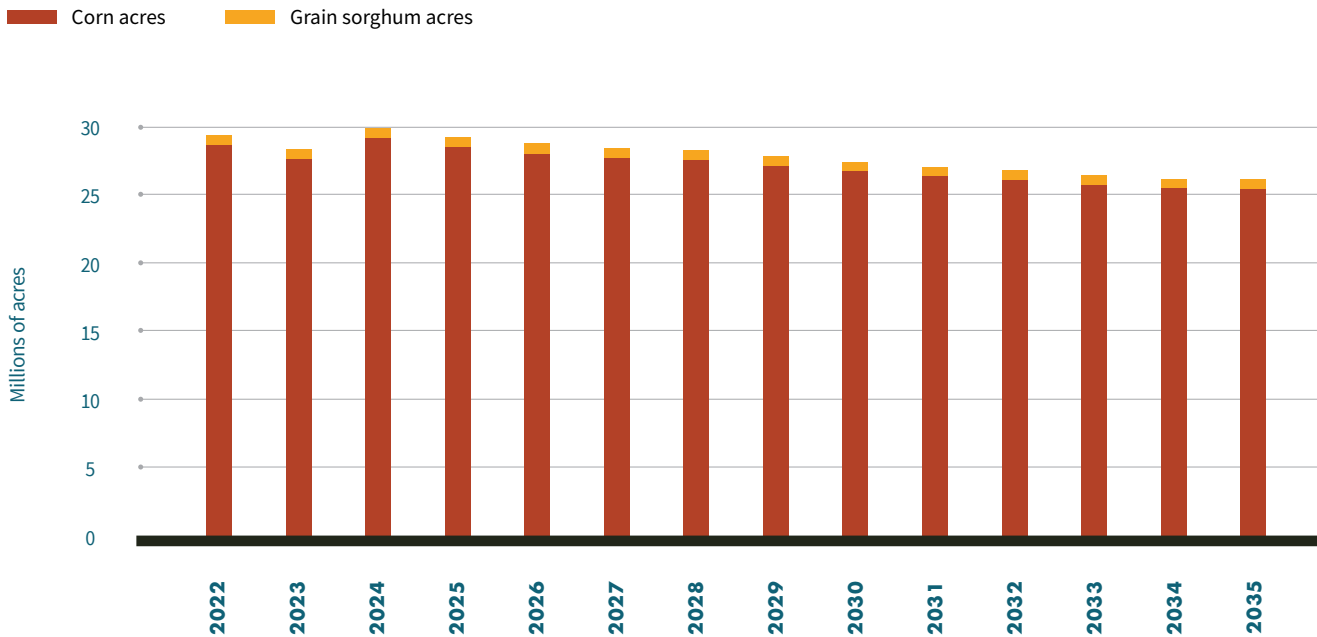
41 Including the expiration of the clean fuels production credit (§ 45Z) after 2027.

42 EIA is not producing an AEO for 2024 as they are in the midst of a major update to the models they use for this work.

To estimate the amount of corn and grain sorghum acreage needed to enable this volume of domestic ethanol production, we first assume that 99% of future production will be derived from corn grain and 1% from grain sorghum.⁴³ The efficiency of conversion of corn and sorghum to ethanol is based on an extrapolation of the historical trend shown in Figure 22, up to a limit of 3 gallons per bushel first achieved in 2026. Per-acre yields for corn and grain sorghum are assumed to continue to grow in line with the historical trends illustrated in Figure 22. Utilizing these inputs suggests that the gross acreage requirements peak at just below 30 million acres in 2024 and then slowly decline as shown in Figure 24. This trend is driven by relatively stable to declining volumetric demand for ethanol and increasing ethanol yields per bushel of corn and grain sorghum, combined with increasing agricultural yields of these feedstocks.



FIGURE 24. PROJECTED U.S. ETHANOL GROSS FEEDSTOCK ACREAGE REQUIREMENTS (2022-2035)



Sources: EIA; USDA; Stillwater analysis

⁴³ Thus, we assume that domestic ethanol production from corn fiber, wheat, or other feedstocks remains a negligible portion of the mix. This is conservative as it will slightly overstate the corresponding demand for corn and grain sorghum acreage.

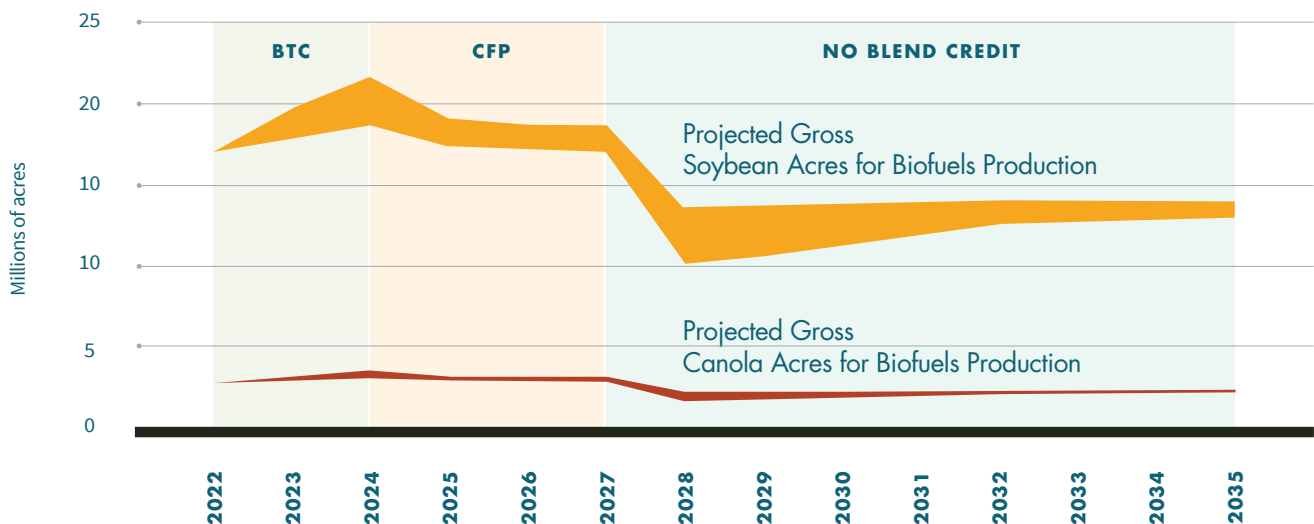
Key factors that could influence this outlook include:

- Domestic gasoline demand—This will be impacted by trends in vehicle miles traveled, the pace at which the domestic vehicle fleet transitions to electric vehicles, and the pace of vehicle turnover to vehicles with higher fuel economy.
- Adoption of higher ethanol blends—EIA’s outlook assumes that retail gasoline sales are predominantly E10 for this period. A more rapid transition to E15, potentially enabled by removal of existing summertime Reid vapor pressure constraints on E15, would enable a significant increase in ethanol demand.
- Potential use of ethanol as a feedstock for SAF production—Ethanol is a potential feedstock for production of SAF via the alcohol-to-jet (ATJ) process. Commercialization of this technology depends on SAF-specific government incentives, SAF plant investments, and choices that the IRS has yet to make on the methodology for determining the CI of SAF produced from corn ethanol via the ATJ process. Our current outlook

assumes that ATJ demand does not become significant before 2035.

To estimate the future demand for soybean and canola acreage required for EIA’s projected production of BD and RD, we need to take into account that, unlike the case for ethanol (where nearly all production comes from corn and grain sorghum), the mix of feedstocks for BD and RD production is more diverse and variable. Thus, we consider two potential demand scenarios for soybeans and canola: one in which soybean oil and canola oil remain at the same share of combined BD and RD feedstock as in recent history (32.5% for soybean oil, 6.8% for canola oil) and another in which soybean oil and canola oil combined (83% soybean oil, 17% canola oil) serve as the marginal feedstock for all increases and decreases in projected BD and RD production. To translate the projected feedstock demands to the required crop acreage, it is assumed that BD and RD yields per pound of feedstock remain constant throughout this time frame, and per-acre yields of soybeans and canola increase in line with historical trends. This results in the two bands shown in [Figure 25](#).

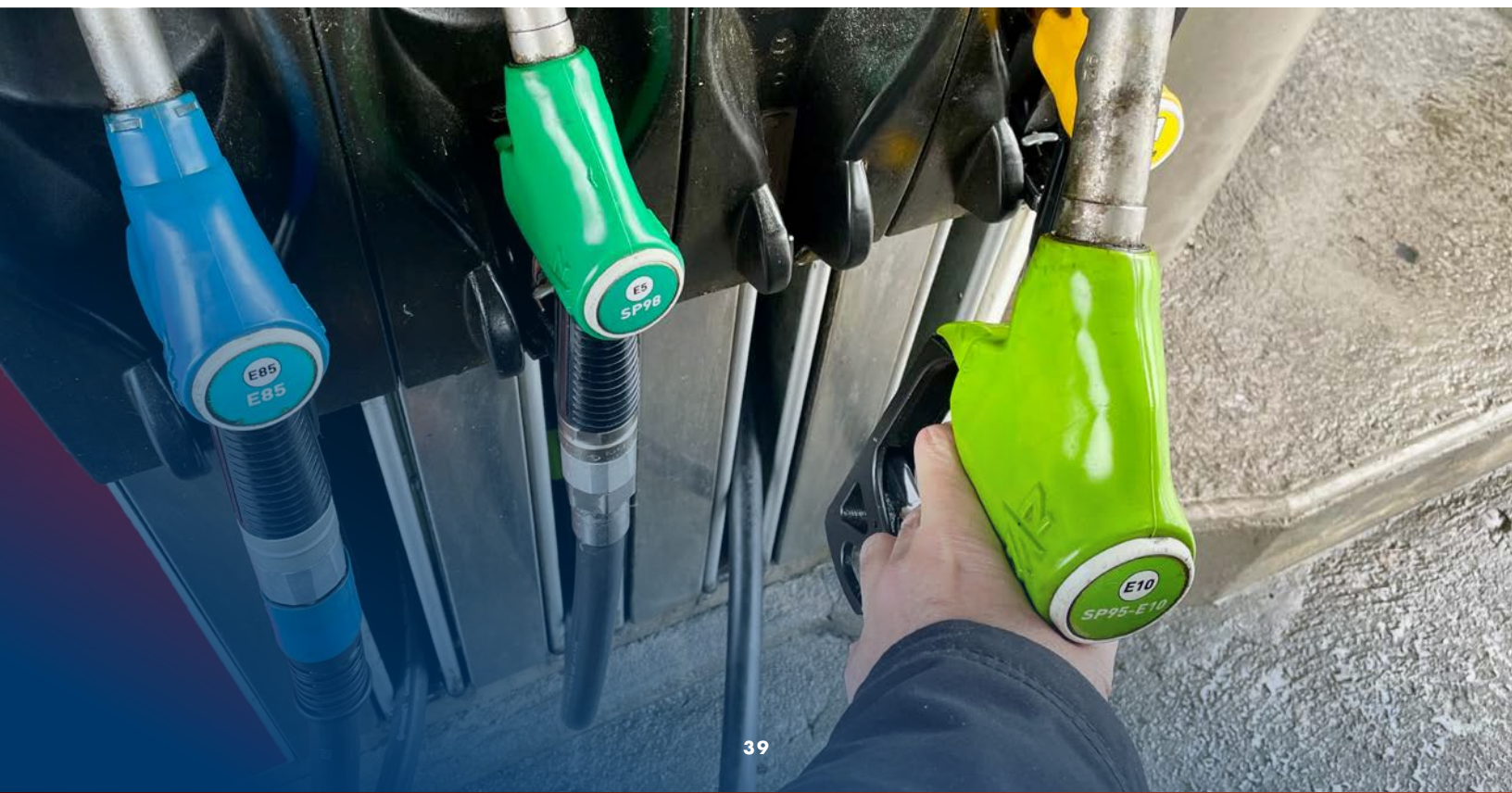
FIGURE 25. PROJECTED U.S. BD AND RD GROSS FEEDSTOCK ACREAGE REQUIREMENTS (2022–2035)



Sources: EIA; USDA; Stillwater analysis

Key factors that could influence this outlook include:

- The future of federal biofuel blending credits—In formulating their outlook for biofuels demand in the 2023 AEO, the basis for this analysis, EIA assumed current law as of the fall of 2022. This means that the BTC ends after 2024 and is replaced with the CFPC for 2025 through 2027, and there are no CFPC blending credits for BD or RD after 2027. This results in a small reduction in projected demands in 2025 and a larger reduction for 2028 onward. If Congress elects to extend the CFPC past 2027 or establishes an alternative, EIA’s demand outlook for these fuels would be expected to increase; the extent of any increase depends on the nature of any future federal incentives.
- Future demand for liquid diesel fuel—If the U.S. diesel fleet transitions to other fuels more quickly than projected by EIA, demand for RD and BD may be expected to decrease somewhat.
- Availability of other potential feedstocks—The bands shown in Figure 25 assume a mix of available feedstocks similar to that in recent history. If alternative feedstocks become commercially available at competitive costs, this could reduce demand for soybean oil and canola oil as biofuel feedstocks. Potential new feedstocks include cover crops such as camelina, pennycress, and carinata. Additionally, potential breakthroughs in the cost of non-lipid RD pathways such as Fischer-Tropsch (FT) could make alternative feedstocks such as forestry waste and municipal solid waste viable competitors.
- Development of demand for SAF—Currently, nearly all production of SAF is from the same feedstocks as BD and RD. Hence, any near-term growth in domestic SAF production is most likely to come at the expense of feedstock availability for BD and RD. Potential breakthroughs in the development of ATJ or FT technologies could offset this factor.





SECTION 3.

Biofuels Production

In this section, we look at the inputs into biofuels production broken down into two primary components: feedstock production and feedstock conversion to biofuel. For the three biofuels—ethanol, BD, and RD—similarities in the stages of production can be presented in a generalized flow. The production can be broken into three stages, with generalized inputs for each step.

[Figure 1](#) at the beginning of this report shows the steps and their inputs. The first step is farming to produce the crop that becomes biofuel feedstock.

The second step is feedstock production, which prepares the crop so it becomes feedstock. The last step is the conversion of the feedstock to biofuels and by-products.

The production of crop-based renewable fuels arches over two industries: agriculture and the smaller biofuels industry. As illustrated in Figure 1, the portion of the agriculture sector that produces biofuel feedstocks also supplies the global food and feed market, which is much larger than the biofuel feedstock market. To properly describe the inputs and costs of biofuels production, this section breaks the topic into two components—the inputs into feedstock production (i.e., the agricultural sector producing the biofuel feedstocks) and the feedstock conversion to biofuels (i.e., biofuels production). We outline these inputs for each fuel type.

3.1 ETHANOL PRODUCTION INPUTS

The utilities required to produce ethanol include electricity, steam, and cooling water; the quantities of each range significantly within the literature reporting on this subject. Typical utilities usage can be estimated by using the GREET model, published annually by Argonne National Laboratory.⁴⁴ It covers required inputs and emission factors for a wide range of fuel and vehicle technologies, with a focus on the current state of technology as practiced in the U.S. This model is updated annually based on extensive review of industry data, with the 2022 model being the most current version as of this writing. There are many other published studies on this topic, most of which are done on a one-off basis in different years; as a result, they have different assumptions of crop yields, agricultural input requirements, process technologies, and allocation of inputs between the biofuel and co-products. For this report, we focus on the GREET model, as it is widely respected in the industry and regularly updated.

[Table 4](#) summarizes the water, electricity, and natural gas inputs required—as reported in the 2022 GREET model—for production of corn ethanol at a dry mill plant with corn oil co-production; this is the dominant technology currently in use for ethanol production in the U.S. These inputs are split between those required to produce corn and transport it

to the ethanol plant (corn production) and those required to convert the corn to ethanol and co-products and transport the product to market (ethanol production).

- **Corn production**

Water—In most of the U.S. corn belt, water is primarily supplied from rainfall. Irrigation is used in drier areas or during drought

Natural gas—Natural gas is primarily used as an input to produce fertilizers and herbicides. Additionally, natural gas and propane are utilized as needed to dry corn when weather conditions force the crop to be harvested before it naturally dries to the 15% maximum moisture content required for long-term storage.

Petroleum—Fuel, predominantly diesel, is needed to power agricultural equipment used to prepare the field for planting, plant the crop, operate irrigation equipment where needed, spread fertilizer, and harvest the crop.

- **Ethanol production**

Water—Water is primarily utilized as part of the fermentation media, for production of steam used for process heating, and for process cooling. Most U.S. plants operate at or near zero water discharge (i.e., water brought into the plant is recycled repeatedly so that freshwater input is limited to that required to replace evaporative losses).

TABLE 4. INPUT REQUIREMENTS FOR ONE GALLON OF ETHANOL VIA U.S. DRY MILL CORN ETHANOL PLANTS WITH CORN OIL CO-PRODUCTION

INPUT	UNITS	CORN PRODUCTION	ETHANOL PRODUCTION	TOTAL
WATER	gallons/gallon	28.3	3.3	31.6
ELECTRICITY	kWh/gallon	n/a	0.63	0.63
ENZYMES	\$/gallon	n/a	0.034	0.034
NATURAL GAS*	BTU/gallon	5,426*	22,386	27,812*
PETROLEUM	DGE/gallon	0.027	0.008	0.035

Sources: GREET model; Stillwater analysis

*Includes natural gas used to produce fertilizers

44 GREET model

Electricity—Electricity is primarily used to provide power to the mill and to the centrifuges used to separate the distillers grains from the ethanol-water mix produced in the fermenters and to drive the various pumps required to move liquid streams through the plant. Plants recovering corn oil typically have an additional electric-powered centrifuge to separate corn oil from the thin stillage. (The GREET model assumes a grid average mix of primary energy for power generation.)

Natural gas—Natural gas is primarily used to produce steam required for process heating and to dry the distillers grains co-product. The drying of distillers grains represents about 30% of natural gas consumption at plants that produce dried distillers grains. The replacement of molecular sieve dryers (required to produce anhydrous ethanol) with membrane dryers, a technology upgrade that is becoming increasingly common in the industry, offers further reductions in natural gas usage.

Enzymes—Two enzymes, alpha-amylase and glucoamylase, are used to catalyze conversion of the starch molecules in the corn into sugar molecules that can be fermented to ethanol.



3.2 BIODIESEL PRODUCTION INPUTS

[Table 5](#) summarizes the inputs required for growing soybeans and for BD production from soybean oil at U.S. plants. Unlike ethanol, where nearly all production comes from a single feedstock (corn), U.S. BD producers use a mix of feedstocks (primarily soybean oil, canola oil, inedible tallow, distillers corn oil, and UCO). This mix can vary significantly among individual producers and over time based on local availability and short-term economics. As input requirements vary significantly between feedstocks, both for feedstock production and conversion to BD, the GREET model reports input requirements for individual feedstocks. As soybean oil is the most commonly used feedstock, we report the GREET model values based on soybean oil.

- **Soybean oil production**—This includes inputs required both to grow soybeans and to extract the soybean oil at a crushing plant, with soy meal as a co-product.

Water—Water consumption is primarily to grow the soybeans. In most soybean-producing regions of the U.S., the water is primarily derived from rainfall, with irrigation used only when required by drought.

Natural gas—Natural gas is required to produce fertilizer and herbicides and to produce a portion of the electricity required for crushing the soybeans to extract the oil. (The GREET model assumes a grid average mix of primary energy for power generation.)

Petroleum—Fuel, predominantly diesel, is needed to power agricultural equipment used to prepare the field for planting, plant the crop, operate irrigation equipment where needed, spread fertilizer, and harvest the crop.

- **Soy biodiesel production**

Water—Water consumption is primarily for washing stages in the process to separate the BD product from excess methanol reactant and the co-product glycerin. Water is recycled in the process to minimize freshwater demand.

TABLE 5. INPUT REQUIREMENTS FOR U.S. SOYBEAN OIL BD PRODUCTION

INPUT	UNITS	SOYBEAN OIL PRODUCTION	SOY BIODIESEL PRODUCTION	TOTAL
WATER	gallons/gallon	74.1	0.7	74.8
NATURAL GAS*	BTU/gallon	1,779*	18,186*	19,965*
METHANOL	lbs/gallon	n/a	0.71	0.71
PETROLEUM	DGE/gallon	0.023	0.010	0.033

Sources: GREET model; ISU Biodiesel Profitability model; Stillwater analysis

*Includes natural gas used to produce methanol and fertilizers

TABLE 6. INPUT REQUIREMENTS FOR U.S. CANOLA OIL BD PRODUCTION

INPUT	UNITS	CANOLA OIL PRODUCTION	CANOLA BD PRODUCTION	TOTAL
WATER	gallons/gallon	1.79	0.49	2.28
NATURAL GAS*	BTU/gallon	10,600*	19,200*	29,700*
METHANOL	lbs/gallon	n/a	0.71	0.71
PETROLEUM	DGE/gallon	0.032	0.010	0.042

Sources: GREET model; ISU Biodiesel Profitability model; Stillwater analysis

*Includes natural gas used to produce methanol and fertilizers.

Natural gas—Natural gas is used to produce methanol, which is consumed in the production of BD, and to produce power.

Methanol—Methanol reacts with the triglyceride molecules in the soybean oil to convert them to the mix of methyl esters in BD.

Similar to Table 5, [Table 6](#) summarizes the inputs required for growing canola and for BD production from canola oil at U.S. plants.

3.3 RENEWABLE DIESEL PRODUCTION INPUTS

[Table 7](#) summarizes the inputs required for growing soybeans and for RD production at U.S. plants.

Unlike ethanol, where nearly all production comes from a single feedstock (corn), U.S. RD producers use a mix of feedstocks (primarily soybean oil, canola oil, inedible tallow, distillers corn oil, and UCO), as shown in Figure 7. This mix can vary significantly among individual producers and over time based on local availability and short-term economics.

As input requirements vary significantly between feedstocks, both for feedstock production and conversion to RD, the GREET model reports input requirements for individual feedstocks. As soybean oil is the most commonly used feedstock, we report the GREET model values based on soybean oil.

- **Soybean oil production**—This includes inputs required both to grow soybeans and to extract the soybean oil at a crushing plant.

Water—Water consumption is primarily to grow the soybeans. In most soybean-producing regions of the U.S. the water is primarily derived from rainfall, with irrigation used only when required by drought.

Natural gas—Natural gas is required to produce fertilizer and herbicides and to produce a portion of the electricity required for crushing the soybeans to extract the oil. (The GREET model assumes a grid average mix of primary energy for power generation.)

TABLE 7. INPUT REQUIREMENTS FOR U.S. SOYBEAN OIL RD PRODUCTION

INPUT	UNITS	SOYBEAN OIL PRODUCTION	SOY RD PRODUCTION	TOTAL
WATER	Gallons/gallon	77.0	1.1	78.1
NATURAL GAS*	BTU/gallon	1,847*	22,510*	24,357*
HYDROGEN	SCF/gallon	n/a	1500–2500	1500–2500
PETROLEUM	DGE/gallon	0.024	0.011	0.035

Sources: GREET; Stillwater analysis

*Includes natural gas used to produce hydrogen and fertilizers.

TABLE 8. INPUT REQUIREMENTS FOR U.S. CANOLA OIL RD PRODUCTION

INPUT	UNITS	CANOLA OIL PRODUCTION	CANOLA BIODIESEL PRODUCTION	TOTAL
WATER	Gallons/gallon	1.86	0.87	2.28
NATURAL GAS*	BTU/gallon	11,000*	23,500*	34,500*
HYDROGEN	SCF/gallon	n/a	1500–2500	1500–2500
PETROLEUM	DGE/gallon	0.033	0.011	0.045

Sources: GREET; Stillwater analysis

*Includes natural gas used to produce hydrogen and fertilizers.

Petroleum—Fuel, predominantly diesel, is needed to power agricultural equipment used to prepare the field for planting, plant the crop, operate irrigation equipment where needed, spread fertilizer, and harvest the crop.

- Soy renewable diesel production**

Water—Water consumption is primarily for steam generated to provide process heat. Water is recycled in the process to minimize freshwater demand.

Natural gas—Natural gas is used to produce hydrogen, which is consumed in the production of RD, as fuel for process heaters, and for production of power.

Hydrogen—Hydrogen is reacted with the feedstock to convert it into RD and co-products.

Similar to Table 7, [Table 8](#) summarizes the inputs required for growing canola and for RD production from canola oil at U.S. plants.

We have excluded here any analysis of sorghum and sugarcane feedstocks, as sorghum is not produced in material quantities in the U.S. nor is it used as a primary feedstock for biofuels, and the amount of sugarcane used for ethanol production in the U.S. is so small as to be irrelevant. Most of the sugarcane ethanol used in the U.S. was produced in Brazil. As the focus of this paper is on U.S. production, we will not expand on sugarcane or sorghum inputs.

SECTION 4.

Ancillary Commercial Products

As is common with most chemical processes, the production of ethanol, BD, RD, and SAF is accompanied by the production of co-products or by-products.⁴⁵ More background on these ancillary products is provided in this section.

4.1 ETHANOL CO-PRODUCTS

The major components of a kernel of corn, grain⁴⁶ sorghum, or other grain are starch, protein, fiber, oil, and water. The fermentation process converts the starch to ethanol and CO₂, with about 6.3 pounds of CO₂ being produced for each gallon of ethanol. Corn and grain sorghum contain 3%–6% oil; most grain ethanol plants in the U.S. recover a portion of that oil, typically between 0.6 and 1.2 pounds per bushel of grain.⁴⁷ The rest of the corn kernel, including all the protein and fiber, unrecovered oil, and unconverted starch, is recovered out of the fermentation process as wet distillers grains with

solubles (WDGS); this is a slurry containing about 70% water. We discuss the disposition of these co-products in the subsections that follow.

4.1.1 CARBON DIOXIDE

The CO₂ stream coming off ethanol fermenters is very pure. Many grain ethanol plants include equipment to capture this gas for sale as either food-grade (used in carbonated beverages including beer) or industrial grade (used for, e.g., dry ice and fire extinguishers) CO₂. This usage is limited by the demand for CO₂ in the vicinity of the ethanol plant as long-distance transport of CO₂ is relatively costly. A few ethanol plants currently capture this CO₂ and inject it into permanent storage wells to lower the CI of their ethanol production and qualify for federal 45Q tax credits.⁴⁸ The increased value of 45Q tax credits with passage of the IRA and the increasing value of CI reductions in states with LCF regulations is expected to increase this practice. Currently, the RFS does not incentivize carbon capture and storage practices.

⁴⁵ The distinction between the terms “co-product” and “by-product” is somewhat arbitrary. “Co-product” is commonly used to denote those ancillary products that materially contribute to the overall value of the production process, whereas “by-product” is generally used for ancillary products of lesser or negative value.

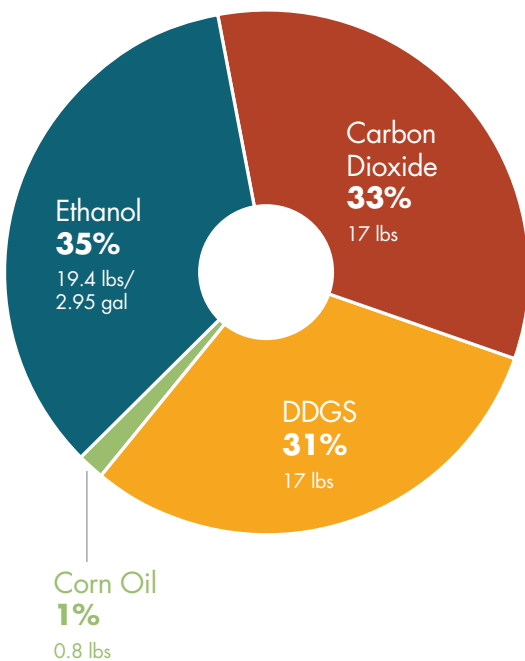
⁴⁶ E.g., wheat, barley, and rye.

⁴⁷ One bushel of corn or grain sorghum is 56 pounds with a maximum 15% moisture content.

⁴⁸ 26 U.S. Code § 45Q - Credit for Carbon Oxide Sequestration

An overview of the mix of products from processing a bushel of corn at a U.S. dry mill ethanol plant in 2022 is presented in [Figure 26](#).

FIGURE 26. AVERAGE PRODUCT MIX (BY WEIGHT) FROM U.S. DRY MILL ETHANOL PLANTS (2022)



Sources: USDA; Stillwater analysis

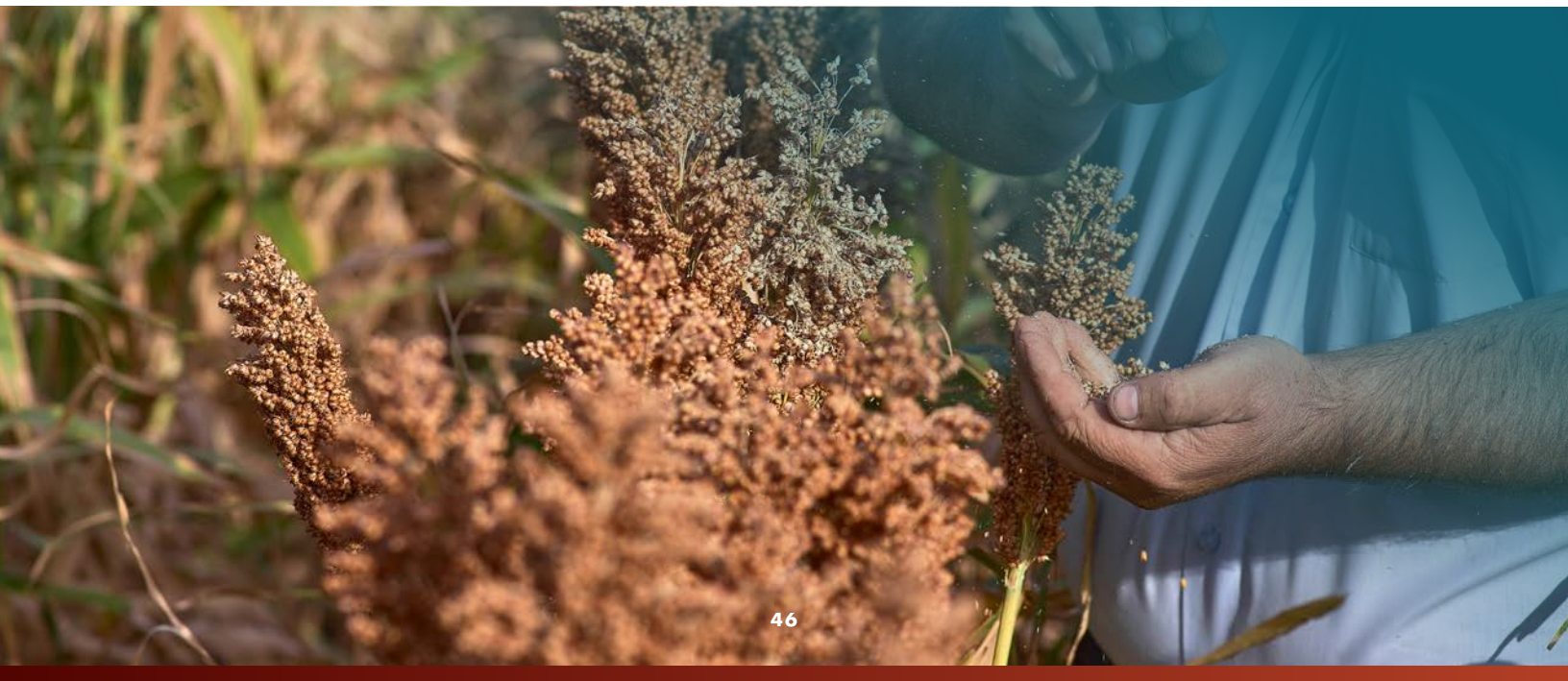
4.1.2 CORN/GRAIN SORGHUM OIL

The practice of recovering non-food-grade corn or grain sorghum oil at dry mill ethanol plants⁴⁹ began about 15 years ago and has grown to be very common practice due to growth in demand for this product as a feedstock for BD and RD production. It also has some use as animal feed. The technology for oil recovery has steadily improved, allowing a growing proportion of the oil content of the grain to be recovered. As this is a non-food-grade product, its value is dependent upon demand for this oil as a BD/RD/SAF feedstock. Accordingly, changes in any of the federal and state regulations and incentives driving demand for these fuels directly impact the economics of recovery of the oil from the distillers grains.

4.1.3 DISTILLERS GRAINS

A slurry containing all parts of the grain kernel other than the starch and recovered oil is produced in the grain ethanol production process. This slurry, known as WDGS, contains about 70% water and can either be sold to local feedlots or dried for sale in more remote markets. Given that the WDGS quickly rots,

⁴⁹ The large majority of U.S. grain ethanol production occurs at dry mill plants, relatively low-capital facilities optimized for fuel-grade ethanol production. There are also several wet mill plants in operation; these plants are considerably more capital-intensive and are designed to maximize total value from the mix of products from the corn kernel; the corn oil produced at these facilities is food grade and not approved for use as a biofuel feedstock.



it must be consumed within two to three days in order to be marketable; thus, its commercial value is limited to feedlots located within a short drive of the ethanol plant. As most ethanol plants do not have sufficient demand for WDGS in the immediate vicinity, they dry the WDGS to less than 10% moisture in order to produce a high-protein product known as DDGS, which can be stored for longer periods.⁵⁰ Production of DDGS requires the use of natural-gas-fired dryers; the natural gas consumed in these dryers represents approximately one-third of the natural gas demand at a dry mill ethanol plant. This natural gas demand is a key differentiator of CI between dry mill ethanol plants; plants that are able to place most of their distillers grains as WDGS earn a significantly lower (more favorable) CI for their ethanol production, and this represents an additional source of value. Future growth of state LCF programs beyond California, Oregon, and Washington may, therefore, encourage more ethanol producers to work on securing local WDGS demand in order to reduce their CIs. Production of distillers grains displaces demand for soy meal, corn grain, and other grains as livestock feed.

4.2 BIODIESEL CO-PRODUCT

BD is produced by reacting the lipid feedstock (one of the many types of fats, oils, and greases) with methanol to produce BD and crude glycerol.⁵¹ Approximately 10 pounds of crude glycerol is produced for each 100 pounds of BD. The crude glycerol contains residual moisture and other impurities that must be removed in order to produce a commodity-grade glycerol. Some BD producers refine their crude glycerol prior to sale, while others sell the crude product to third parties for the required purification.

Once refined, glycerol has a wide range of markets, including use as a moisturizer, humectant, and lubricant in a variety of personal care products; a sweetener and preservative in food products; and a component used to adjust the taste and smoothness of oral medications such as cough medicines. The growth of glycerol volumes produced as a co-product of BD manufacture has largely displaced manufacture of glycerol via petrochemical processes. Accordingly, petrochemical production of glycerol would likely need to increase if BD production were to decline.

4.3 RENEWABLE DIESEL AND SAF CO-PRODUCTS

The large majority of RD and SAF currently being supplied to the U.S. market is derived from hydrotreatment of lipid feedstocks, sometimes referred to as the hydroprocessed esters and fatty acids (HEFA) process. Additional processes currently being developed for commercialization of these fuels include gasification of waste feedstocks combined with an FT process to produce a range of hydrocarbons that may then undergo further processing to optimize the product mix (both RD and SAF) and the ATJ process, which can convert ethanol or isobutanol to, primarily, SAF. A number of other processes are currently in various stages of technological development with no clear timeline for commercialization.

A common feature of the HEFA, FT, and ATJ processes is that they all produce mixtures of paraffins and isoparaffins that can, to some extent, be optimized to maximize yield of the desired RD or SAF products. In addition to the desired product, they co-produce renewable fuel gas, renewable propane, RN, and, in the case of the FT process, paraffinic waxes. We discuss the disposition of these co-products in the subsections that follow.

⁵⁰ DDGS is sufficiently stable that it is commonly sold to markets around the globe.

⁵¹ Also known as glycerin.

4.3.1 RENEWABLE FUEL GAS

Renewable fuel gas results from cracking reactions that occur as part of both the primary reaction and additional processing to optimize the product mix. The primary use of this fuel gas is to displace demand for pipeline natural gas that would otherwise be required to produce hydrogen or provide heat and steam utilized within the plant. As a co-product, renewable fuel gas reduces the plant's cost for purchase of natural gas. This displacement of natural gas purchases also lowers the CI assigned to the primary products, thereby increasing their value in states with LCF programs and across the country, given the CFPC provision of the IRA.

4.3.2 RENEWABLE PROPANE (RENEWABLE LIQUIFIED PETROLEUM GAS)

The HEFA process converts the glycerin backbone of FOG feedstocks to propane. This propane can be utilized internally in the same manner as renewable fuel gas. Alternatively, it can be separated and sold as a direct substitute for fossil propane, particularly where there are local markets that provide value for the renewable attribute of this product. The two primary uses for propane are as a heating fuel, particularly in areas where pipeline natural gas is not readily available, and as a petrochemical feedstock. A much smaller use of propane is for transportation fuel in specially designed vehicles; as a transportation fuel, renewable propane is eligible for RFS RINs (1.1 D5 RINs per gallon) and LCF and CFPC credits where applicable. Due to the limited market size and relatively high cost to segregate and transport renewable propane, most product is either consumed within the production plant or commingled with fossil propane.

4.3.3 RENEWABLE NAPHTHA

The paraffinic naphtha produced in these processes is most valuable when used as a component of transportation fuel, as it is eligible for RFS RINs and LCF and CFPC credits where applicable. While it can be used as a component of gasoline, it has undesirably high vapor pressure and an undesirably low octane value. Many refineries have the ability to isomerize RN; this process increases the octane but also results in an increase in its already high vapor pressure. In California, RN has found use as the required hydrocarbon component of E85; the 85% ethanol has very high octane and low vapor pressure, which can offset those properties of the RN. The other market for paraffinic naphtha is as a petrochemical feedstock; this market typically, however, does not value the renewable attribute.

4.3.4 PARAFFINIC WAXES

FT processes produce a high percentage of paraffinic waxes. Most of this wax then undergoes further processing to maximize the yield of RD or SAF. There is, however, a limited market for the waxes; they are used in moisture, grease, and odor barriers in paper and cardboard packaging used for food; cosmetics; candles; hot-melt adhesives; and wood panels used in construction.



SECTION 5.

Production Costs of Biofuels

In this section, we discuss the total cost to produce biofuels from crop-based feedstocks. In the prior sections, inputs have been broken into two categories: feedstock production inputs and inputs required for the conversion of feedstocks to biofuels (i.e., biofuels production).

Crop-based biofuel feedstocks have markets that are independent of biofuels and are traded domestically as well as globally primarily for food and animal feed. Therefore, the cost of the feedstock that will be converted to biofuel is not the total cost to the feedstock producers but the value set by the commodity markets, which are driven by the primary food and feed markets for these feedstocks.

Thus, the true cost of biofuels production is not the sum of the feedstock production and conversion costs but the value of the feedstock in the commodity market plus the cost to convert to biofuels.

Broadly speaking, feedstock cost accounts for the majority of the cost of producing biofuels, while conversion costs account for the remainder.

5.1 FEEDSTOCK COSTS OF BIOFUELS

The primary feedstock for ethanol is corn, and the most widely used feedstock for BD and RD is soybean oil. Soybeans are crushed to produce soybean meal and soybean oil; thus, soybean oil prices are a function of soybean prices. Since fuel production is not the primary use for any of the biofuel feedstocks, the commodity prices are reflective of the U.S. and

world markets for corn and soybeans in their primary use cases as food and feed. The U.S. produces both soybeans and corn in excess of domestic needs and participates in a robust export market. It is these commodity market prices that set the cost of these feedstocks for biofuel production.

[Table 9](#) illustrates that in 2022/23, exports amounted to about 12% of U.S. corn production and about 47% of U.S. soybean production. U.S. corn production made up about 30% of total global corn consumption, and U.S. soybean production was about 31% of total global soybean consumption.

The production of corn and soybeans in the U.S. competes for the same farmland. According to numerous articles covering planting decisions,⁵² farmers allocate acres annually between soy and corn based on their estimates of relative profitability on their land—this calculation considers factors such as projected crop prices, anticipated yields, and input costs (such as seeds, fertilizer, pesticides, irrigation requirements, etc.). Farmers must make planting decisions in the winter to have time to order seed and take delivery prior to planting season.

While feedstocks other than corn (sugarcane, sorghum, etc.) are occasionally used for ethanol production, they must compete with the economics of producing ethanol from corn. Similarly, canola oil and other oils that may be used for BD and RD production must compete with the economics of using soybean oil for the same purpose.



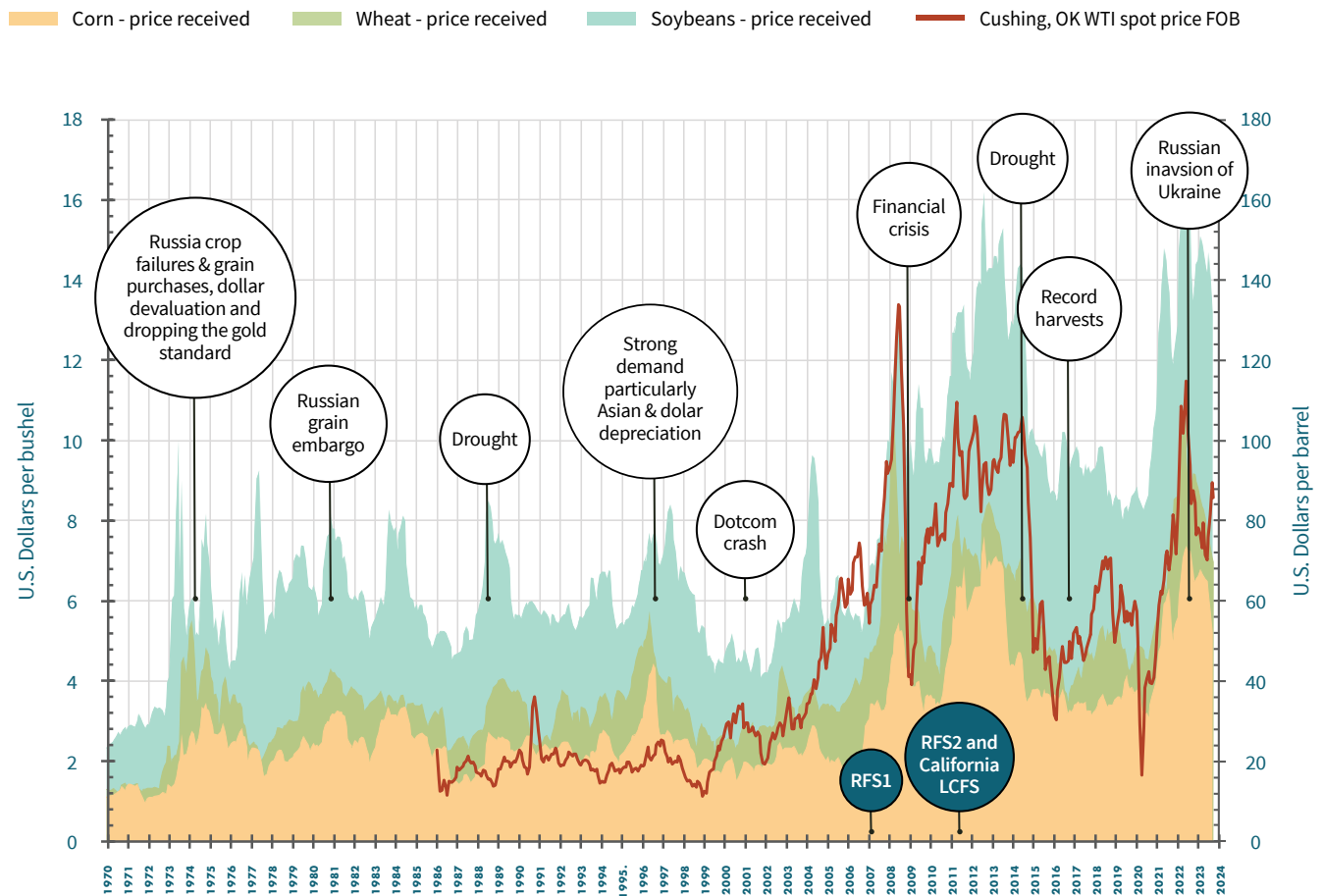
TABLE 9. CORN AND SOYBEAN STATISTICS, MILLION METRIC TONS (2022/23)

	U.S.		GLOBAL	
	CORN	SOYBEAN	CORN	SOYBEAN
PRODUCTION	348	116	1,158	378
EXPORTS	42	54	180	172
CONSUMPTION	308	61	1,157	372

Sources: USDA, PSD Online, Grains: World Markets and Trade and Oilseeds: World Markets and Trade reports

52 E.g., Matt Erickson | Corn vs. soybeans: Determining profitability in 2023

FIGURE 27. U.S. HISTORICAL GRAIN AND CRUDE OIL PRICES



Sources: USDA; EIA; Stillwater analysis

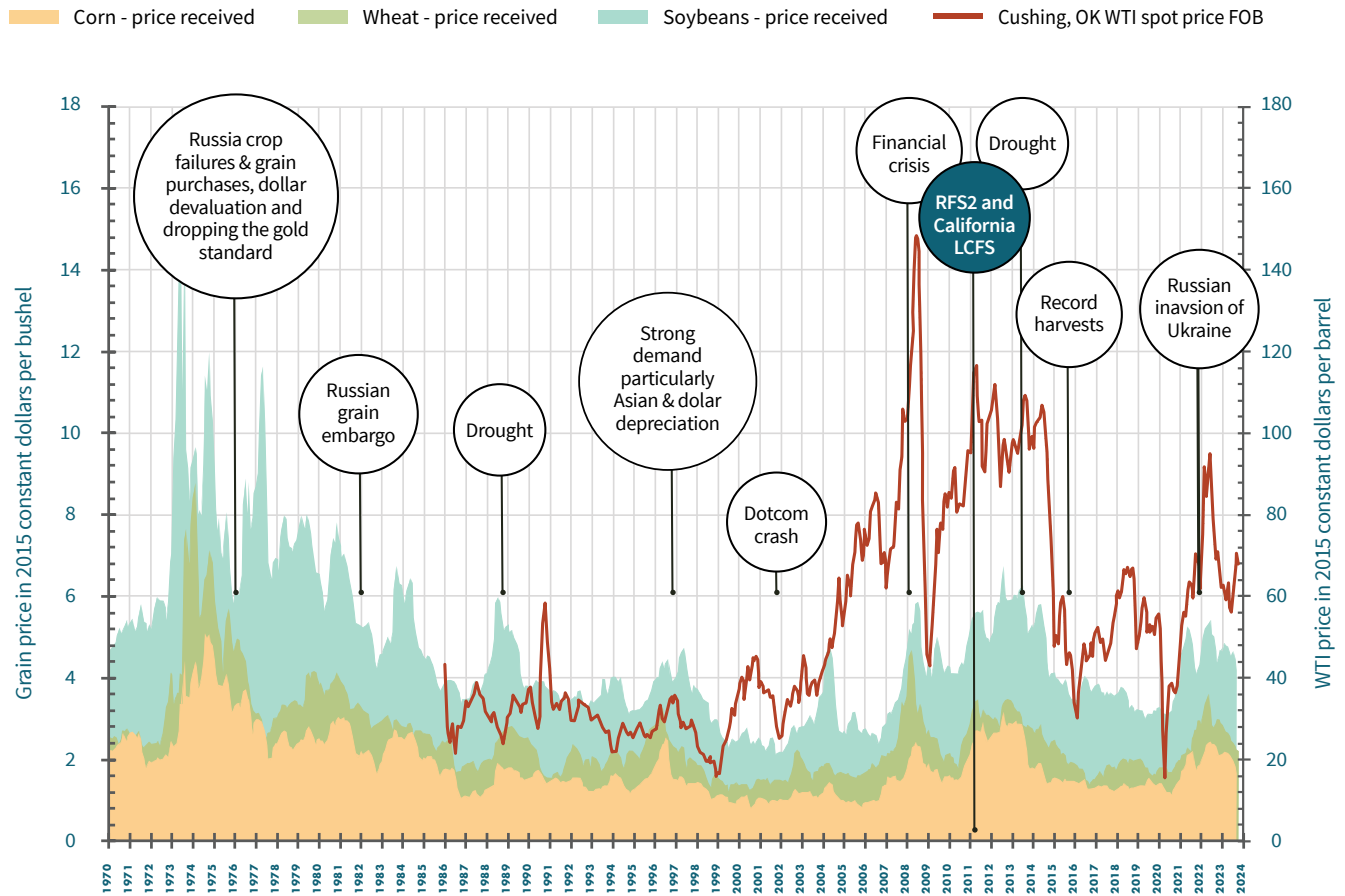
Since corn and soybeans are global commodities, their prices depend on a wide range of factors. [Figure 27](#) is a plot of corn, soybean, and wheat prices since 1970. Overlaid on the plot are highlighted selected events that drove price changes, illustrating the range of factors at play. Also shown on the plot is the price of oil (reference scale on right side), as energy is a key input into agriculture.

As can be seen in Figure 27, the three grain commodity prices tend to move together, and grain prices have experienced volatility over this 55-year period.

The causes for the volatility can be attributed to a number of factors, including:

- international events
- international demand for grains
- rapid changes in the economy
- weather
- government policies in response to the above
- oil prices (as the cost of oil drives fuel prices and the cost of natural gas drives fertilizer prices)

FIGURE 28. U.S. HISTORICAL GRAIN AND CRUDE OIL PRICES (CONSTANT 2015\$)



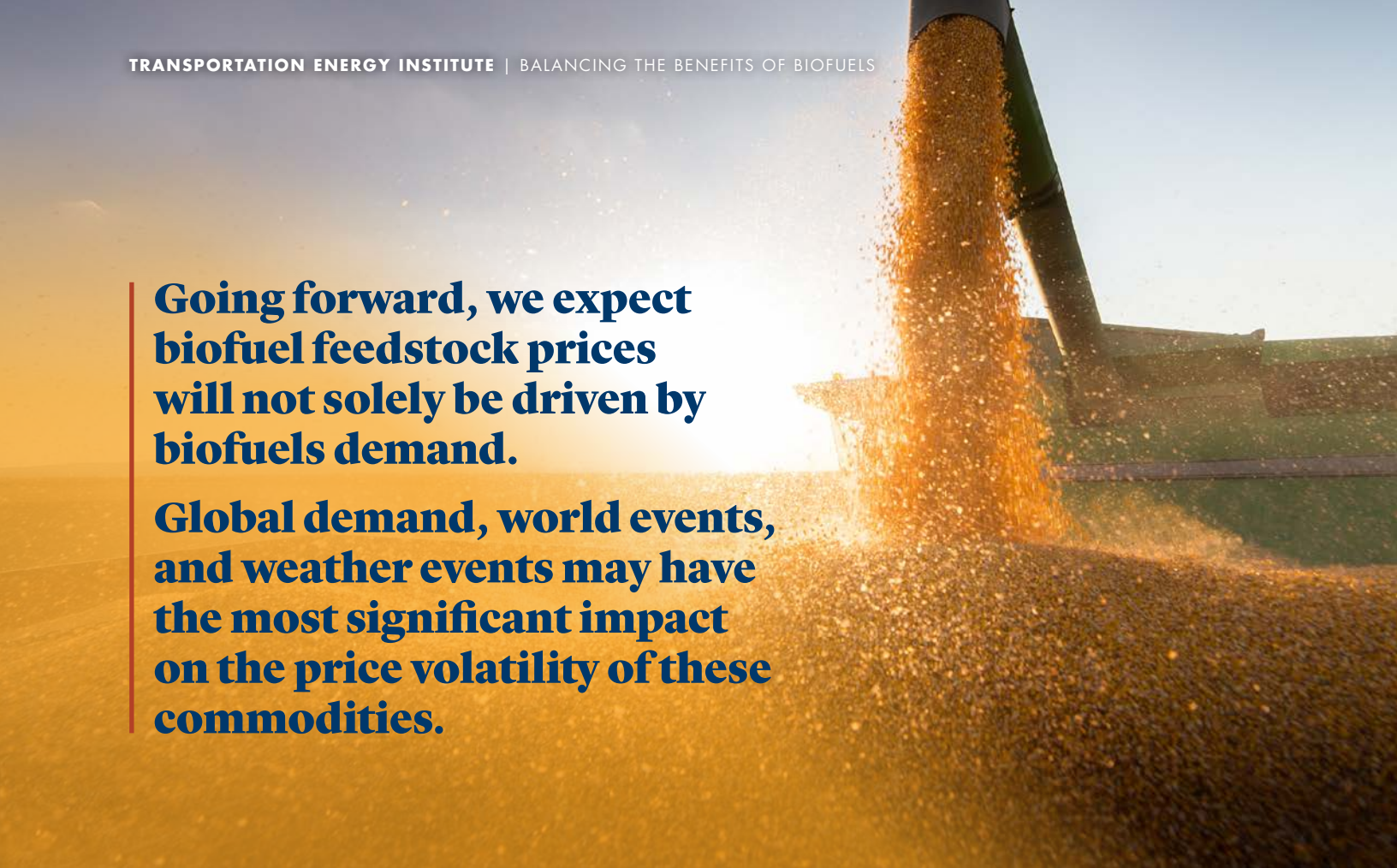
Sources: USDA; EIA; Stillwater analysis

Importantly, it does not appear that the increased demand for biofuels and their agricultural feedstocks—incentivized by the RFS and BTC—has driven the volatility in these commodity prices. Another indicator of the lack of impact of biofuels on grain prices is the similar volatility of wheat, which is not a biofuel feedstock, and corn and soybeans, which are biofuel feedstocks, since the inception of the RFS.

Figure 28, which presents corn and soybean prices in constant dollar terms (in 2015 dollars), shows that the patterns of price volatility after RFS2 implementation in 2010 and California’s LCFS implementation in 2011 are not significantly different from the trends observed before the

implementation of those programs. The impact of biofuels on these commodity prices is discussed in further detail in section 7.2.1.





Going forward, we expect biofuel feedstock prices will not solely be driven by biofuels demand.

Global demand, world events, and weather events may have the most significant impact on the price volatility of these commodities.

5.2 FEEDSTOCK TO BIOFUEL CONVERSION COSTS

Each biofuel is produced via paths that differ in process type, severity of processing, and investment required per unit of capacity. Here, in sections 5.2.1 and 5.2.2, we discuss the production costs of the different biofuels, broken into operating and financing elements—variable costs; fixed costs; and financing, overhead, and noncash costs.

- **Variable costs**—These are costs that, to the largest extent, vary directly with the production rate. Included in variable costs are feedstocks and reactants, natural gas, electricity, catalysts and chemicals, water, and disposal costs. Variable costs per unit do not vary (or vary little) with the plant utilization rate. Note that by-products are not included as a negative operating cost but as an additional revenue stream for purposes of tabulating operating costs.
- **Fixed costs**—These are costs that are essentially fixed and are not a function of the production rate if the facility is operating. Included in fixed costs are the cost of labor, salaries, maintenance, property taxes, and fees. Since these costs do not vary with the production rate, the cost per unit will vary inversely with the plant utilization rate.
- **Financing, overhead, and noncash costs**—These are costs associated with the financial structure of the production plant, or amortization of the plant value for financial accounting purposes. Also included in this category are the costs associated with ownership organization. The financing, overhead, and noncash depreciation are specific to the plant and its investment, finance, and ownership structures. For purposes of this report, we generally include these as fixed costs. However, these costs can vary widely across similar plants.

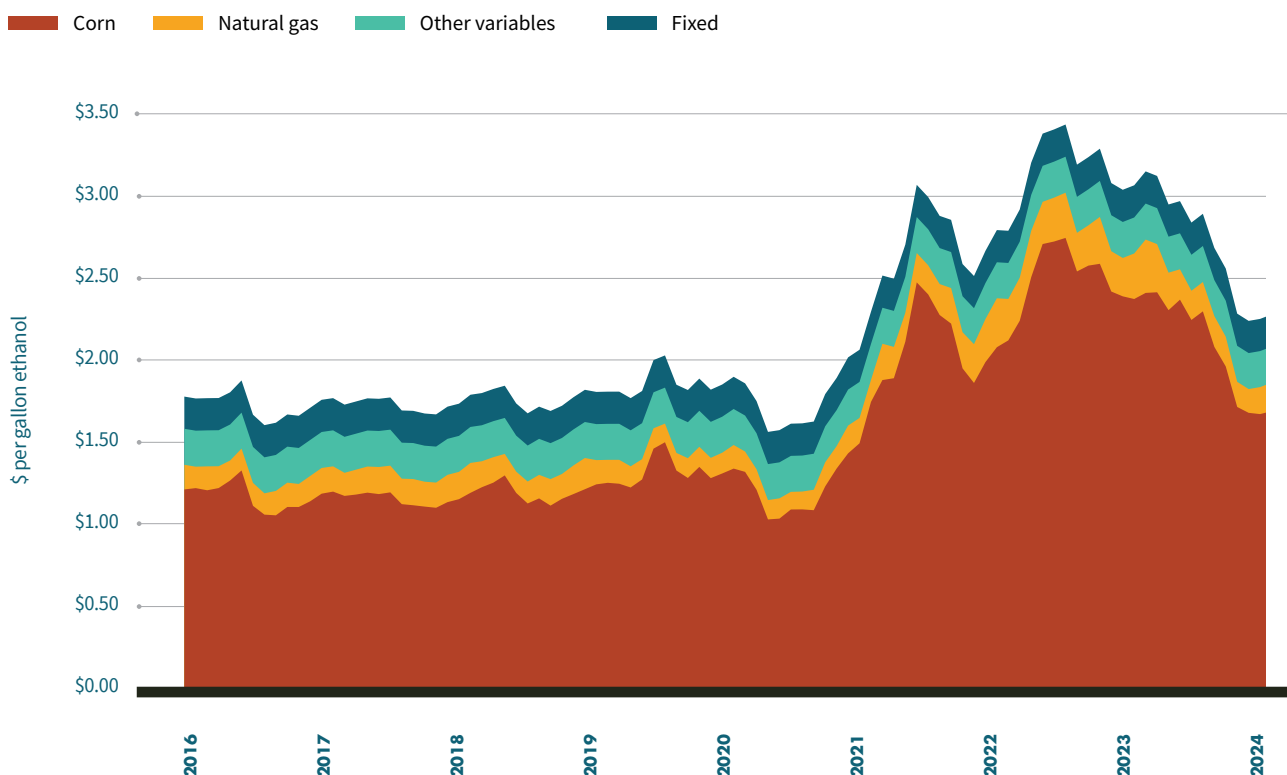
5.2.1 PER-GALLON PRODUCTION COST FOR ETHANOL AND BIODIESEL

The ISU Extension and Outreach Ag Decision Maker site⁵³ features economic models that track ethanol and BD plant profitability. These models incorporate variable and fixed costs, yields, and investment and financing costs for a generalized plant located in the Midwest. Historical charts from these models break down the elements of biofuel production costs for ethanol and BD and are reproduced in Figures 29 and 30.

Corn is the primary renewable feedstock for ethanol and accounts for 76.6% of the cost of ethanol production. After the cost of corn, 14.8% of the cost of ethanol production is the variable costs, with roughly half of this for natural gas energy. The remaining 8.7% is the fixed costs, which include but are not limited to repairs and maintenance, depreciation, interest, labor and management, property taxes, and insurance. (These figures are based on August 2023 values.) [Figure 29](#) shows historical data over the last eight years.

For BD, the primary feedstock is soybean oil, which accounts for 88.2% of the cost of BD production. Methanol, required to convert the oil into BD, accounts for 2.7% of the total costs. Variable costs (natural gas, chemicals and ingredients, transportation, water, electricity, and other) make up 4.3% of the total cost, while fixed costs (repairs and maintenance, depreciation, interest, labor and management, marketing and procurement, and property taxes, insurance, etc.) account for 4.7% of the total. (These figures are based on August 2023 values.) [Figure 30](#) shows historical data over the last eight years.

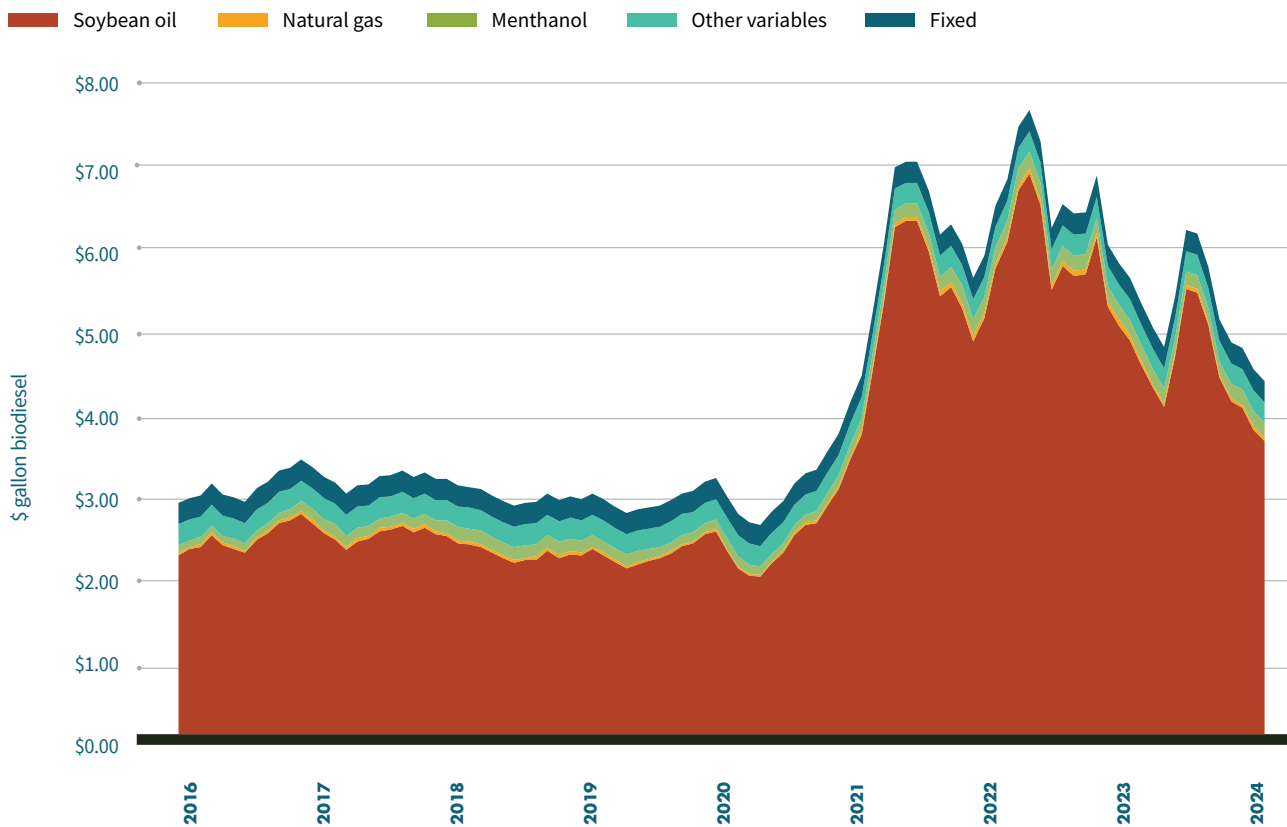
FIGURE 29. COST OF ETHANOL PRODUCTION (CORN COST AT CORN MARKET PRICE)



Source: ISU Extension and Outreach | Tracking Ethanol Profitability model

53 ISU Extension and Outreach | Ag Decision Maker

FIGURE 30. COST PER GALLON OF BD PRODUCTION



Source: Iowa State University Extension - Biodiesel Profitability Model

Tables 10 and 11 show the cost components and their percent of total production costs from the ethanol and BD plant profitability models, based on August 2023 values.

For ethanol production, the corn feedstock comprises 76.6% of the total cost of production. Natural gas at 7.2% and depreciation at 4.3% are the next highest cost components, with all others under 1.8% of the total cost of production.

For BD production, the soybean oil feedstock comprises 88.2% of the total cost of production. Methanol is the next highest cost component at 2.7%. All other individual cost components are under 1.6% of the total cost of production.

Because the production of ethanol and BD are dependent on corn and soybean oil, the future prices of these feedstocks are the most significant factors in the production costs of these two biofuels. For ethanol, natural gas price is also important, as ethanol plants are significant consumers of natural gas. For BD, methanol price is important, as methanol is a required reactant. It is produced from natural gas and its price is closely correlated with that of natural gas. Other costs that are meaningful in aggregate tend to be small individually. A larger factor in production cost might be utilization rate. Fixed costs in absolute terms do not vary with rate and would increase on a per-unit-of-production basis as utilization rate decreases.

TABLE 10. ETHANOL PRODUCTION COSTS

	COST PER GALLON OF ETHANOL	PERCENT OF TOTAL
FEEDSTOCK		
CORN (\$5.59/bu @ 2.85 gal/bu)	\$1.961	76.6%
SUBTOTAL FEEDSTOCK COSTS	\$1.961	76.6%
VARIABLE COSTS		
NATURAL GAS	\$0.185	7.2%
ENZYMES	\$0.034	1.3%
CHEMICALS AND YEASTS	\$0.036	1.4%
DENATURANTS	\$0.047	1.8%
TRANSPORTATION	\$0.008	0.3%
ELECTRICITY	\$0.039	1.5%
WATER	\$0.012	0.5%
OTHER	\$0.020	0.8%
SUBTOTAL VARIABLE COSTS	\$0.381	14.7%
FIXED COSTS		
REPAIRS & MAINTENANCE	\$0.025	1.0%
DEPRECIATION	\$0.110	4.3%
INTEREST	\$0.046	1.8%
LABOR & MANAGEMENT	\$0.038	1.5%
PROPERTY TAXES, INSURANCE, ETC.	\$0.002	0.1%
SUBTOTAL FIXED COSTS	\$0.221	8.7%
TOTAL PRODUCTION COST	\$2.563	100.*%

Source: Stillwater analysis of ISU Extension and Outreach | Tracking Biodiesel Profitability model

Units: bushel (bu); gallons (gal)

*Total does not add to 100% due to rounding.

TABLE 11. BD PRODUCTION COSTS

	COST PER GALLON OF BIODIESEL	PERCENT OF TOTAL
FEEDSTOCKS		
SOYBEAN OIL (\$0.72/lb @ 7.55 lb/gal)	\$5.436	88.2%
METHANOL	\$0.166	2.7%
SUBTOTAL FEEDSTOCK COSTS	\$5.602	90.9%
VARIABLE COSTS		
NATURAL GAS	\$0.043	0.7%
CHEMICALS AND INGREDIENTS	\$0.057	0.9%
TRANSPORTATION	\$0.100	1.6%
WATER	\$0.007	0.1%
ELECTRICITY	\$0.030	0.5%
OTHER	\$0.030	0.5%
SUBTOTAL VARIABLE COSTS	\$0.267	4.3%
FIXED COSTS		
REPAIRS & MAINTENANCE	\$0.030	0.5%
DEPRECIATION	\$0.091	1.5%
INTEREST	\$0.065	1.0%
LABOR & MANAGEMENT	\$0.054	0.9%
MARKETING & PROCUREMENT	\$0.040	0.6%
PROPERTY TAXES, INSURANCE, ETC.	\$0.012	0.2%
SUBTOTAL FIXED COSTS	\$0.292	4.7%
TOTAL PRODUCTION COST	\$6.161	100.0*%

Source: Stillwater analysis of ISU Extension and Outreach | Tracking Biodiesel Profitability model

Units: pound (lb); gallon (gal)

*Total does not add to 100% due to rounding

5.2.2 PER-GALLON PRODUCTION COST FOR RENEWABLE DIESEL

Unfortunately, a generalized open-source profitability model similar to those for ethanol and BD is not available for RD. For RD producers and technology providers, the costs and yields of production are currently considered proprietary. To address the cost of production for RD, Stillwater has employed our knowledge and experience in petroleum refining technologies to develop an order-of-magnitude breakdown of production costs.

RD production facilities use four processes that are also used in petroleum refining and in seed oil processing.

1. **Pretreatment removes trace contaminants, solids, trace metals, etc.**
2. **Hydroprocessing is used to hydrogenate most of the lipids to produce hydrocarbons and water.**
3. **Hydrocracking is used to complete the hydrogenation process and isomerize the paraffin molecules to improve product quality. The hydrocracking process is also used to “crack” the heavier diesel molecules to jet fuel and lighter-range molecules for HEFA SAF production.**
4. **Steam methane reforming generates the hydrogen that is consumed in the hydrogenation and hydrocracking processes.**

Table 12 shows the estimated yield for an operation processing FOG, with RD as the target product, based on Stillwater’s knowledge and experience.

Of note in the table is the large amount of hydrogen required to convert the lipid molecules in the FOG

TABLE 12. ESTIMATED RD YIELDS

INPUTS	
FEEDSTOCK	1 gallon
HYDROGEN	1500–2500 SCF
OUTPUTS	
RENEWABLE DIESEL	0.90–.95 gallons
PROPANE	0.08–.12 gallons
RENEWABLE NAPHTHA	0.01–.04 gallons
RENEWABLE GASES	200–500 SCF
TOTAL OUTPUTS	~1.05 gallons

Source: Stillwater estimates
Units: standard cubic feet (SCF)

feedstock to RD. To generate the volume of hydrogen needed to support processing a gallon of feedstock would require some 500–900 standard cubic feet (SCF) of natural gas. At a \$6 per million BTU price, the natural gas cost would be ~\$3.00–\$5.40 per gallon of RD. If natural gas were used to generate the hydrogen, it would approach the cost of the FOG feedstock. Fortunately, in an RD plant, the renewable by-products (off-gases, propane, and even the naphtha) can be used to generate hydrogen, displacing natural gas and its high cost.⁵⁴

To estimate the remaining costs, data from petroleum refining is used, as the hydrotreating and hydrocracking processes for RD production parallel those used in petroleum refining. These processes use a combination of high temperatures (400°F–750°F) and pressures (300–2500 psi) under a solid catalyst in a reactor to react the feedstock with hydrogen and convert the feedstock molecules to the desired biofuel molecules. The reactor product is further processed, usually by distillation, to produce specification RD and other renewable products. The processes are similar enough to use hydrotreating and hydrocracking costs as an order-of-magnitude estimate for RD production costs.

⁵⁴ A further benefit to the plant of using these by-products as hydrogen feedstocks is that it lowers the CI of the SAF and RD products, thereby increasing their market value under the CFPC and in states with LCF programs.

TABLE 13. ESTIMATED FEED AND UTILITIES FOR AN RD PRODUCTION FACILITY

	USAGE PER GALLON OF RD PRODUCED	ESTIMATED COST PER GALLON OF RD PRODUCED	PRICE USED	PERCENT OF TOTAL PRODUCTION COST
FEEDSTOCK				
SOYBEAN OIL	8.0 lb	\$5.76	\$0.72	61.6%
OPERATING COSTS				
NATURAL GAS	0.2 million BTU	\$1.23	\$6.17	13.2%
ELECTRICITY	20 kWh	\$1.00	\$0.05	10.7%
WATER	100 gal	\$0.35	\$0.00	3.7%
OTHER		\$1.00	estimated	10.7%
TOTAL PRODUCTION COSTS		\$9.34		100.0*%

Source: Stillwater estimates

Note: These are rough estimates.

*Total does not add to 100% due to rounding

Table 13 displays Stillwater’s estimate of RD production costs using the 2006 edition of the Refining Processes 2006 Handbook by Hydrocarbon Processing as a reference. The commodity prices used are consistent with those used in the BD profitability model in Figure 30.

The cost of RD production is less dependent than ethanol and BD on the feedstock cost as feedstock is only 61.6% of the total cost. Natural gas and electricity costs are a much higher percentage of the total cost of production than for ethanol or BD due to the required hydrogen and the energy required to power the much higher temperatures and pressures used in the RD refining process. In addition to the higher per-gallon natural gas and electricity use required, the higher severity of the processes requires higher specification processing equipment⁵⁵ and, thus, an increased investment per gallon of product than ethanol or BD. In short, RD production costs are more sensitive to natural gas and electricity prices than ethanol or BD and less sensitive to feedstock prices.



⁵⁵ E.g., equipment designed to safely and reliably operate at higher pressures and temperatures than what is required for the safe and reliable operation of ethanol and biodiesel plants.



SECTION 6.

Effect of Government Policies on Performance of Biofuels

6.1 PROGRAMS IMPROVING PRODUCERS' ENVIRONMENTAL IMPACT

Biofuel production in the U.S. has grown since 2007 largely due to two government policies: the federal RFS and state-level LCF programs. Overviews of these programs are provided in the appendix. These policies have significantly increased biofuel production (for the biofuels they pertain to) and the mix of biofuels produced. Both policies rely on low-carbon biofuels for compliance but in differing ways. Whereas LCF standards reward producers of lower CI fuels and encourage the development of second- and third-generation biofuels, the federal RFS has maintained a heavy reliance on first-generation biofuels such as ethanol and BD.

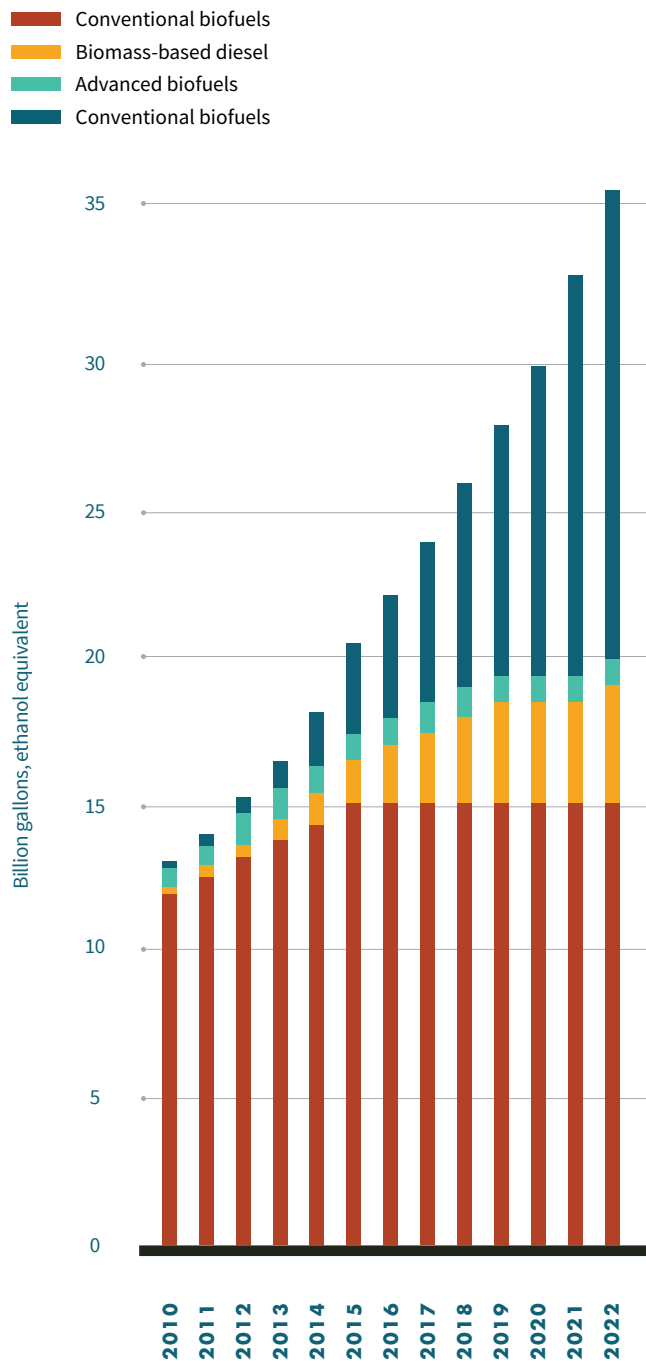
IN ANALYZING THE EFFECTS OF THESE POLICIES ON GHG EMISSIONS INTENSITY AND OVERALL GHG EMISSIONS, THE RELEVANT COMPARISON CONDUCTED BY RESEARCHERS HAS BEEN RELATIVE TO LEVELS IN THE ABSENCE OF THE POLICY. IN ANALYZING THE EFFECTS ON WATER QUALITY, THE COMPARISON PRESENTED IN THIS SECTION IS RELATIVE TO THE IMPACTS OF AGRICULTURE ON WATER QUALITY IN THE ABSENCE OF BIOFUEL POLICY.

NOTABLY, THIS IS NOT A COMPARISON BETWEEN THE EFFECTS OF BIOFUEL PRODUCTION AND PETROLEUM FUEL PRODUCTION ON WATER QUALITY.

The design of the RFS has two implications for the mix of fuels and incentives to lower their GHG intensity. First, since a biofuel is only required to achieve a GHG reduction that meets the threshold, there is no incentive for biorefineries to make continuous improvements to lower the CI of the biofuel below the threshold. As noted, the CI of biofuel includes not only the lifecycle emissions, from the production of the feedstock all the way to its conversion to biofuel in the refinery, but also the emissions related to land use change. Modeling by EPA for the Regulatory Impact Analysis in 2010⁵⁶ assessed that corn ethanol produced in a dry mill plant with natural gas for its process energy had a median CI reduction of 21% relative to gasoline. The 95% confidence interval around that midpoint ranged from a 7% reduction to a 32% reduction due to uncertainty in the land use change assumptions.

Second, the mix of biofuels incentivized by the RFS is likely to be based on cost considerations subject to the nested volumetric requirements and not their CI. The nested structure of the RFS allows for advanced biofuels (such as BD) to fill the requirements of conventional renewable fuel (or corn ethanol). In recent years, as ethanol consumption hit a blend wall at 10% blend with gasoline, blenders have chosen to increase blending of BD to comply with the RFS rather than expand sales of E85. BD has been a lower-cost option to comply with the RFS due to the \$1 per gallon tax credit provided, while expanding sales of E85 would have required lowering its price to energy parity with E10.⁵⁷ As a result, BD production and blending has grown rapidly in recent years, while domestic corn ethanol consumption has stagnated and been lower than the upper bound of 15 billion gallons. To date, there has been negligible production of cellulosic biofuels. The actual volumes of biofuels produced are shown in [Figures 31](#) and [32](#).

FIGURE 31. RFS BIOFUEL FUEL VOLUMES SPECIFIED BY THE ENERGY INDEPENDENCE AND SECURITY ACT OF 2007 (2010–2022)



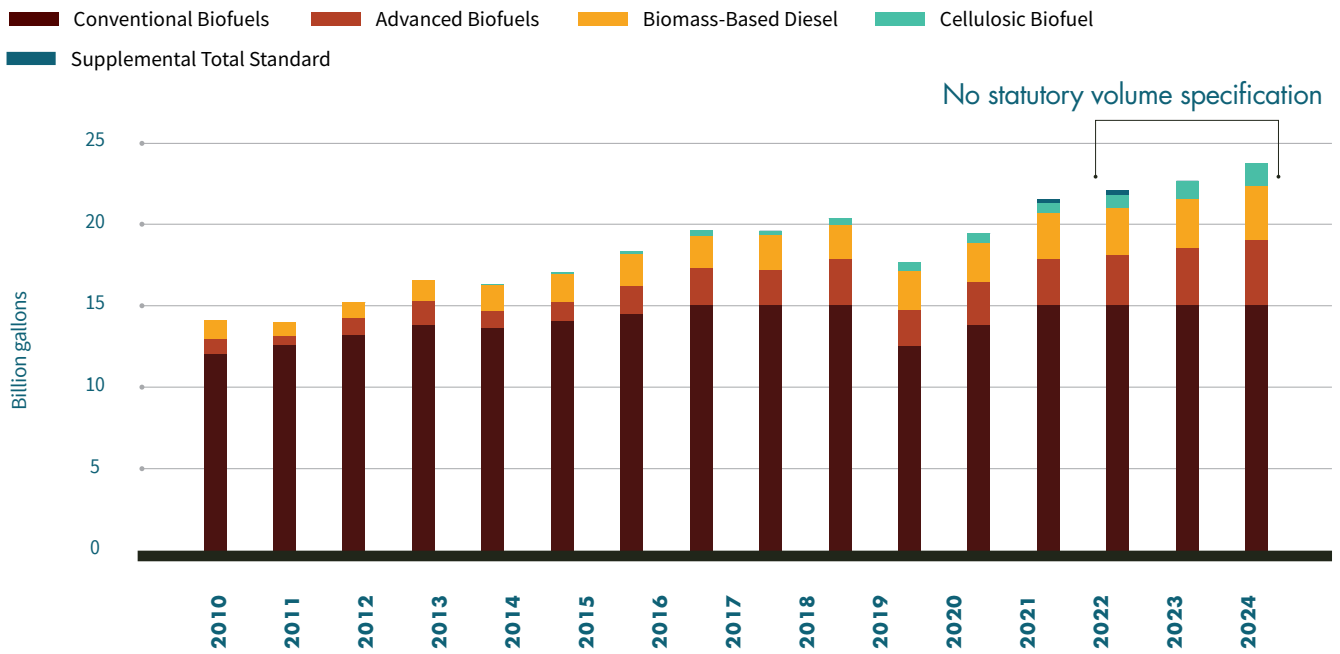
Source: EIA | EPA finalizes Renewable Fuel Standard for 2019, reflecting cellulosic biofuel shortfalls

Note: Data for biomass-based diesel are actual gallons, not ethanol equivalent.

56 EPA | Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis (2010)

57 Jia Zhong and Madhu Khanna | Assessing the efficiency implications of renewable fuel policy design in the United States

FIGURE 32. RFS ANNUAL VOLUME STANDARDS AS FINALIZED BY EPA (2010-2025)

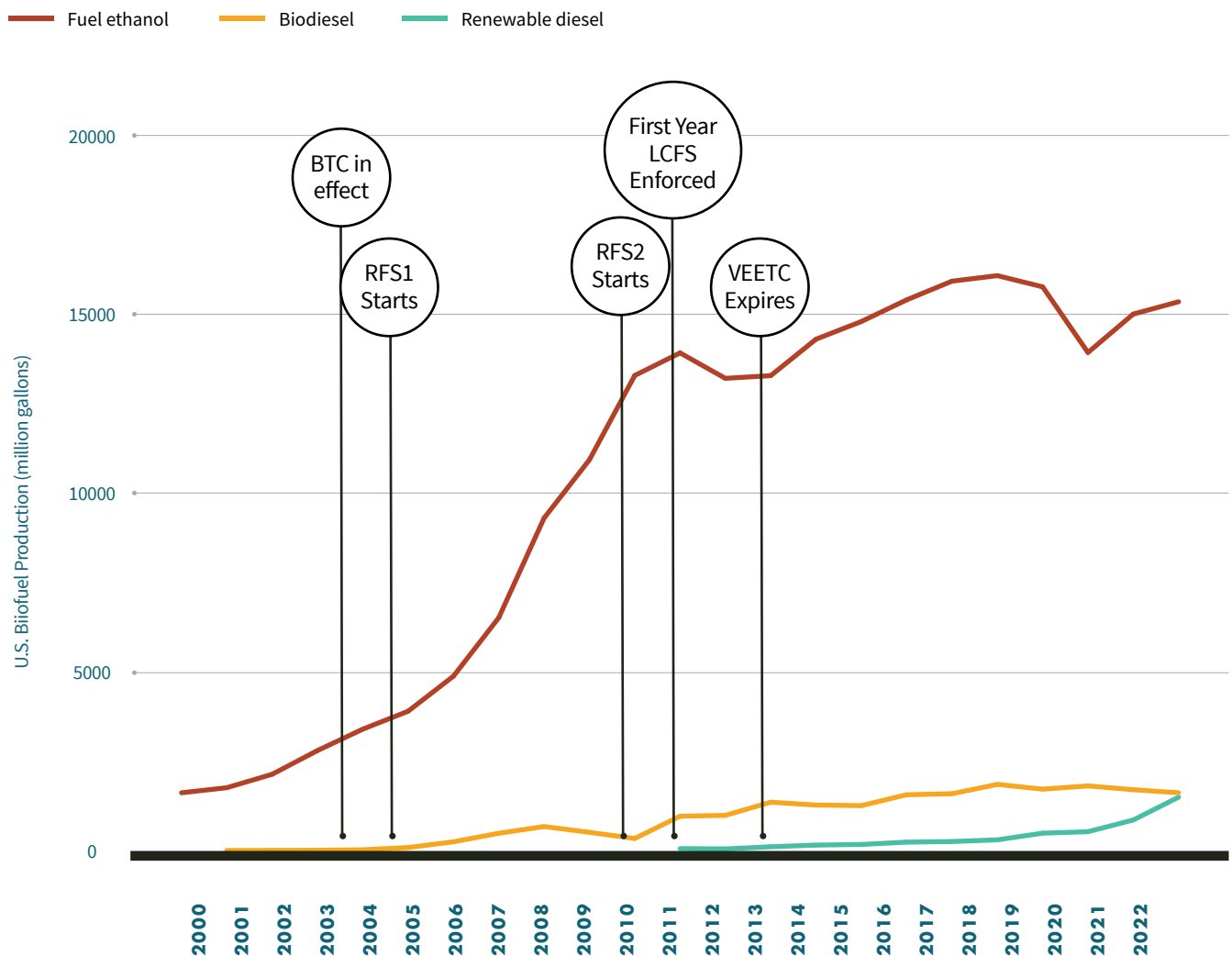


Sources: EIA; USDA; Stillwater analysis



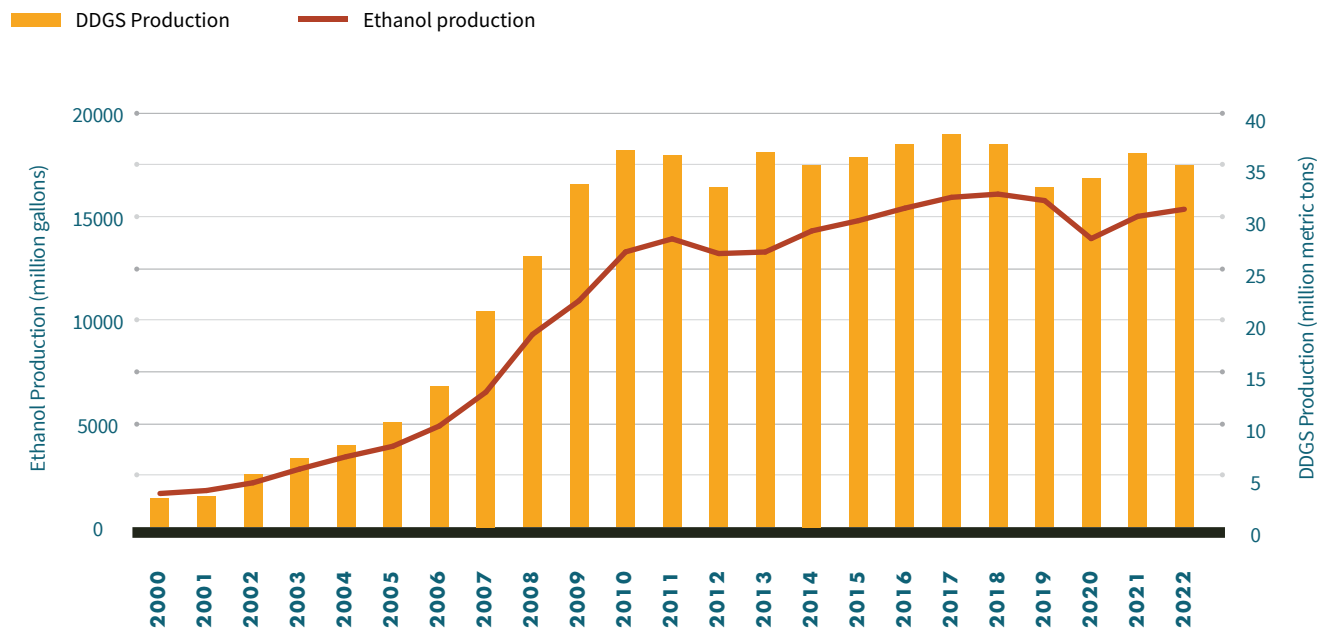
U.S. production of ethanol, BD, and RD is presented in [Figure 33](#). While U.S. domestic demand for ethanol has stagnated below the 15 billion gallon per year RFS limit, U.S. ethanol exports have grown above domestic demand, with the surplus exported to Canada, Brazil, and many other countries. U.S. BD producers, in contrast, predominantly supply the domestic market with volumes exceeding the RFS obligations. Domestic RD production has been growing rapidly in recent years, largely driven by LCF requirements in California, Oregon, and Washington; while much of this demand was initially supplied by imports, these imported volumes have started to decrease as domestic production has grown. Going forward, it is expected that limited feedstock supplies will cause BD and RD producers to compete with each other for available feedstock volumes.

FIGURE 33. U.S. ETHANOL, BD, AND RD PRODUCTION (2000-2022)



Source: USDA Economic Research Service

FIGURE 34. U.S. ETHANOL AND DDGS PRODUCTION (2000-2022)



Source: USDA WASDE; Stillwater analysis

Figure 34 shows historical U.S. ethanol production overlaid with the co-production of DDGS. DDGS is widely used as a high-protein animal feed both in the U.S. and globally. U.S. exports of DDGS have grown from 0.8 million metric tons in 2000 to 10 to 12 million metric tons per year since 2013; exports now represent about 32% of demand for U.S. DDGS production. Replacing the feed protein content of the 35.1 million metric tons of DDGS produced in 2022 would require the U.S. to harvest an additional 15 million acres of soybeans and 5 million acres of corn each year (based on 2022 average yields.) From 2002 onward, DDGS production has grown more rapidly than ethanol production; this occurred as new fuel ethanol production capacity built since then has predominantly been at dry mills (where all DDGS is produced) rather than at wet mills (which produce corn gluten meal, corn gluten feed, and a variety of other products instead of DDGS.)⁵⁸

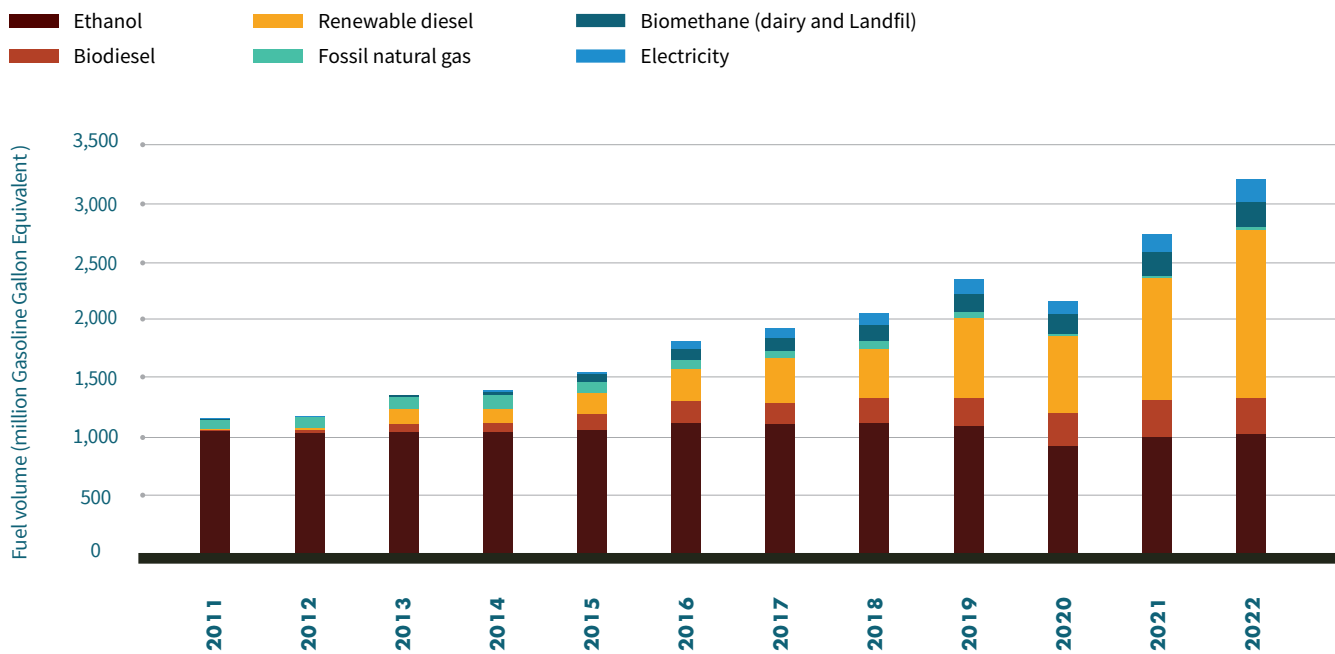
Unlike the RFS, which sets a volumetric standard, LCF programs set a standard for the reduction in the CI of transportation fuels in a given jurisdiction. California’s LCFS required a 10% reduction in the CI of the state’s transportation fuels by 2020 and a 20% reduction in CI by 2030. Unlike the RFS, the mix of fuels under an LCF program is determined by each one’s relative cost and CI; required volumes are not set by the regulators. Under California’s LCFS, the indirect land use change (ILUC)⁵⁹ values for corn ethanol pathways prior to 2016 were assessed at 30 grams of CO₂ equivalent per megajoule (gCO₂e/MJ). This value was lowered to 19.8 gCO₂e/MJ after 2016. The policy incentivizes the blending of fuels by implicitly subsidizing fuels with CIs below the standard and penalizing fuels with CIs above the standard. It also creates incentives for incrementally lowering the CI of biofuels to make them more competitive for blenders and profitable for producers.

58 Wet mills are typically large, highly capital-intensive facilities designed to produce a mixture of products (including ethanol), chosen to maximize the value of each bushel of corn processed. Dry mills are facilities designed to maximize production of ethanol at a minimum capital cost.

59 There are significant differences in the ILUC values used by the California Air Resources Board and EPA and represented in the GREET model.

Reliance on corn ethanol to comply with the LCFS, as measured by the share of credits attributable to ethanol usage, has been declining, and the use of BD and RD has been growing, as shown in [Figure 35](#). About two-thirds of the renewable fuels consumed in California are biomass-based diesel (BD and RD), and almost all the RD being produced in the U.S. is being sold in California to comply with the LCFS.⁶⁰ RD usage in California has grown more rapidly than BD usage as RD meets the same specifications (ASTM D975) as petroleum diesel, enabling it to be used in all diesel engines in blends of up to 100% RD, while BD blends are limited to 5% (for all engines and infrastructure, with no additional labeling required) or 20% (for most diesel engines and infrastructure; labeling and compliance with additional California regulatory conditions required).

FIGURE 35. ALTERNATIVE FUELS SOLD IN CALIFORNIA (2011-2022)

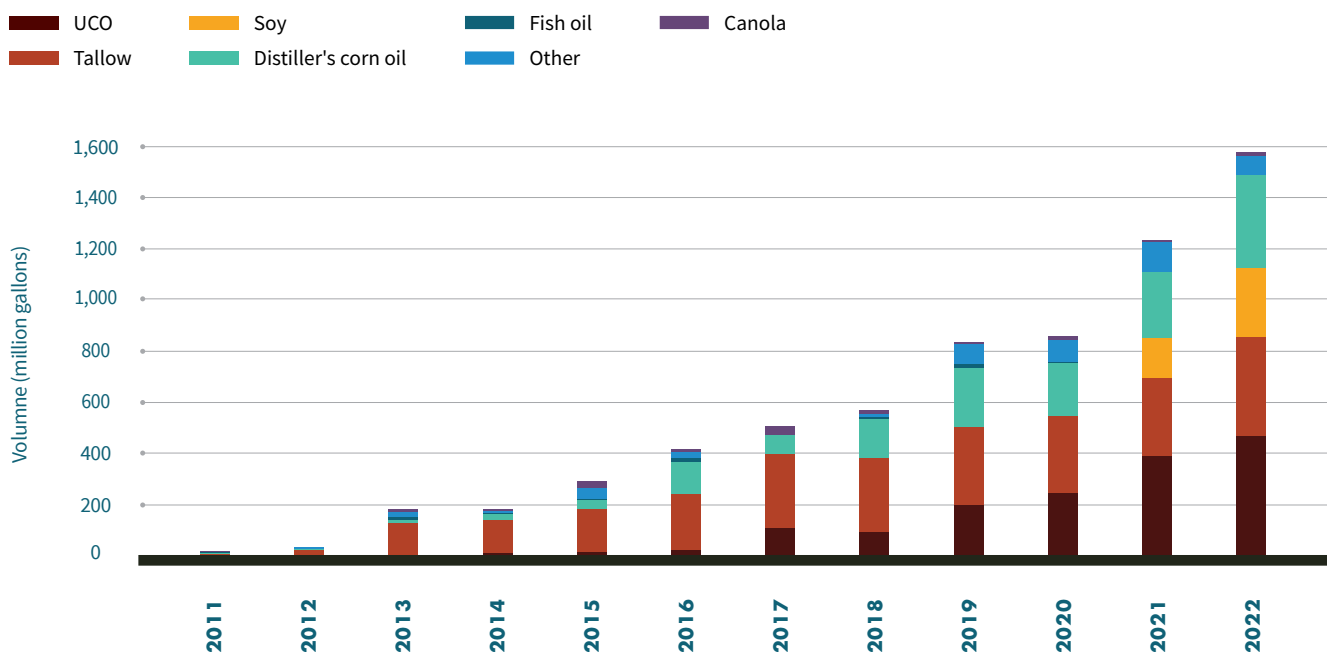


Source: California Air Resources Board | Low Carbon Fuel Standard 2023 Amendments: Standardized Regulatory Impact Assessment

60 Renewable Fuels Association | Corn Ethanol’s Energy Balance Continues to Improve



FIGURE 36. MIX OF FEEDSTOCKS FOR BD PRODUCTION FOR CALIFORNIA (2011-2022)



Source: California Air Resources Board | LCFS Data Dashboard

In the early years after the LCFS was established, the feedstocks of BD and RD were largely wastes and other non-crop-based sources, including UCO, tallow, corn oil extracted from distillers grains and solubles (DGS), and oils from fish processing. Over time, as shown in [Figure 36](#), the available supply of feedstocks has become fully utilized, and the share of soybean BD and RD in the fuel mix has grown to about 250 million gallons in 2022. Biofuels production capacity has more than tripled in the U.S. since 2021; although BD capacity declined 13% over that period, RD capacity has grown appreciably.⁶¹ This growth in biofuels production capacity has led to increased production of feedstocks like canola, soybeans, and yellow grease to meet the growing demand. The increasing demand is also being met by imported feedstocks in the form of animal and vegetable oils and fats.

Thus, both the RFS and the LCFS have induced a switch toward biomass-based diesel (BBD) but for very different reasons. The RFS has led to BBD uptake because its nested structure and the subsidy with the \$1.00/gallon BTC has enabled BBD (D4) RINs to substitute for the conventional (D6) RINs earned by corn ethanol, while the statute explicitly precludes corn ethanol from qualifying for advanced biofuel (D5) RINs, regardless of its CI.⁶² The LCFS has incentivized BD because of its lower CI relative to corn ethanol and its cost effectiveness (again, due to the BTC) in meeting the standard. Neither policy has been able to incentivize increased demand for ethanol beyond E10. Both policies can be expected to continue to create demand for RD because its consumption is not subject to any blending limits.

Although the LCFS has induced improvements in the production processes of biofuels to lower their CI, it has not yet incentivized improvements in feedstock

61 EIA | In 2023, U.S. renewable diesel production capacity surpassed biodiesel production capacity

62 Per 40 CFR § 80.1401: “Advanced biofuel” means renewable fuel, other than ethanol derived from cornstarch, that has lifecycle GHG emissions that are at least 50% less than baseline lifecycle greenhouse gas emissions (emphasis added).

production pertaining to site-specific farm practices, including those increasing soil carbon sequestration. Practices like planting cover crops in the winter months between the corn and soybean growing seasons has significant potential to sequester carbon in the soil. Similarly, no-till farming sequesters more carbon compared to conventional tillage practices. However, changes in soil carbon are not included in the CI score of fuels when determining their compliance with LCF programs, and thus there is no mechanism to differentiate payments for feedstocks based on their production practices. Similarly, neither has the RFS created incentives for farmers to lower the CI of corn and soybeans by implementing climate-smart practices due to its threshold-based approach to ensure compliance with the GHG-reduction requirements for the different fuels.

6.1.1 COST-BENEFIT ASSOCIATED WITH THESE POLICIES

Several studies have found that the RFS and the LCFS have established economic costs and benefits for agricultural consumers and producers; they also influence the economic well-being of fossil fuel producers, biofuel producers, and fuel consumers in addition to their claimed environmental benefits. Furthermore, these policies impact foreign consumers and producers of food and fuel because the U.S. is a major exporter of agricultural commodities and an importer of oil. Large-scale production of biofuels using food-based feedstocks has changed the mix of crops grown by U.S. farmers and altered the balance of supply and demand for these commodities in both domestic and international markets. (The historical impacts on key U.S. crops, acreage, and exports are discussed in section 2 of this report.) These changes, however, cannot readily be isolated from the many other factors (such as urban sprawl, population growth,

economic growth, and changing dietary preferences) influencing agriculture on a global basis.

Whether, on balance, these policies directly offer net costs or benefits to consumers depends, in part, on the effects of these policies on blended fuel prices. This will depend in turn, on the incentives for blenders in the U.S. to choose to blend biofuel with fossil fuel in cases where the blending decision is voluntary. Any impacts on fuel prices depend on the effect of these policies on global crude oil prices. The U.S. was a growing and major importer of oil and petroleum products from the world market until about 2006. Following the shale oil boom, which began in 2006, and the simultaneous growth in renewable fuel usage in the U.S., imports have been declining; from 2006 to 2023, imports declined from 14 million barrels per day (bpd) to 8 million bpd.⁶³ Over time, U.S. exports of petroleum products have increased; in 2022, U.S. petroleum product exports were 9.6 million bpd in the form of distillate fuel oil, residual fuel oil, and ethanol blended into motor gasoline.⁶⁴

The effect of U.S. trade in fuel markets on the world price of oil and petroleum products depends not only on the U.S. share of the world market but also on the structure of the oil and petroleum product market and the response by OPEC to changes in demand and supply in the world markets.

In assessing the overall costs and benefits of U.S. renewable fuel policies, it is important to consider the difficult-to-quantify benefits of the reduced GHG emissions they enable. While overall growth in global GHG emissions remains a concern, the use of biofuels has contributed significantly toward addressing it.

Several studies have quantified the domestic costs and benefits of biofuel policies.^{65,66} These papers

63 EIA | U.S. Imports of Crude Oil and Petroleum Products

64 Statista | Total Petroleum Exports from the United States in Selected Years from 1950 to 2022

65 Xiaoguang Chen et al. | Meeting the mandate for biofuels: Implications for land use, food and fuel prices

66 Xiaoguang Chen et al. | Alternative transportation fuel standards: Welfare effects and climate benefits

analyzed impacts from before the shale gas boom and, assuming competitive markets for oil, showed that the RFS and LCFS contribute to reducing U.S. demand for crude oil. This benefit is potentially offset, in part, by raising the price of U.S. exports of corn and soybeans. The overall effect of reducing U.S. crude oil demand and increasing the value of U.S. agricultural exports is an improvement in the overall terms of trade for the U.S. One study estimated the cost-to-benefit ratio of a 36-billion-gallon mandate to be \$0.53 per gallon of biofuel produced due to the RFS over pre-RFS baseline levels. They estimated that corn prices would be 24% higher and gasoline prices 8% lower due to the RFS in 2022 and the net social benefit would be \$122 billion (a 0.7% improvement) in 2007 prices, relative to a baseline scenario.⁶⁷ These benefits do not include the benefits generated by lowering GHG emissions.

Another study similarly found that the improvement in the terms of trade generated by the 36-billion-gallon RFS mandate led to both costs and benefits to consumers, producers, and the government. Including the reduction in GHG emissions (valued at the social cost of carbon of \$52 per metric ton), this study found an increase in net social benefits to the U.S. of \$110 billion.⁶⁸

The distribution of these impacts across consumers and producers was not, however, equitable. An improvement in the terms of trade generated by the 36-billion-gallon RFS mandate arises because biofuels potentially raise the price of U.S. exported commodities, like corn and soybeans, benefiting agricultural producers. Biofuels can also potentially lower the price of commodities imported into the U.S. (like oil) by reducing domestic demand for oil; this benefits fuel consumers through lower fuel prices. Hence, U.S. agricultural consumers and fuel producers lose while the agricultural producers and fuel end users gain.

TABLE 14. EFFECT OF THE RFS ON SOCIAL WELFARE RELATIVE TO BASELINE SCENARIO, 2007–2030 (\$ BILLION)

	RFS
U.S. FUEL CONSUMERS (A)	42.7
U.S. FUEL PRODUCERS (B)	-203.5
U.S. AGRICULTURAL CONSUMERS (C)	-124.0
U.S. AGRICULTURAL PRODUCERS (D)	296.6
U.S. GOVERNMENT (E)	35.0
REDUCTION IN U.S. SOCIAL COST OF CARBON¹ (F)	63.4
U.S. ECONOMIC SURPLUS (Δ = A + B + C + D + E)	46.7
U.S. SOCIAL WELFARE² (Δ + F)	110.1 (0.4%)*
REST OF THE WORLD AGRICULTURAL CONSUMERS AND PRODUCERS (G)	-96.8
REST OF THE WORLD GASOLINE CONSUMERS AND PRODUCERS (H)	-249.2
SUGARCANE ETHANOL CONSUMERS AND PRODUCERS (I)	21.9
REST OF THE WORLD ECONOMIC SURPLUS³ (Π = G + H + I)	-324.1
REDUCTION IN GLOBAL SOCIAL COSTS OF CARBON¹ (K)	2.4
WORLD SOCIAL WELFARE (Δ + Π + K)	-274.9 (-1.0%)*

Source: Xiaoguang Chen, et al. | Alternative transportation fuel standards: Welfare effects and climate benefits

Notes:

1. The social cost of carbon is valued at a carbon price of \$52 per metric ton of CO₂ equivalent and discounted over the period 2007–2030.
2. Social welfare is defined as the sum of net economic benefits to agricultural and fuel consumers and producers and government net of environmental damages due to greenhouse gas emissions.
3. World economic surplus is the sum of net benefits to consumers and producers of agricultural commodities and fossil fuel in the rest of the world (excluding the U.S.).

* Numbers in parentheses represent the percentage change in social welfare under each policy relative to U.S. social welfare under the no-policy baseline scenario.

67 Xiaoguang Chen et al. | Meeting the mandate for biofuels: Implications for land use, food and fuel prices

68 Xiaoguang Chen et al. | Alternative transportation fuel standards: Welfare effects and climate benefits



Taking a global perspective, the RFS has a large net negative impact on agricultural consumers' and producers' surplus in the rest of the world, with a reduction of \$97 billion over the 2007–2030 period relative to a policy-free baseline scenario. The RFS also leads to a net reduction in the sum of gasoline consumers' and producers' surplus in the rest of the world of \$250 billion. Sugarcane ethanol producers in Brazil gain somewhat through increased exports to the U.S., but overall, the rest of the world's economic surplus declines by \$324 billion. The net change in world social welfare⁶⁹ is estimated to be negative \$275 billion. Equity impacts on consumers in low-income, food-importing countries were not considered.

More recently, the U.S. fuel sector has undergone a shift, with declining oil imports and growing petroleum product exports following the shale gas boom. The U.S. has a small market share in petroleum products and is a price taker in the world market. This affects the impact of the biofuel

mandate on the fuel market. Specifically, the large-scale production of ethanol displaces gasoline, but the displacement of petroleum diesel is much smaller due to volumes of both BD and RD. As a result, it is unlikely that oil imports and refining of oil to produce petroleum products will be reduced because demand for domestic diesel still has to be met. Instead, it is likely that exports of gasoline and diesel may increase with increasing production of biofuels.⁷⁰ As a result, the gain in the net benefits to the agricultural sector are not sufficient to offset the costs of the RFS on the fuel sector to producers and consumers of blended fuel. This analysis does not consider the benefits from ethanol to improving energy security. Maintaining the corn ethanol mandate at 15 billion gallons until 2030 will lead to a discounted cumulative value of an economic cost of \$109 billion over the 2016–2030 period compared to the counterfactual baseline scenario.⁷¹ The benefits from reducing GHG emissions over this period (at the social cost of carbon of \$50 per metric ton of CO₂ equivalent) equates to \$39 billion.

69 Social welfare is defined as the sum of net economic benefits to agricultural and fuel consumers and producers and government net of environmental damages due to GHG emissions.

70 Luoye Chen et al. | The economic and environmental costs and benefits of the renewable fuel standard

71 Luoye Chen et al. | The economic and environmental costs and benefits of the renewable fuel standard

TABLE 15. EFFECTS OF THE CORN ETHANOL MANDATE ON SOCIAL WELFARE (2016–2030)

	NO-POLICY SCENARIO	CORN ETHANOL MANDATE CHANGE RELATIVE TO NO-POLICY SCENARIO	
	QUANTITY (\$ BILLION)	ABSOLUTE CHANGE (\$ BILLION)	PERCENT CHANGE
Agricultural Sector Total (a)	2,992	56	1.9%
Agricultural Consumers	2,155	(49)	(2.3%)
Agricultural Producers	837	105	12.5%
Transportation Fuel Sector Total (b)	7,305	(161)	(2.2%)
Crude Oil Producer	65	(1)	(1.7%)
Gasoline Consumers	4,256	(108)	(2.5%)
Diesel Consumers	2,984	(51)	(1.7%)
Government Revenue (c)	854	(4)	(0.5%)
Economic Benefits (a + b + c), (I)	11,151	(109)	(1.0%)
Social Cost of GHG Emissions (d)	(1,561)	39	(2.5%)
Social Cost of Nitrogen Damages (e)	(1,032)	(129)	12.5%
Values of Environmental Effects (d + e), (II)	(2,593)	(90)	3.5%
Total Social Welfare (I + II)	8,558	(199)	(2.3%)

Source: Luoye Chen, et al. | The economic and environmental costs and benefits of the renewable fuel standard

Note: All values are discounted cumulative numbers over 2016–2030 (discounted rate 3%).

Thus, the economic costs of the RFS are greater than the monetized value of the GHG savings. Additionally, the extent of damages caused by nitrogen (N) leakage to land, air, and water resources that result in N being transported to drinking water wells, coastal zones, and the atmosphere ranges from a low value of \$5.45 per kilogram (kg) of N applied to a medium value of \$10.17 per kg N applied to a high value of \$16.87 per kg N applied. At the median value, the discounted value of the damages due to N leakage is \$129 billion over the 2016–2030 period. The net economic and environmental cost of the RFS is therefore estimated to be \$199 billion, as shown in Table 15 (with a range of \$99 billion to \$284 billion at different values of the social cost of carbon and the social cost of N) over this period.⁷² The \$199 billion represents the net loss in social welfare relative to a no-policy scenario after accounting for the economic costs and benefits on the agricultural and fuel sectors, the net benefits from GHG reduction, and the net costs from N-leakage-related damages.⁷³

A few studies have also compared the costs and benefits of the RFS to a hypothetical national LCFS that would achieve the same level of reduction in GHG emissions. Considering production of both corn and cellulosic biofuels and analyzing the fuel market effects of biofuels before the shale gas period, the hypothetical national LCFS allowed flexibility in the mix of corn and cellulosic biofuels and provided greater incentive to vary the mix of biofuel feedstocks used to meet the LCFS based on their CIs than the RFS, which had volumetric targets for corn ethanol. A 2014 study found that an LCFS could achieve the same reduction in U.S. GHG emissions

⁷² Luoye Chen et al. | The economic and environmental costs and benefits of the renewable fuel standard

⁷³ Accounting for environmental damage (other than GHG emissions) caused by the fossil fuels that are displaced by biofuels falls beyond the scope of this report.

with a smaller total volume of ethanol and thus lead to a lesser reduction in fossil fuel use.⁷⁴ For all these reasons, the RFS led to a larger improvement in the terms of trade and in social net benefits than the LCFS.⁷⁵ Additionally, a 2017 study examined the costs and benefits of regulating the ILUC effect of biofuels.⁷⁶ In an effort to reduce ILUC, the California LCFS has included the ILUC-related factor as a part of the CI of biofuels. This study showed that while this policy led to additional abatement of cumulative emissions, the monetized value of that reduction was much smaller than the cost of abatement measured in terms of the loss in social welfare due to this policy.

6.2 IMPACT ON ENVIRONMENT OF PROGRAMS IMPLEMENTED BY FARMERS AND BIOFUELS PRODUCERS

Over time, improvements in production practices, greater crop varieties, and more intensive cropping⁷⁷ have led to yield improvements without corresponding increases in the use of inputs, thus contributing to lowering the lifecycle CI of corn. The increase in corn yields is also likely to have contributed to a lower ILUC impact of corn ethanol production and thus lower ILUC-related emissions.

One study found that carbon emissions from corn ethanol fell 23% between 2005 and 2019 due to increased corn yields per acre, decreased fertilizer

74 Xiaoguang Chen et al. | Alternative transportation fuel standards: Welfare effects and climate benefits

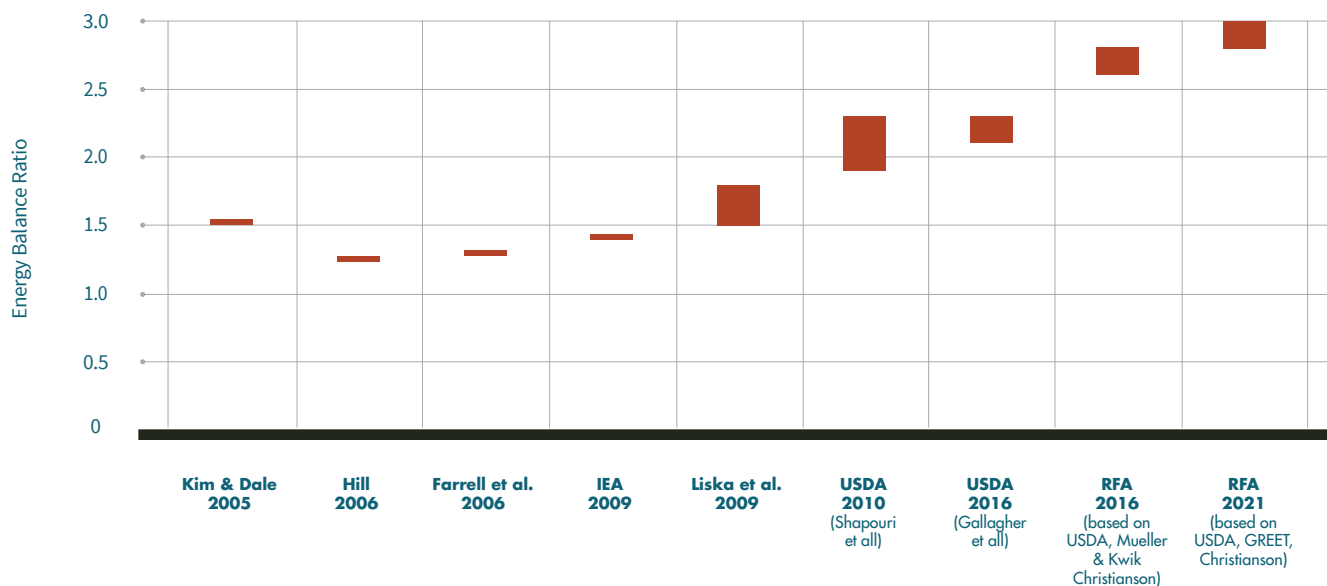
75 Xiaoguang Chen et al. | Alternative transportation fuel standards: Welfare effects and climate benefits

76 Madhu Khanna et al. | The social inefficiency of regulating indirect land use change due to biofuels

77 Ruiqing Miao et al. | Responsiveness of crop yield and acreage to prices and climate



FIGURE 37. DRY MILL CORN ETHANOL AVERAGE ENERGY BALANCE RATIO ESTIMATES (2005–2021)



Source: Renewable Fuels Association | Corn ethanol’s energy balance continues to improve

use, and improved ethanol production processes.⁷⁸ The amount of energy used in these aspects of corn production has fallen to 8,481 BTU per gallon of ethanol, nearly 6% lower than the 9,007 BTU estimated by the USDA in 2016 (based on 2010 data). Additionally, there has been a 6.5% increase in ethanol yield and a 24% reduction in ethanol plant energy use, which have reduced the CI of corn ethanol.

Another study shows that the energy efficiency of corn ethanol production has improved over time, as shown in Figure 37; the average energy balance ratio (the ratio of energy output to energy input) for corn ethanol in 2021 was estimated to be 2.8–3.0, compared to 2.1–2.3 in 2016, and the ratio for the top-performing quartile of biorefineries was 3.7–4.02.⁷⁹ The amount of energy used for corn production had fallen by 6% in 2016 compared to 2010. The thermal energy and electricity usage for corn production has also been declining and was 3% lower in 2021 compared to 2015, and average electricity use declined by 11% over this period.

The cost of producing corn ethanol has also fallen over time because the efficiency of the production process has increased as the scale of production has increased. The increase in volume of biofuel production has led to a process of “learning by doing,” which is estimated to have reduced the processing cost of ethanol by 45% since 1983 as production volumes increased 17-fold.⁸⁰ The per-gallon industrial cost of ethanol production declined by 25% with every doubling in the cumulative number of gallons produced.

78 Uisung Lee et al. | Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: Implications for greenhouse gas emission reductions

79 Renewable Fuels Association | Corn Ethanol’s Energy Balance Continues to Improve

80 Xiaoguang Chen and Madhu Khanna | Explaining the reductions in US corn ethanol processing costs: Testing competing hypotheses

SECTION 7.

Food Versus Fuel Considerations in the U.S.

7.1 FEEDSTOCKS USED FOR BOTH FOOD AND FUEL

Overall demand for food, both in the U.S. and globally, is set primarily by growth in population and secondarily by economic growth. How that overall food demand translates into demand for corn, grain sorghum,⁸¹ soybeans, and canola will also be dependent on trends in food preferences (e.g., preference for meat versus vegetables in the diet), which are difficult to predict and outside the scope of this report.

As discussed in section 2, the demand for ethanol, and consequently corn used in the ethanol production process, will gradually decrease from 2024 through 2035. This will be primarily due to the E10 blend wall limitations on gasoline products, a downward trend in U.S. gasoline demand, and a decrease in the inventory of FFVs, partially offset by expected growth in sales of E15. As per-acre corn yields are expected to continue to increase, U.S. crop acreage used to grow this corn is also expected to decrease. Total corn acres will likely decrease more slowly than indicated by reduced ethanol production, as corn grain demand for livestock feed will grow in response to lower DDGS production

at ethanol plants and U.S. and global demand for corn is expected to increase in response to continued population growth. An additional potential offset to this trend of reducing corn demand is the yet-to-be-demonstrated commercialization of SAF produced via the ATJ process. If this technology becomes commercially viable and capable of achieving the maximum 50 kg CO₂e/mmBTU requirement to qualify for CFPC tax credits, U.S. corn ethanol production might continue at current levels or even grow.

Soybean oil and canola oil, like all the other significant BD and RD feedstocks, are by-products. Soybeans and canola are primarily grown to meet demand for their high-protein meal, with overall demand for oils adjusting to meet available supply. This overall demand includes both food use, which grows with population and per-capita wealth, and biofuels. While not identical, soy and canola oils and meals are close substitutes, enabling a large overlap in their potential uses.

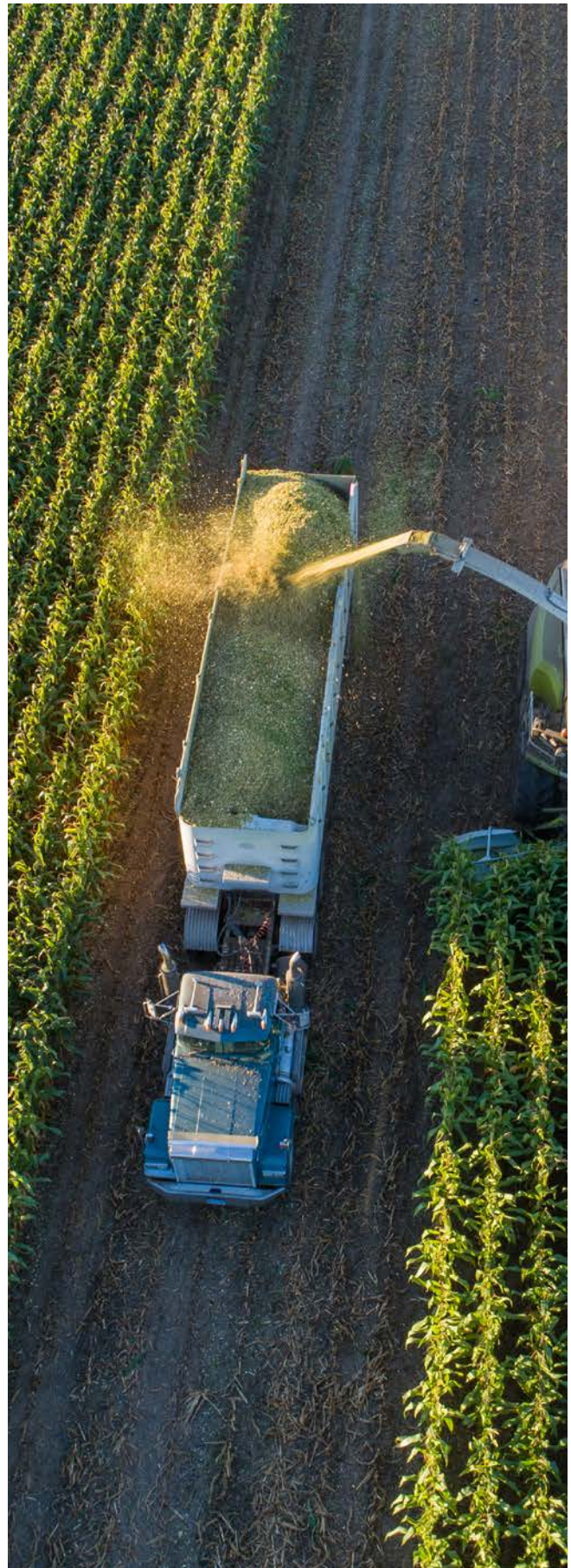
Total U.S. soybean demand can be expected to increase with the projected decrease in corn ethanol production, as there will be an increase in demand for soybean meal (in addition to increased demand for corn grain) to replace lost production of DDGS at

⁸¹ Grain sorghum is not typically used as human food; its dominant use is as livestock feed.

ethanol plants. This will make increased volumes of soybean oil available for use as BD and RD feedstock. As shown in Figure 25, demand for soybean oil as a biofuel feedstock is expected to hold relatively steady through 2027 and then potentially decrease if the CFPC is allowed to expire as scheduled in 2027 and no new state LCF programs are enacted. If federal tax credits are extended or new state LCF programs are implemented, the use of soybean oil as biofuel feedstock will be expected to remain at 2025–2027 levels or potentially rise to the extent that supplies are available.

Demand for canola oil as a biofuel feedstock in the U.S. is smaller than that for soybean oil. The important differences between soybeans and canola are that canola has a much higher oil content (44% for canola versus 20% for soybeans) and canola is primarily grown in areas that are not well suited for soybeans. Ideally, farmers would be able to switch back and forth between growing canola and soybeans in order to balance the market demands for meal and oil. They are not able to do that readily, however, due to climate requirements for the respective crops and the fact that the seed-crushing facilities need to be configured differently for the two crops.

Over the longer term, we expect that usage of soybean oil and canola oil as biofuel feedstocks will be constrained by growing demand for these commodities in food markets as population continues to grow. The fact that the economics for growing soybeans and canola are heavily dependent on markets for their meal further serves to limit availability of the oils. If a consistent policy environment driving demand for liquid biofuels continues and strengthens, there will be incentive for soybean seed producers to commercialize new soybean varieties with a higher oil content and for technology developers to continue work on biomass-based FT technologies, as they offer the potential to enable a much larger range of possible feedstocks.



7.2 IMPLICATIONS OF EXPANDED PRODUCTION OF BIOFUEL FEEDSTOCKS ON OVERALL AGRICULTURAL PRODUCTION

Given our evaluation of acreage required for current and future biofuels production, in this section we will explore the implications of the necessary expansion on overall agricultural production capacity and opportunity in the U.S. and globally.

The supply of commodity crops available to U.S. biofuel producers in the short run varies due to factors including:

- The annual planting decisions of individual farmers, based on their perceptions of expected prices. This can be informed by existing inventory levels, forecast weather for the growing season, water availability (in areas dependent upon irrigation), relative prices and availability of seeds, and desire to rotate crops to manage long-term soil health.
- Actual weather conditions occurring during the planting season.
- Demand for commodity crops in export markets.

Over the long term, additional forces coming into play include:

- Loss of suitable cropland—land permanently taken out of production for other uses, potentially offset by new land brought into production.
- Developments of seed technology and agronomic practices that enhance yields.
- Climate change, which may alter the range of land suitable for growing specific crops and the yields attainable.

Biofuel policies in most of the world have historically been driven by a desire to use surplus agricultural production that was being exported at low value to displace high-cost imports of crude oil and petroleum products. Accordingly, governments have periodically increased or decreased biofuel

mandates and incentives in response to the size of crop surpluses and crude oil prices largely out of concern for potential impacts on food prices and availability. This remains the case today in most of the world outside North America and Europe.

In the generally wealthier economies of North America and Europe, biofuel policies have become more closely linked with climate policies. As a result, biofuel requirements and incentives are less likely to be subject to short-term revisions in response to typical annual variations in feedstock supplies. In these markets, food costs typically represent a lower share of income, and markets are more resilient to food price changes. Governments in these markets retain the ability to modify or waive biofuel requirements in response to extreme concerns over feedstock availability but are expected to use those tools sparingly.

7.2.1 EFFECTS OF BIOFUELS ON AGRICULTURAL PRODUCTION AND PRICES

A meta-analysis of the literature on the subject concludes that biofuels are not a leading source of high commodity prices. Here we take a closer look at the data underlying this conclusion.

Production of corn ethanol and BD has grown in recent decades. BD production from soybean and corn oil has grown from 91 million gallons in 2005 to about 1.3 billion gallons in 2018, and BD constituted about 7.4% of total biofuel production in 2018. Over this period, corn ethanol production grew from 3.9 billion to 16.1 billion gallons, and a growing share of corn and soybeans is being used for biofuel; corn ethanol is currently using 40% of corn produced, while soy BD is using 50% of soybeans.

Diversion of this quantity of commodities from food/feed to fuel affects the availability of commodities to meet other demands. Crop prices need to increase to induce additional production of these crops. The extent to which an increase in crop prices is needed to achieve a new equilibrium between demand



and supply will depend on various factors, such as the extent to which the price increase induces an increase in intensity of production on existing cropland, how much additional land needs to be brought into production, and the ease of converting non-cropland to crop production. The expansion of biofuel production after 2007 was accompanied by a spike in crop prices in 2008 and 2010–2012. Such increases in crop prices benefit producers in the agricultural sector in the U.S. and in countries that export agricultural commodities, while having adverse economic impacts on agricultural consumers domestically and even more so in low-income countries that are net importers of these agricultural products.

Comparing crop prices before and after the expansion of biofuels production and attributing the increase to biofuels is neither accurate nor valid because the change in prices could be caused by many other factors that may have also changed

over that time. Isolating the extent to which biofuel production has contributed to a change in crop production and prices requires comparing these outcomes with biofuels and a counterfactual case without biofuels.

A sizeable body of literature examines the relationship between food and biofuel prices since 2007. In general, these studies find that biofuel production increased agricultural commodity prices by 10%–30%.⁸² These studies used a variety of models to conduct their analyses. Some used partial equilibrium models of the most relevant sectors in the economy (food and fuel markets); others used general equilibrium models that are economy-wide or even global and consider the feedback between the food and fuel markets and the rest of the economy. Another approach is an econometric assessment that uses historical data to isolate and attribute a portion of the commodity price impact to biofuels.^{83,84}

⁸² Madhu Khanna et al. | [Lessons learned from US experience with biofuels: Comparing the hype with the evidence](#)

⁸³ Madhu Khanna et al. | [Lessons learned from US experience with biofuels: Comparing the hype with the evidence](#)

⁸⁴ Karel Janda and Ladislav Křišťoufek | [The Relationship Between fuel and food prices: Methods and outcomes](#)

Studies using simulation models include many features and assumptions that affect the estimated impacts of biofuels on the prices of food, fuel, and other goods. Some of the key assumptions include the responsiveness of crop yields and technological improvements to higher crop prices; the ease with which farmers can change crops or engage in double-cropping (i.e., growing more than one crop on the land during a year); and the productivity of marginal land that can be utilized if crop prices increase. More flexibility in cropping choice and higher productivity of marginal lands tend to reduce the impacts of biofuel on crop prices. Models differ in the extent to which they include co-products of corn ethanol production, in particular DDGS, that is used as livestock feed. The extent to which these models allow crop yields to increase with an increase in crop prices has an impact on the extent to which corn ethanol production led to an increase in corn prices. A positive yield-price elasticity is consistent with the historical observation that periods of high farm prices are generally followed by investments in agricultural production that increase the supply of corn. Based on empirical evidence that corn yield is responsive to corn price, models that include a positive yield-price elasticity show smaller increases in crop prices due to biofuels. Studies that allowed for crop yields to grow over time due to improved crop varieties also projected a smaller impact because improved crop yields enabled supply to catch up with the increase in demand for corn for food and biofuel.

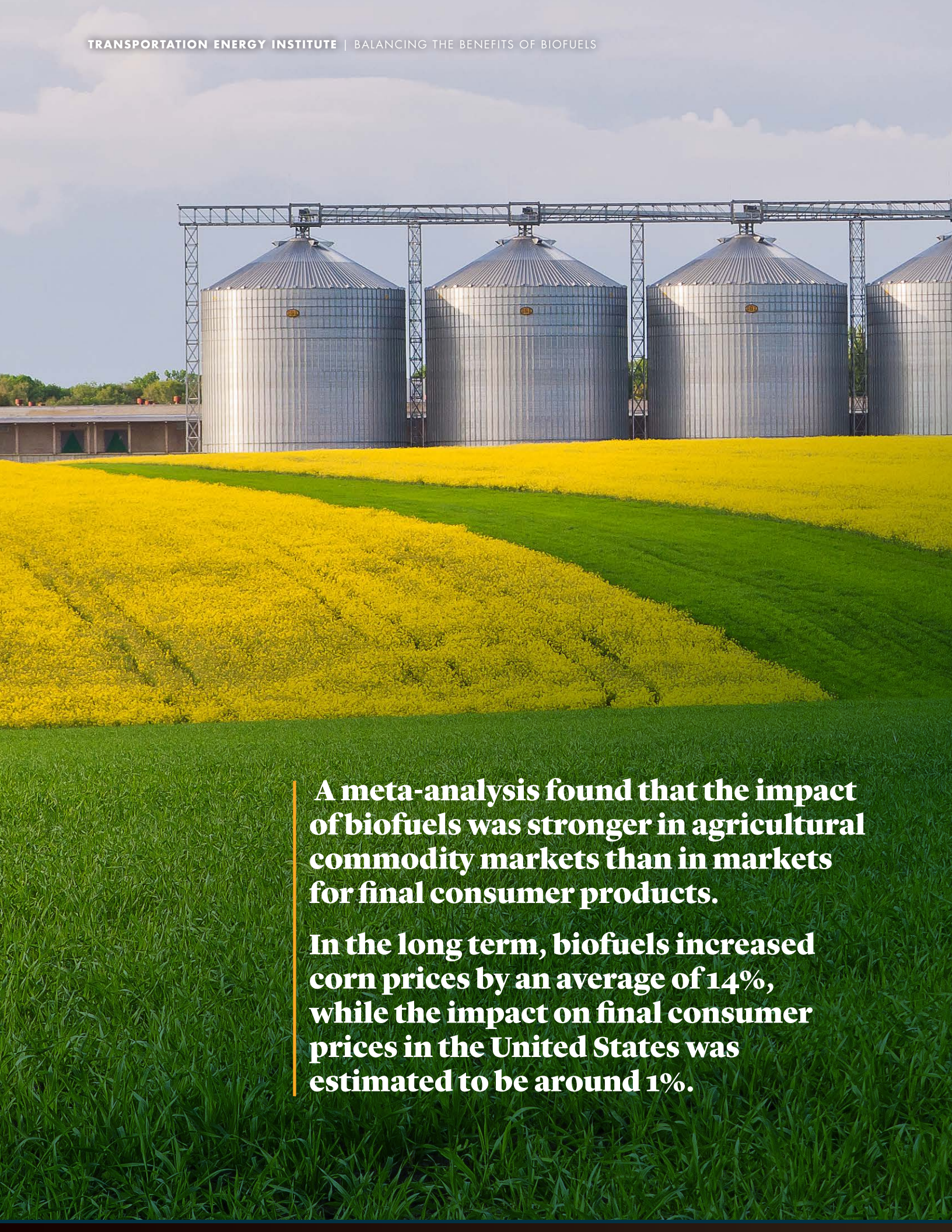
Studies vary widely in their projected estimates of the impact of biofuels on crop prices. In general, the various studies consistently find that corn ethanol production was an important contributor to the increase in crop prices but also that only a portion of the observed increase can be attributed to corn ethanol. Most studies suggest that the effect of biofuels on agricultural commodity prices was between 10% and 30%. The spikes in crop prices in 2007–2008 and 2010–2011 occurred due to a combination of low crop inventories, growth in demand and changes in stock policies in China, high energy prices, stagnation of productivity growth due to underinvestment in agricultural research, and restrictive trade policies across the world. A meta-analysis found that the impact of biofuels was stronger in agricultural commodity markets than in markets for final consumer products and that in the long term, biofuels increased corn prices by an average of 14%, while the impact on final consumer prices in the United States was estimated to be around 1%.⁸⁵ Another analysis similarly concluded that the effect of ethanol production on agricultural commodity prices varied over time; it had no effect prior to the 2008 food crisis, it increased corn prices by 15% and other crop prices by 5% during the food crisis of 2010–2012, and it contributed to about a 10% increase in crop prices after that.⁸⁶ Overall, a meta-analysis of the literature on the subject concludes that biofuels are not a leading source of high commodity prices.

A retrospective analysis separates out the effect of corn ethanol and soybean BD on crop prices over the 2007–2018 period.⁸⁷ This analysis finds that demand for corn ethanol by 2018 had increased land rent by 30%, corn prices by 31%, and soybean prices by 21% in 2018 compared to a baseline scenario where corn ethanol and BD production levels were maintained at the 2005 level. This analysis conducts a comparison of one scenario including biofuels versus a second scenario without biofuels, assuming all other factors such as the costs of production of corn and soybeans remain the same. The addition of the demand for BD led to a further increase in land rent by 7%, an increase in corn prices by 4%, and an increase in soybean prices by 8% compared to the scenario with only an increase in corn ethanol.

85 Gail Hochman and David Zilberman | Corn ethanol and U.S. biofuel policy 10 years later: A quantitative assessment

86 Ondrej Filip et al. | Food versus fuel: An updated and expanded evidence

87 Weiwei Wang and Madhu Khanna | Land use effects of biofuel production in the US



A meta-analysis found that the impact of biofuels was stronger in agricultural commodity markets than in markets for final consumer products.

In the long term, biofuels increased corn prices by an average of 14%, while the impact on final consumer prices in the United States was estimated to be around 1%.

The Scenario 1 column of [Table 16](#) shows the baseline scenario with corn ethanol and soybean BD at 2005 levels. The Scenario 2 column shows the scenario with corn ethanol levels as observed over the 2007–2018 period and soy BD at 2005 levels. The last column shows the scenario with corn ethanol and soy BD at observed levels over the 2007–2018 period. All other assumptions about costs of production, domestic and export demands, and land availability are the same across the three scenarios.



TABLE 16. EFFECT OF BIOFUEL PRODUCTION ON LAND RENTS AND CROP PRICES

	SCENARIO 1 (EtOH & BD 2005)	SCENARIO 2 (EtOH Observed & BD 2005)		SCENARIO 3 (EtOH & BD Observed)	
	BASELINE VALUE	SCENARIO 2 VALUE	PERCENT CHANGE	SCENARIO 3 VALUE	PERCENT CHANGE
Total Cropland in 2018 (Million Acres)	320.5	328.1	2.4%	329.2	0.3%
Cropland in 2007 Remaining in Crop Production in 2018	301.1	301.7	0.2%	301.9	0.1%
Conversion of Cropland Pasture by 2018	8.9	12.1	36.6%	12.3	1.2%
Conversion of CRP Land by 2018	9.2	12.8	39.9%	13.6	6.1%
Land under Corn (Million Acres)	76.4	98.6	29.1%	97.9	-0.7%
Corn for Food	68.2	64.3	-5.6%	63.9	-0.7%
Corn for Ethanol	8.2	34.3	317.4%	34.0	-0.7%
Land under Soybeans	80.2	71.2	-11.2%	76.1	6.9%
Soybeans for Biodiesel	1.4	1.5	7.1%	16.5	1079%
Soybeans for Food/feed	78.8	69.7	-11.5%	59.6	-14.5%
Other Food/Feed Crops	164.0	158.3	-3.5%	155.1	-2.0%
Corn Price (\$/bu)	3.0	4.0	31.4%	4.2	4.3%
Soybeans Price (\$/bu)	7.9	9.5	20.6%	10.3	8.2%
Land Rent (\$/ac)	127.7	165.7	29.8%	176.6	6.6%
Land Use Change Elasticity	n/a	7.9%	n/a	5.1%	n/a
Total CRP Maintenance Costs (\$Billion)	23.9	35.2	46.9%	37.0	5.2%

Source: [Weiwei Wang and Madhu Khanna | Land use effects of biofuel production in the US](#)
Units: bushels (bu); acres (ac)

7.2.2 FORESEEABLE SCENARIOS THAT COULD MEANINGFULLY DEplete FEEDSTOCK SUPPLY

Historical evidence suggests that technological advances in agriculture have enabled it to continue to improve productivity at a rate that has outpaced the increase in demand, and as a result, land in agricultural use has been declining. There have also been major gains in the efficiency of the livestock sector, which has been increasingly replaced by poultry. The livestock industry has therefore become more land efficient and is using fewer land resources. U.S. calorie production has grown faster than the demand for food and feed, and this has contributed to a decline in land in the agricultural sector.⁸⁸

In the near term (the next 10 years), total area planted to the major field crops—corn, soybeans, wheat, and others—is expected to remain similar to 2023 levels or decline marginally due to an increase in weather-related prevented plantings. Yields of corn, soybeans, and wheat are expected to increase at rates similar to those observed historically due to continuing advancements in production practices and in technology, including improvements in seed varieties and chemicals used in agriculture. These higher yields are expected to more than compensate for reduced planted acreage, resulting in record-high production for corn and soybeans. As a result, corn and soybean prices are expected to fall for the next five years and then stabilize.⁸⁹

The supply of corn is more elastic in the long run than in the short run; that is, a given percentage increase in corn prices leads to a larger increase in corn supply in the long run than in the short run. Thus, if biofuel mandates are relatively certain for the foreseeable future and the market has time to respond to them, the price impacts are likely to be

modest. Projecting forward to 2030, maintaining corn ethanol at the 2016 level until 2030 is expected to increase corn prices by 7% by 2030 relative to a pre-RFS baseline level, because of growth in corn productivity and supply outpacing the growth in demand.⁹⁰

The studies referenced here have assumed that current climate conditions will prevail and that there is no adverse impact of climate change on crop yields. Studies indicate, however, that the changing climate is expected to have significant adverse impacts on the yields of corn and soybeans in the U.S. by mid-century.⁹¹ The extent to which this impact will be mitigated by improvements in crop varieties that are more drought tolerant and heat resistant and by adaptation in crop management practices is uncertain. There is also the potential for a change in the spatial pattern of corn and soybean production across regions in the U.S. to mitigate the effect of change in the climate.⁹² The net impact of climate change on crop yields and markets after considering potential adaptation measures remains uncertain.

7.2.3 IMPACT OF INCREASED BIOFUELS-RELATED FEEDSTOCK PRODUCTION ON THE RELATIONSHIP BETWEEN EACH BIOFUEL AND THE PRODUCTION OF FEEDSTOCK FOR FOOD PRODUCTION

A 2021 study examined the effects of maintaining corn ethanol at 15 billion gallons until 2030 and compared those effects relative to a pre-RFS level of 6.5 billion gallons of corn ethanol.⁹³ The study found that the increased production of ethanol would result in a 23% increase in corn acres and a 21% increase in corn production. The share of corn used for biofuel would be 33% and corn prices would be 12% higher.

88 Farzad Taheripour et al. | Technological progress in US agriculture: Implications for biofuel production

89 Brian Williams et al. | Declining crop prices, rising production and exports highlight U.S. agricultural projections to 2032

90 Yuanyao Lee et al. | Quantifying uncertainties in greenhouse gas savings and abatement costs with cellulosic biofuels

91 Chengzheng Yu et al. | Maladaptation of U.S. corn and soybeans to a changing climate

92 James Rising and Naresh Devineni | Crop switching reduces agricultural losses from climate change in the United States by half under RCP 8.5

93 Luoye Chen et al. | The economic and environmental costs and benefits of the renewable fuel standard

The effects of the increase in demand for soybean BD is leading to growing domestic demand for soybean oil. The U.S. became a net importer of soybean oil in 2022–2023 due to demands from low-carbon fuel mandates. Continued increase in demand for soybean BD is expected to increase the establishment of new crushing facilities and the expansion of existing facilities as well as lead to increased demand for other oil feedstocks such as canola oil, tallow, and UCO.⁹⁴

7.2.4 GLOBAL MARKETS AND FEEDSTOCK COMPETITION

Since 2000, there has been a dramatic increase in global ethanol production. According to EPA data, the U.S. and Brazil have been the two largest producers of ethanol, with a combined production that represented 83% of global supply in 2019, and they are the two primary net exporters of ethanol. The U.S. was a net importer of ethanol in 2004–2006 but has been a net exporter since 2010. Ethanol imports from Brazil have been irregular and generally a small fraction (2%) of total U.S. production. Two concerns related to international impacts of ethanol mandates in the U.S. are the increased demand for feedstock production overseas for import to the U.S. that it induces (e.g., ethanol from corn or sugarcane) and the increased demand for corn that increases traded crop prices and induces crop production overseas. [Figure 38](#) presents annual U.S. production, import, and export volumes since 2010. [Figure 39](#) shows the corresponding data for Brazil since 2012.

Ethanol imports by the U.S. have primarily been from Brazil and have been relatively small. Production of sugarcane ethanol in Brazil was induced primarily by Brazil’s own domestic policies. Since 2010, the U.S. has been a net exporter of ethanol, with exports going to 70 different countries; this may have had some small land-sparing effects in those countries

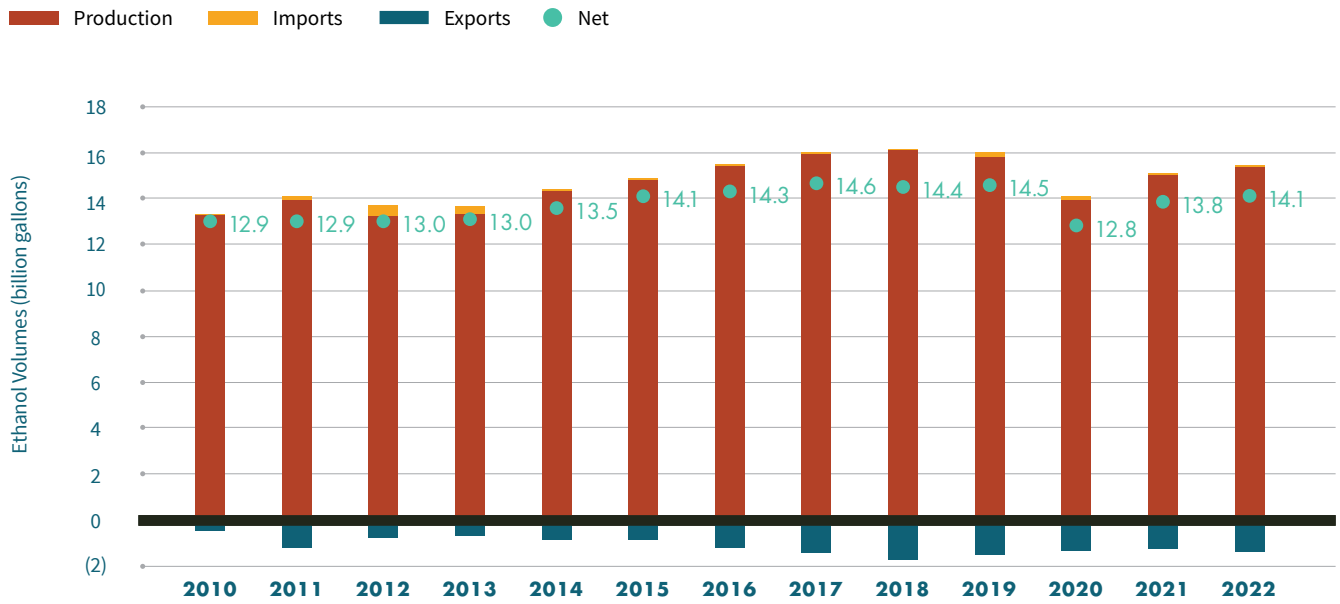
since they did not need to produce their own ethanol. Ethanol trade between the U.S. and Brazil has been seasonal and influenced by short-term effects of weather, currency exchange rates, and the spot prices of ethanol and sugar. Since 2014, Brazil has increased corn-based ethanol production due to poor weather impacting sugarcane production, high sugar prices that favor more sugar relative to ethanol production, and incentives under domestic biofuel policies. The volume of corn ethanol in Brazil has increased to nearly 900 million gallons, or 11% of total Brazilian ethanol production in 2021.

A few early studies examined the effects of biofuel production/consumption on crop and livestock markets in the three major biofuel-producing areas—the U.S., Brazil, and the EU. Biofuel production increases crop prices, which leads to increased input costs for the livestock industry. It also leads to conversion of pastureland to crop production and can increase the production costs of ruminant livestock. On the other hand, biofuel production yields by-products that can be used in the livestock industry as animal feed; the extent to which these by-products can be used varies across different livestock industries. One study found that growth in the U.S. and EU biofuels industries would lead to “larger absolute reductions in livestock production overseas” than in the U.S. and EU due to higher grain prices, which would be “offset locally by the lower cost of by-products.” The study also found that nonruminant production would be “cut more than ruminant livestock, because it is less able to use biofuel by-products in its feed rations.” The biofuel-producing regions were expected to reduce their coarse grains exports, increase imports of oilseeds and vegetable oils, and increase their exports of processed feed materials.⁹⁵

94 S&P Global | US shifts to net soybean oil importer on biofuel boom: Foreign Agricultural Service

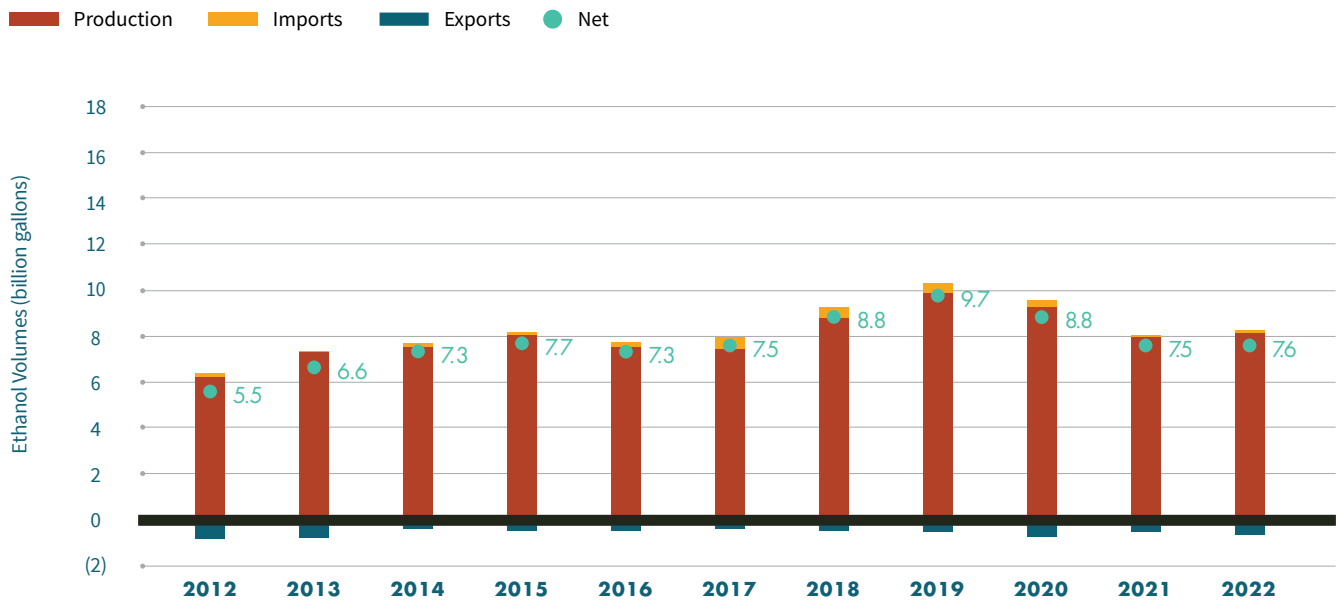
95 Farzad Taheripour et al. | Implications of biofuels mandates for the global livestock industry: A computable general equilibrium analysis

FIGURE 38. U.S. ANNUAL ETHANOL PRODUCTION, IMPORTS, AND EXPORTS (2010–2022)



Source: USDA | Bioenergy Statistics, January 2024

FIGURE 39. BRAZIL ANNUAL ETHANOL PRODUCTION, IMPORTS, AND EXPORTS (2012–2022)



Sources: Brazil Biofuels Annual, GAIN Report BR15006, 8/10/2015; Brazil Biofuels Annual, GAIN Report BR2023-0018, 9/5/2023.

BD production, for its part, uses a variety of feedstocks (domestic and international) and comes from different countries, although it has been dominated by domestic sources like FOG and soybean oil. In 2016, imports of soybean oil BD from Argentina and palm oil BD from Southeast Asia (734 million gallons total) were almost equal to the BD produced domestically from domestic soybeans (865 million gallons). Imports from Argentina and Southeast Asia have dropped to zero since 2017 due to restrictions on imports by the U.S. following an antidumping complaint and countervailing duties. Overall, production of BD in these countries is influenced more by their domestic policies than by the demands created by U.S. biofuel mandates.⁹⁶



Concerns have been raised that U.S. biofuel policy could be leading to land use changes in Southeast Asia, specifically Malaysia and Indonesia. This is due to the role of substitution among vegetable oils in linking these economies in markets for vegetable oil; increased demand for soybean BD in the U.S. could lead to more palm oil production in Southeast Asia on peatland and thereby release carbon.

One study estimated that the production of 15 billion gallons of corn ethanol and two billion gallons of soy BD together could potentially create demand for palm oil from Malaysia and Indonesia.⁹⁷ This would expand cropland on carbon-rich peatland in these countries. Conversion of this peatland to palm oil plantations would result in a significant loss of soil carbon and lead to a large increase in the ILUC-related CI of soybean-based BD. The magnitude of this effect is sensitive to assumptions about the ease of substitution among all types of vegetable oils and animal fats in the U.S. The greater the substitutability among vegetable oils in the U.S., the greater the potential to meet the demand for soybean BD by reducing consumption of vegetable oils in the U.S., thereby lowering the demand for palm oil from Southeast Asia and thus lowering the ILUC-related CI of soybean BD.

7.3 CONCLUSION

As demonstrated in the previous sections, the interplay between food and fuel is complex. Demand for food, both in the U.S. and globally, is set primarily by growth in population and secondarily by economic growth. A meta-analysis of the literature on the subject, however, supports the finding that biofuels are not a leading source of high prices of commodities, including food crops.

⁹⁶ The use of palm-based biofuels in the U.S. is minimal as palm-based BD, unlike BD produced from other commercial feedstocks, does not qualify for D4 RINs under the RFS (it does qualify for less-valuable D6 RINs) due to its high CI. This high CI is attributable to the very high ILUC factor assigned to increased palm oil production in Southeast Asia. Further, this high CI means that palm-derived BD or RD would be an undesirable, deficit-generating fuel in the LCF programs of California, Oregon, and Washington.

⁹⁷ Farzad Taheripour and Wallace E. Tyner | US biofuel production and policy: Implications for land use changes in Malaysia and Indonesia



SECTION 8.

Policy Impacts

As demonstrated in the preceding sections of this report, the production of biofuels overlaps with many different sectors, and government policies play a role in each of these sectors. Policies that have affected the cost of biofuels include those that have impacted the price of commodity grains and oilseeds and those that have impacted the inputs into the conversion of those feedstocks to biofuels, primarily related to energy. Additionally, programs incentivizing renewable fuel usage—such as the RFS and LCF programs—have increased demand for biofuels. We present here a list of high-level examples of policies that may impact the biofuels sector. In the subsections that follow, we expand on the significant historical impacts of these policies.

Several types of federal policies have impacted the cost of feedstock production and prices of commodity grains and oilseeds.

- Agricultural policies—primarily subsidies, crop insurance, and preferences for family farming—have shaped the practices and costs of producing commodity grains and oilseeds.
- Monetary and fiscal policy changes have impacted the cost of agriculture, reducing grain production and increasing the price for commodity grains and oilseeds.
- Trade policies that reduce or add barriers for exports (including embargoes) have impacted global grain prices.
- Foreign policy changes can also affect the prices for commodity grains and oilseeds if they result in actions by other governments that impact the global markets for these products.
- Environmental and climate change policies, including water policies, that have raised the cost of fossil fuels have impacted the cost of grain production.

These are primarily policies at the federal level, but state and local government policies have probably also impacted the cost of feedstock production. Some of these policies include property taxes, land use restrictions, and emissions standards.

Policies that impact the price of energy and therefore the cost to convert feedstock to biofuels include those that have affected the price of crude oil and natural gas. In addition to impacting the market value of the fuels that biofuels are intended to displace, crude oil and natural gas prices are important as they directly impact the price of fertilizers, methanol, electricity, and fuel used in farming, feedstock processing, and biofuels processing.



Lastly, renewable fuels and low-carbon policies have impacted the cost of biofuels. **These biofuels policies have acted as subsidies to allow economic production of biofuels.**

- The RFS program’s mandate for renewable fuels has increased the demand for biofuels beyond what would otherwise be economic to produce. To compensate for this, the RFS has subsidized the cost of biofuels production by adding the RINs incentive.
- The BTC is another incentive for BD and RD production.
- Some policies require the use of biofuels in government fleets, which has expanded biofuel demand.
- Federal grant and guarantee programs often assist biofuels production on a plant-by-plant basis.
- In California and Oregon, and more recently in Washington State, LCF programs have added further incentives to the use of low-carbon biofuels in the form of marketable credits.
- Also in California, and more recently in Oregon and Washington, carbon cap programs require priced carbon allowances for petroleum gasoline and diesel, a cost that has raised the prices of those fuels. Biofuels do not require allowances when they displace petroleum fuels and do not incur that cost, effectively increasing their value.

8.1 HISTORICAL POLICY IMPACTS

The list above offers examples of types of policies that might impact feedstock and renewable fuel production. This section details the historical effects of the primary policies that have meaningfully impacted crop-based biofuels.

8.1.1 FEEDSTOCKS

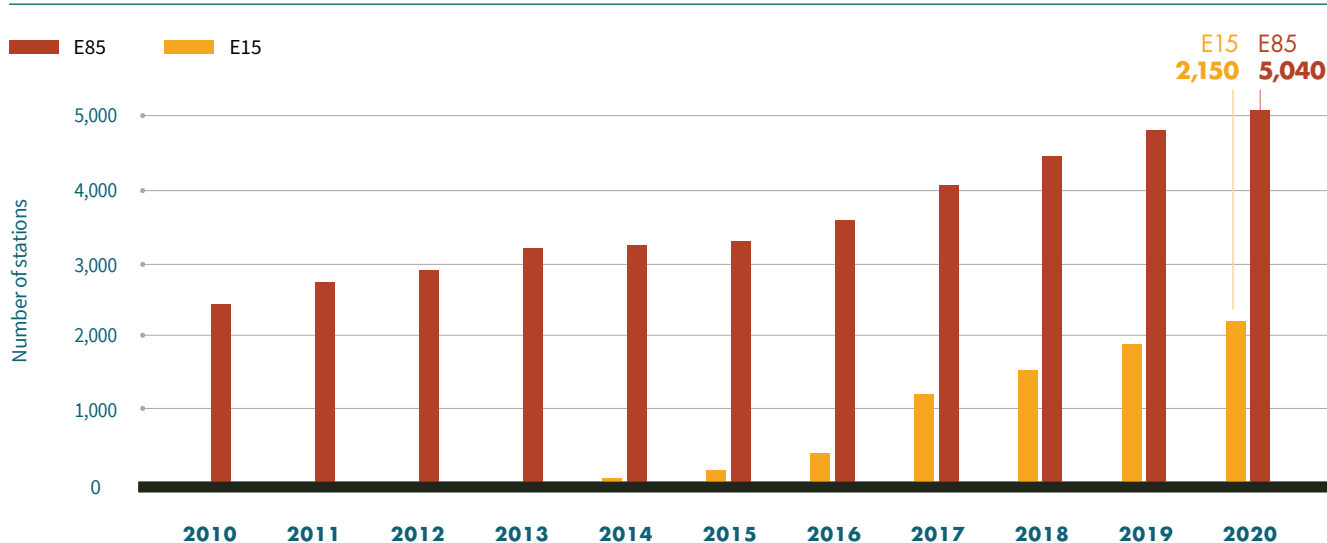
The initial implementation of renewable fuel mandates such as the RFS caused increases in the demand for such fuels and their feedstocks. In order to avoid over- or underproduction of renewable fuel feedstocks, the RFS aims to find a new balance between traditional fuels (i.e., gasoline or diesel) and new, renewable fuels (i.e., E10, RD, or BD). Introducing new renewable fuels too quickly or too slowly, however, can result in a mismatch between production capacity and demand, resulting in dramatic increases or decreases in prices. The RFS allows EPA to send early signals of renewable fuels mandate changes to the market, which should reduce the variability of production and price. The lack of long-term RFS blending targets has served to limit the program’s effectiveness for incentivizing

investment; these adverse impacts have been compounded in those years when EPA has set the RFS volume requirements retroactively.

8.1.2 ETHANOL

Federal programs like the RFS mandate the incorporation of renewables into the gasoline and diesel pools, but there can be physical limitations such as compatibility with existing vehicles and fuel distribution infrastructure. Ethanol has a high octane value and has served as a low-cost alternative to MTBE since MTBE was banned. The national gasoline pool was able to quickly absorb 10% ethanol from corn and grain sorghum but has had difficulty reaching 15% ethanol (E15) due to federal regulatory issues, infrastructure complexities, and various state regulations creating further obstacles to its widespread adoption. Higher blends of ethanol (such as E85) can only be used in FFVs, of which fewer are being produced due to recent changes in vehicle emissions standard regulations. Data on the number of U.S. retail stations offering E15 and E85 is presented in [Figure 40](#). The RFS is not expected to incentivize additional feedstock production for use in ethanol. In fact, the impact of improvements in

FIGURE 40. U.S. RETAIL STATIONS OFFERING E15 AND E85 (2010–2020)



Source: Renewable Fuels Association

the yields of both feedstock and ethanol production is likely to be compounded by future reductions in ethanol demand from improved engine fuel efficiencies and a growing share of EVs in the light-duty vehicle fleet. These forces will decrease the demand for ethanol feedstock acreage use and production.



Recent analysis by EPA for the Third Triennial Report to Congress⁹⁸ concluded that the RFS program itself played a small role in the growth of corn ethanol in the U.S. According to EPA, the RFS led to an additional 0–0.4 billion gallons per year of ethanol between 2002 and 2012 and 0–2.1 billion gallons after that. Other factors—including but not limited to the ban on MTBE, the Volumetric Ethanol Excise Tax Credit, and years with high oil prices—play a major role in stimulating growth in corn ethanol. EPA’s findings are supported by other independent studies as well.^{99,100}

These studies provide evidence that the RFS may have had a small effect in inducing biofuel production beyond levels that would have been

induced by market forces such as the price competitiveness of biofuels and federal and state policies like reformulated gasoline requirements, or by the octane content of ethanol, which also affects ethanol market attractiveness. They find that the price competitiveness of ethanol with gasoline may explain much of the growth in the ethanol industry from 2002 to 2019. The ethanol tax credit and the ban on MTBE accelerated the growth of ethanol earlier than price competitiveness alone would have enabled. These studies suggest that the RFS was more important in later years and they estimate that it led to an increase in ethanol production of 1.1–3.6 billion gallons per year over and above the level that would have been induced by other market and policy factors. Sensitivity analysis suggested a production increase of up to 2 billion gallons per year.¹⁰¹

Similarly, another retrospective analysis examined the extent to which the expansion in biofuels can be attributed to the RFS.¹⁰² While the RFS provided assured demand for biofuels, other drivers of the expansion in biofuel production also contributed, particularly over the 2004–2011 period. A number of drivers aside from the RFS, such as higher crude oil prices, the ban on MTBE, and tax credit incentives, led to an expansion in the ethanol industry between 2004 and 2011. This retrospective analysis estimates that the RFS increased corn ethanol production by only 0.6 billion gallons over this period.¹⁰³ Between 2011 and 2016, crude oil prices were low and the RFS was more binding; over this period, the RFS boosted consumption of ethanol by 1.8 billion gallons.

A review of studies examining the effects of the RFS on livestock markets shows that the average increase in the prices of beef, milk, pork, and poultry per billion-gallon increase in corn ethanol were relatively

98 EPA | [Biofuels and the Environment: Third Triennial Report to Congress \(External Review Draft\)](#)

99 Farzad Taheripour et al. | [Economic impacts of the U.S. Renewable Fuel Standard: An ex-post evaluation](#)

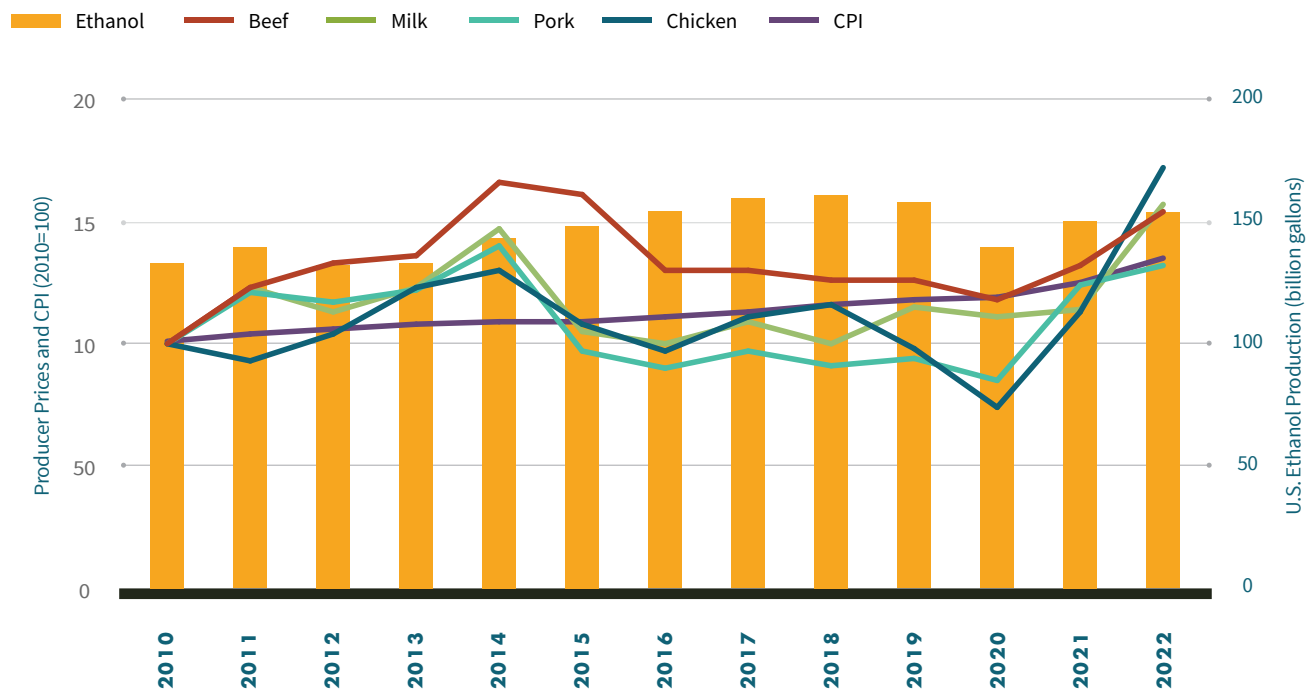
100 Emily Newes et al. | [Ethanol production in the United States: The roles of policy, price, and demand](#)

101 Emily Newes et al. | [Ethanol production in the United States: The roles of policy, price, and demand](#)

102 K.G. Austin et al. | [A review of domestic land use change attributable to U.S. biofuel policy](#)

103 Farzad Taheripour et al. | [Economic impacts of the U.S. Renewable Fuel Standard: An ex-post evaluation](#)

FIGURE 41. PRODUCER PRICES AND CPI (2010 = 100) COMPARED TO U.S. ETHANOL PRODUCTION (2010–2022)



Source: USDA WASDE; Stillwater analysis

small, around 1% or less.¹⁰⁴ The average decreases in livestock production per billion-gallon increase in corn ethanol was also very small. These studies suggest that on average about 0.7 million acres of land is needed domestically in the U.S. for each billion-gallon increase in corn ethanol production from all causes. [Figure 41](#) shows the historical trends in beef, milk, pork, and chicken producer prices, the Consumer Price Index (CPI), and annual U.S. ethanol production. As can be seen, these commodity prices show no obvious correlation with ethanol production.

8.1.3 BIODIESEL AND RENEWABLE DIESEL

While the RFS has played a relatively minor role in inducing production of corn ethanol, it has played an important role in inducing production of BD and RD after about 2010, when the BD mandate became binding. BD and RD production was not incentivized by the ban on MTBE, and oil prices were not high enough to make BD competitive with diesel. The nested design of the RFS together with the BD tax credit and the joint gasoline and diesel compliance base made it possible for BD to become the biofuel used to comply with the RFS after the 10% ethanol blend wall was reached. According to a 2023 EPA review of studies conducting prospective analysis, the RFS increased BBD consumption by 0.9–1.65 gallons for every gallon in the BBD volume obligations.¹⁰⁵ Another study estimates that the RFS induced additional BD production by 1.2 billion gallons in the 2011–2016 period.¹⁰⁶

¹⁰⁴ Jane O’Malley and Stephanie Searle | [The impact of the U.S. Renewable Fuel Standard on food and feed prices](#)

¹⁰⁵ EPA | [Biofuels and the Environment: Third Triennial Report to Congress \(External Review Draft\)](#)

¹⁰⁶ Farzad Taheripour et al. | [Economic impacts of the U.S. Renewable Fuel Standard: An ex-post evaluation](#)

A review of studies examining the effects of the RFS on livestock markets suggests that for every billion-gallon increase in BBD production, soybean prices were estimated to increase 1.8–6.5%.¹⁰⁷ The RFS was also estimated to have a limited impact on soybean meal production (decrease of 1.2% per billion gallons of BD) and to put downward pressure on soybean meal prices (decrease of 4.1% per billion gallons of BD).

Similarly, a 2022 study found that the medium- to long-run price impacts of biofuel production due to the RFS were not large.¹⁰⁸ It also showed that biofuel production increased U.S. annual farm incomes by \$8.3 billion between 2004 and 2011 and by an extra \$2.3 billion annually between 2011 and 2016. It estimated that 28% of the expansion in farm incomes over the period 2004–2011 and 100% of the additional income over the period of 2011–2016 was due to the RFS. Farm income here is defined to include value added (gains in returns to land, labor, and capital) in the crop, livestock, and forest sectors. The gain in farm income was due to the slightly higher crop prices and the accompanying increase in land rents that occurred by retaining land in high-value activities.

BD and RD are also impacted by tax incentives—the BTC through 2024 and the CFPC from 2025 through at least 2027. Without additional regulations or incentives, BD is generally less costly to produce than RD and is therefore used in most states. In a few states—California, Oregon, and Washington—separate credits from LCF programs help to offset

the cost of RD production to the point that it is advantaged over BD. The ability to blend RD at high percentages¹⁰⁹ in diesel fuel creates an additional benefit in states with LCF programs. Hence, most RD is used in these states. There are other programs that impact the national production of BD and RD. The production of RD favors the use of FOG feedstocks over soybean oil, and since much of FOG is produced overseas, this drives the importation of RD into states that provide such incentives in their regulations. Finally, there is the issue of the BTC and its forthcoming replacement, the CFPC, which provide further incentives for BD and RD production. This is a significant driver for the increased production of BD and RD and for the blending of BD and RD into the diesel pool where applicable. As demand for BD and RD increases, so does demand for all the feedstocks used to produce these fuels, including canola.

8.2 POLICY CONCLUSIONS

By creating consistent and growing demand, state LCF programs and the federal RFS and BTC can help drive increased efficiencies in the cultivation of feedstocks for renewable fuels and production of renewable fuels from those feedstocks. To successfully drive renewable fuel production and adoption, however, these programs must reduce the costs of feedstock and fuel production to the point at which the market can afford their use.

107 EPA | [Biofuels and the Environment: Third Triennial Report to Congress \(External Review Draft\)](#)

108 Taheripour et al. | [Economic impacts of the U.S. Renewable Fuel Standard: An ex-post evaluation](#)

109 Up to 100% of the fuel with no modifications required to vehicles and infrastructure.

Conclusions

A combination of policies, including the RFS, tax credits, and the MTBE ban, as well as oil prices, have contributed to the expansion in biofuel production and use in the U.S., while LCF programs have resulted in further increases in demand for biofuels and decreasing CI of transportation fuel in their jurisdictions. These policies have resulted in very large shares of corn and soybeans being used for fuel instead of food or feed. Several broad findings and conclusions can be drawn from this review.

- **Agriculture Land for Biofuels** – While demand for biofuels has increased significantly, from approximately 7 million gallons in 2010 to more than 18 million gallons in 2022, the land required to produce the necessary agriculture feedstocks has not similarly increased. While biofuel feedstock acreage jumped sharply between 2010

and 2011, since then, the acreage requirement has been relatively steady, between 40 and 47 million acres per year (average 44.3 million acres). Additionally, per-acre yields of each of the primary biofuel's feedstocks have been growing steadily over time; the cumulative effect of these trends is that the supply of these feedstocks has grown more rapidly than the acreage dedicated to these crops. It is necessary to look at long-term trends in crop acreage, as there is significant year-to-year variation due to factors such as inventory levels, weather, and anticipated domestic and international market demands. The average over these years is 319 million acres, with the pre-RFS2 years averaging 322 million acres and the post-RFS2 years averaging 318 million acres.

- **Biofuels By-products and Food Production** – The primary co-products from ethanol production include distillers grains, corn oil, and carbon dioxide (CO₂). The nonfood-grade corn oil produced at dry mill ethanol plants is primarily utilized as a feedstock for BD and RD production. Most distillers grains are consumed by cattle (74%), while the rest is fed to swine (18%) and poultry (7%). In addition to distillers grains, corn gluten feed and corn gluten meal are other



co-products sold into the meat production industry. In the absence of corn ethanol production, replacing the protein contributed by the 35.1 million metric tons of dried distillers grains with solubles (DDGS) demand in the U.S. in 2022 would require growing 15 million additional acres of soybeans and 5 million additional acres of corn (based on average U.S. soybean yields of 49.5 bushels per acre and corn yields of 173.3 bushels per acre in 2022).

- **Cost of Biofuels** – Biofuel feedstocks—commodity grains and oilseeds which are traded in global markets—are primarily produced as food and animal feed, and these food and feed markets are the drivers for pricing of these commodities. Thus, the cost of producing the feedstocks is not directly a cost of biofuels production, as the commodity price sets the cost of feedstock to the biofuels industry. Since fuel production is not the primary use for any of the biofuel feedstocks, the commodity prices are reflective of the U.S. and world markets for corn and soybeans in their primary use cases as food and feed. Comparing crop prices before and after the expansion of biofuels production and attributing the increase to biofuels is neither accurate nor valid because the change in prices could be caused by many other factors that may have also changed over that time. Meta-analysis found that the impact of biofuels was stronger in agricultural commodity markets than in markets for final consumer products and that in the long term, biofuels increased corn prices by an average of 14%, while the impact on final consumer prices in the United States was estimated to be around 1%.
- **Carbon Impact of Biofuels** – The CI of corn ethanol related to direct and indirect land use change has been declining over time, as corn yields have increased without corresponding increases in fertilizer use and as the ethanol conversion process has become more efficient.

There is significant potential to lower the biofuels emissions by adopting climate-smart practices for crop production that increase the efficiency of N fertilizer use, reduce use of fossil energy, and increase soil carbon sequestration. Studies of the RFS have found that it has delivered a net social benefit to the U.S. of \$110 billion. This assumes a U.S. social cost of carbon of \$52 per metric ton avoided and a net benefit of avoided carbon emissions of \$63.4 billion, for an estimated carbon reduction of more than 1.2 billion metric tons.

- **Biofuels and Food Production** – The impact of the production of corn ethanol on food prices and indirect land use change was more significant in the early years of the RFS than in the long run. These effects were exacerbated by other factors, including low crop stocks, high energy prices, and growing overseas demand for food. Data shows that 37.6% of the corn produced in the U.S. was used to produce ethanol, and ethanol made up 10.2% of all fuel used in gasoline vehicles in 2022. Corn acreage required to supply fuel grade ethanol production in the U.S. has increased from 15.9 million acres in 2010 to 27.8 million acres in 2022; even with this large increase in corn demand for ethanol, corn production available for all other uses declined by only 4.4% over this period.

Historical evidence suggests that technological advances in agriculture have enabled it to continue to improve productivity at a rate that has outpaced the increase in demand, and as a result, land in agricultural use has been declining. There have also been major gains in the efficiency of the livestock sector, which has been increasingly replaced by poultry. The livestock industry has therefore become more land efficient and is using fewer land resources. U.S. calorie production has grown faster than the demand for food and feed, and this has contributed to a decline in land in the agricultural sector.

APENDIX, ACRONYMS & ABBREVIATIONS

Acronyms & Abbreviations

AEO	EIA's Annual Energy Outlook	HEFA	hydroprocessed esters and fatty acids
ATJ	alcohol-to-jet	ILUC	indirect land use change
BBD	biomass-based diesel	IRA	Inflation Reduction Act of 2022
BD	biodiesel	IRS	Internal Revenue Service
bpd	barrels per day	ISU	Iowa State University
BTC	biomass-based diesel blender's tax credit	kg	kilogram
BTU	British thermal units	kWh	kilowatt hour
bu	bushel	lbs	pounds
CFPC	clean fuel production credit	LCF	low-carbon fuel
CI	carbon intensity	LCFS	California's Low Carbon Fuel Standard
CO₂	carbon dioxide	MJ	megajoule
CRP	USDA's Conservation Reserve Program	mmBTU	million British thermal units
DGE	diesel gallon equivalent	MTBE	methyl tert-butyl ether
DDGS	dried distillers grains with solubles	N	nitrogen
DGS	distillers grains and solubles	RD	renewable diesel
E10	a blend of up to 10% of ethanol with gasoline	RFS	Renewable Fuel Standard, established by the Energy Policy Act of 2005. This program was replaced with RFS2 effective in 2010.
E15	a blend of up to 15% of ethanol with gasoline	RFS2	The original RFS program was extensively amended and expanded in 2007 to establish what is often referred to as RFS2. Colloquially, the term "RFS" is used to refer to both the original and the expanded programs.
E85	a blend of up to 85% of ethanol with gasoline	RN	renewable naphtha
EIA	U.S. Energy Information Administration	SAF	sustainable aviation fuel (synonymous with RJ)
EISA	Energy Independence and Security Act of 2007	SCF	standard cubic feet
EPA	U.S. Environmental Protection Agency	UCO	used cooking oil
FFV	flex-fueled vehicle	USDA	U.S. Department of Agriculture
FOG	fats, oils, and greases	WASDE	USDA's World Agriculture Supply and Demand Estimates
FT	Fischer-Tropsch	WDGS	wet distillers grains with solubles
gal	gallon		
gCO₂e/MJ	grams of carbon dioxide equivalents per megajoule, further abbreviated g/MJ		
GHG	greenhouse gas		
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model		

APPENDIX

Programs Improving Producers' Environmental Impact

The RFS was established by the Energy Independence and Security Act (EISA) of 2007 as a volumetric mandate that sets quantity targets for different types of biofuels. Although the RFS specifies yearly volumes for different types of biofuels, it is implemented by setting blend rates for these different biofuels at the national level. The producers or importers that supply gasoline or diesel for domestic use are required to blend biofuel in the mandated proportion into a fossil fuel base that can be either gasoline or diesel.

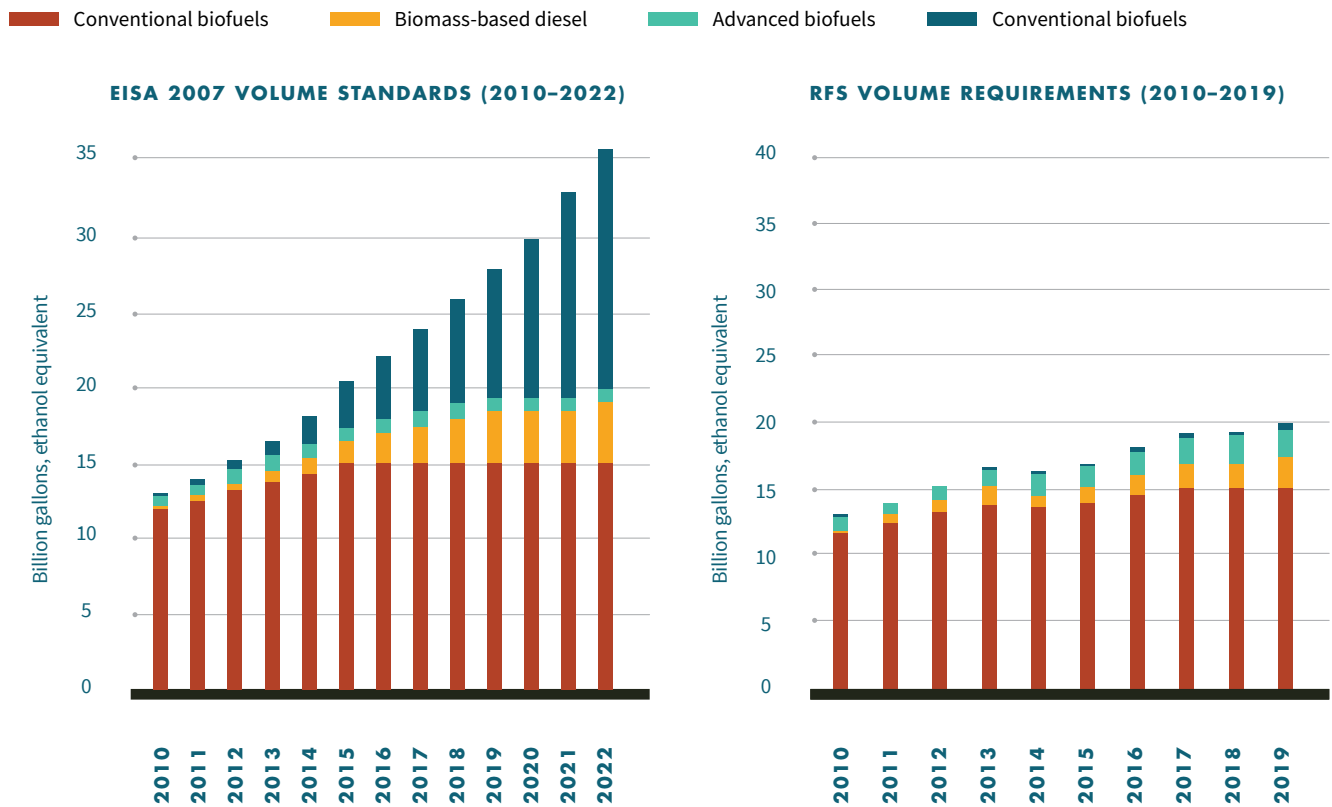
The broad categories of biofuels mandated by the RFS include conventional biofuel (corn ethanol), advanced biofuel (sugarcane ethanol, soybean BD), BBD (mostly made from soybean oil), and cellulosic biofuel (from biomass feedstocks).

The categories differ with respect to their estimated reductions in lifecycle GHG emissions relative to gasoline and diesel and are (a) cellulosic biofuel, which can be produced from wood, grasses, or the inedible parts of plants and must generate a 60% reduction in emissions to qualify under the program; (b) BBD, typically produced from oilseeds (such as soybeans or canola), tallow, or UCO and generating a minimum 50% reduction in emissions to qualify; (c) other advanced biofuels that, along with BD, must generate 50% emissions reductions; and (d) conventional biofuel, which is mostly corn ethanol and must generate at least 20% emissions reductions.

By statute, EPA uses lifecycle analysis to identify a fuel's GHG emissions relative to a baseline reflecting 2005 emissions from conventional fuels. The statute defines lifecycle GHG emissions as the aggregate quantity of GHGs (including direct emissions and indirect emissions such as those from changes in land use) related to the full fuel lifecycle, including all stages of feedstock and fuel production and distribution. The mass values for all GHGs are adjusted to account for their relative global warming potential.



FIGURE A-1. BIOFUEL FUEL VOLUMES MANDATED BY THE RFS AND ACTUALLY PRODUCED

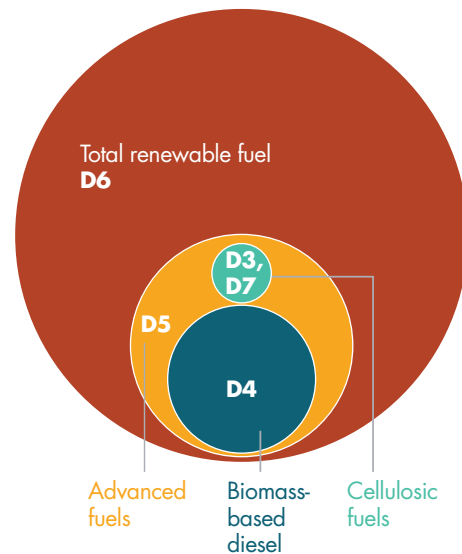


Source: EIA | EPA finalizes Renewable Fuel Standard for 2019, reflecting cellulosic biofuel shortfalls

Note: Data for biomass-based diesel are actual gallons, not ethanol equivalent.

The RFS set an overall target of 36 billion gallons for total biofuels, which includes a minimum target of 16 billion gallons for biofuel from cellulosic feedstocks, at least 1 billion gallons of BBD, and 5 billion gallons for total advanced biofuels by 2022; the rest of the mandate could be met by producing conventional biofuel from cornstarch to a maximum of 15 billion gallons, as shown in [Figure A-1](#). The RFS is designed to have a nested structure (illustrated in [Figure A-2](#)), in which cellulosic ethanol qualifies for the cellulosic, advanced, and conventional biofuel components. BBD qualifies for BBD, advanced, and conventional biofuel compliance. Advanced biofuels qualify for advanced and conventional biofuel components. Corn-based ethanol can only be applied to the conventional biofuel component.

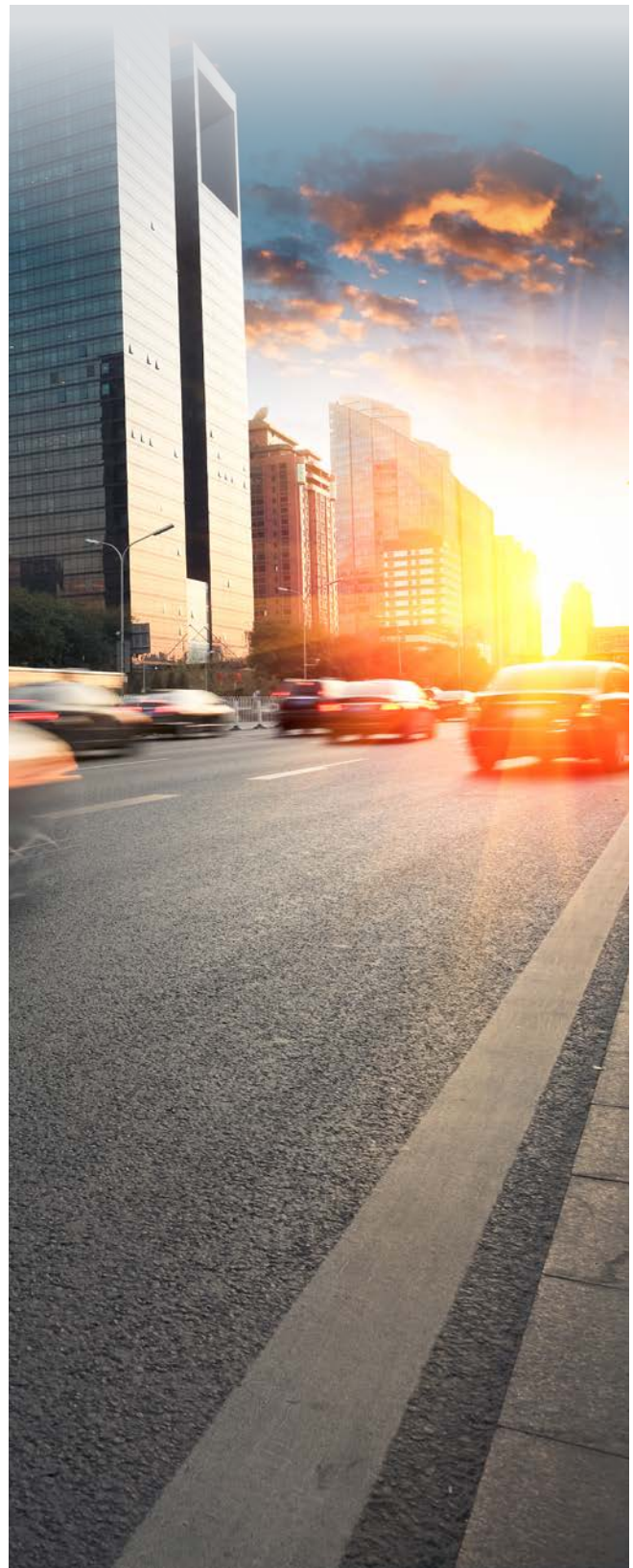
FIGURE A-2. NESTED STRUCTURE OF THE RFS



Source: BioCycle | Renewable fuel and RIN nesting in the RFS

The design of the RFS has two implications for the mix of fuels and incentives to lower their GHG intensity. First, since a biofuel is only required to achieve a GHG reduction that meets the threshold, there is no incentive for biorefineries to make continual improvements to lower the CI of the biofuel below the threshold. As noted, the CI of biofuels includes not only the lifecycle emissions, from the process of production of the feedstock all the way to its conversion to biofuel in the refinery but also the emissions related to land use change. Modeling by EPA for the Regulatory Impact Analysis in 2010¹¹⁰ assessed that corn ethanol produced in a dry mill plant with natural gas for its process energy had a median CI reduction of 21% relative to gasoline. The 95% confidence interval around that midpoint ranged from a 7% reduction to a 32% reduction due to uncertainty in the land use change assumptions.

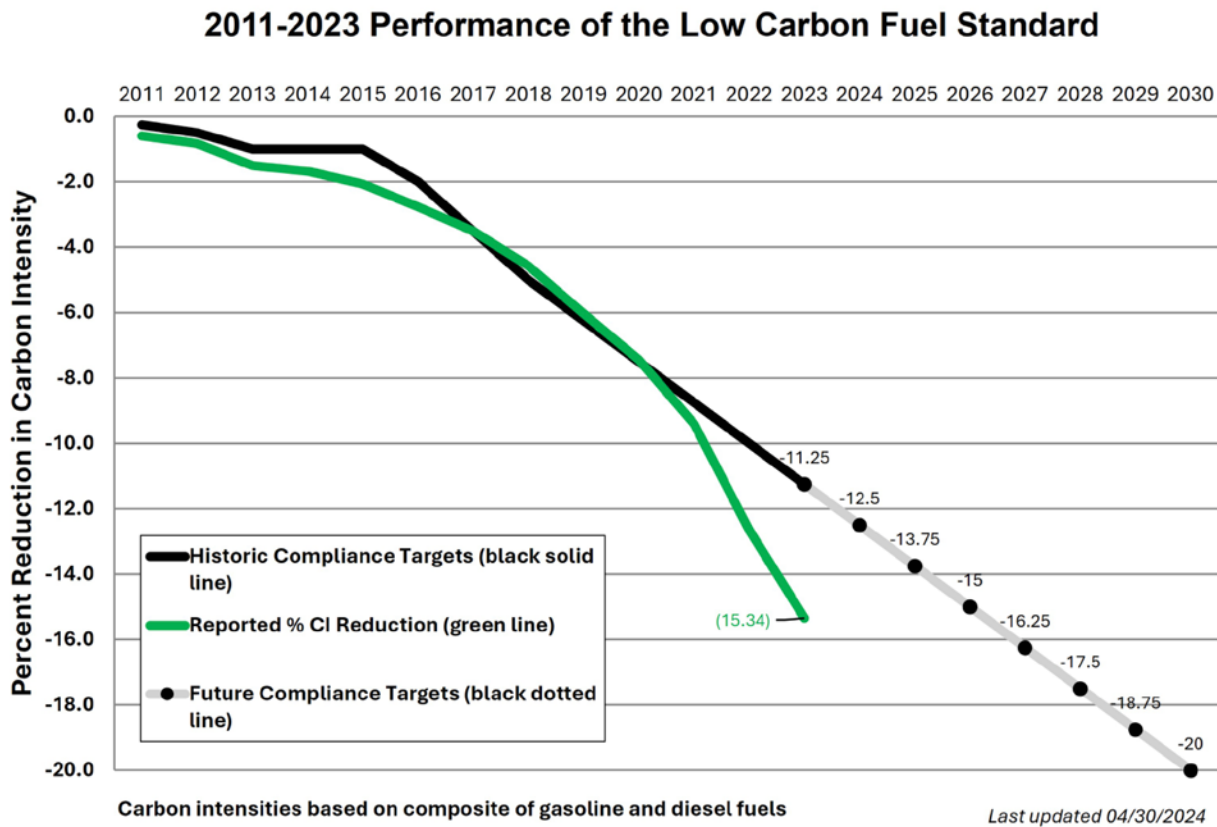
Second, the mix of biofuels incentivized by the RFS is likely to be based on cost considerations subject to the nested volumetric requirements and not their CI. The nested structure of the RFS allows for advanced biofuels (such as BD) to fill the requirements of conventional renewable fuel (or corn ethanol). In recent years, as ethanol consumption hit a blend wall at 10% blend with gasoline, blenders have chosen to increase blending of BD to comply with the RFS rather than expanding sales of E85. BD has been a lower-cost option to comply with the RFS due to the \$1 per gallon tax credit provided, while expanding sales of E85 would have required lowering its price to energy parity with E10.¹¹¹ As a result, BD production and blending has grown rapidly in recent years, while corn ethanol production has stagnated and been lower than the upper bound of 15 billion gallons. To date, there has been negligible production of cellulosic biofuels.



110 EPA | Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis (2010)

111 Jia Zhong and Madhu Khanna | Assessing the efficiency implications of renewable fuel policy design in the United States

FIGURE A-3. PERFORMANCE OF THE LCFS IN CALIFORNIA



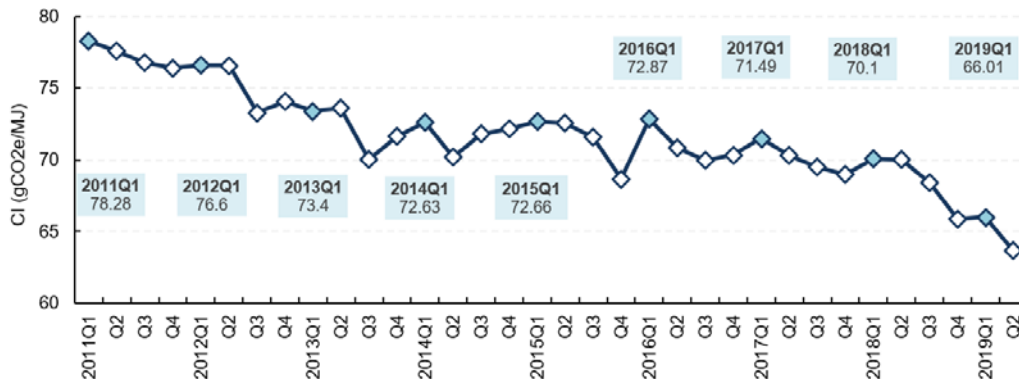
Source: California Air Resources Board | LCFS Data Dashboard

Unlike the RFS, which sets a volumetric standard, LCF programs set a standard for the reduction in the CI of transportation fuels in a given jurisdiction. The California LCFS required a 10% reduction in the CI of California’s transportation fuels by 2020 and a 20% in CI by 2030. Unlike with the RFS, the mix of fuels under an LCF program is determined by each one’s relative cost and CI; they are not subject to volume requirements. Under California’s LCFS, the ILUC values for corn ethanol pathways prior to 2016 were assessed at 30 g/MJ; this value was lowered to 19.8 g/MJ after 2016. The policy incentivizes the blending of fuels by implicitly subsidizing fuels with CIs below the standard and penalizing fuels with CIs above the standard. It also creates incentives for incrementally lowering the CI of biofuels to make them more competitive for blenders and profitable for producers. The California LCFS has been meeting its annual target and significantly exceeded its target for 2022, as shown in [Figure A-3](#).¹¹²

112 Abby Brown et al. | E85 Fueling Infrastructure Trends: A Decade in Review

The LCFS has also been effective in incentivizing the production of corn ethanol with an increasingly lower CI, as shown in [Figure A-4](#). The CI of corn ethanol has declined from 78 gCO₂e/MJ in 2011 to 66 gCO₂e/MJ in 2021. Additionally, [Figure A-5](#) shows that the number of corn ethanol pathways with low CI scores sold in California is larger than in any other state, indicating that the LCFS has been instrumental in incentivizing improvements in the CI of corn ethanol compared to the RFS.

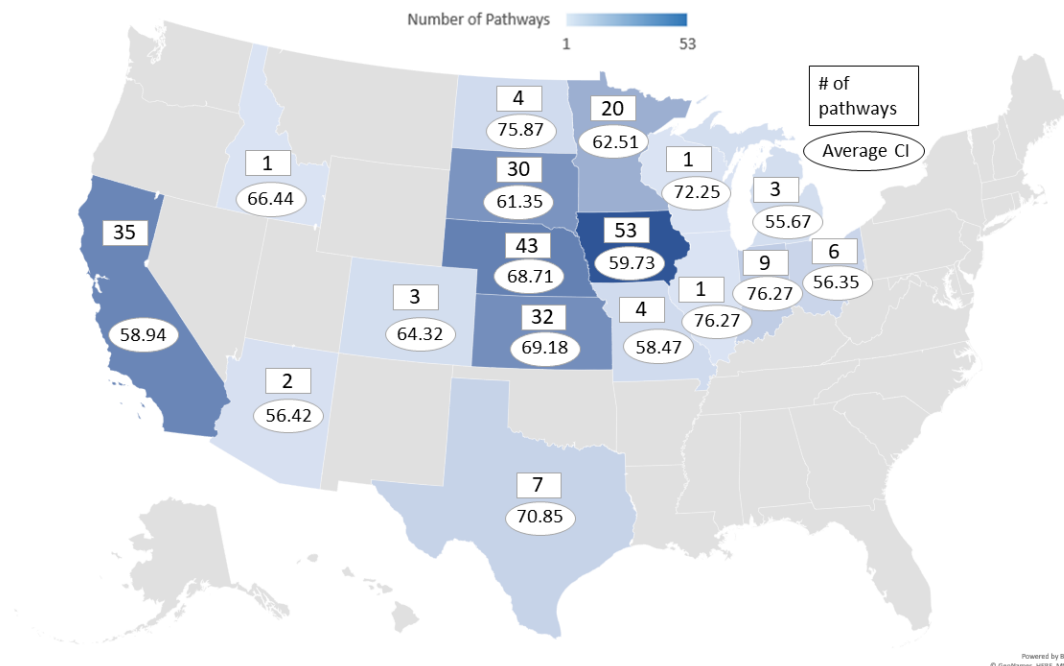
FIGURE A-4. AVERAGE CI OF CORN ETHANOL SOLD FOR COMPLIANCE WITH THE CALIFORNIA LCFS (2011-2019)



Note: CI score is inclusive of all CI pathways, non-U.S. and U.S. pathways

Source: USDA | The California Low Carbon Fuel Standard: Incentivizing greenhouse gas mitigation in the ethanol industry

FIGURE A-5. ETHANOL PATHWAY BY STATE AND CI SCORE

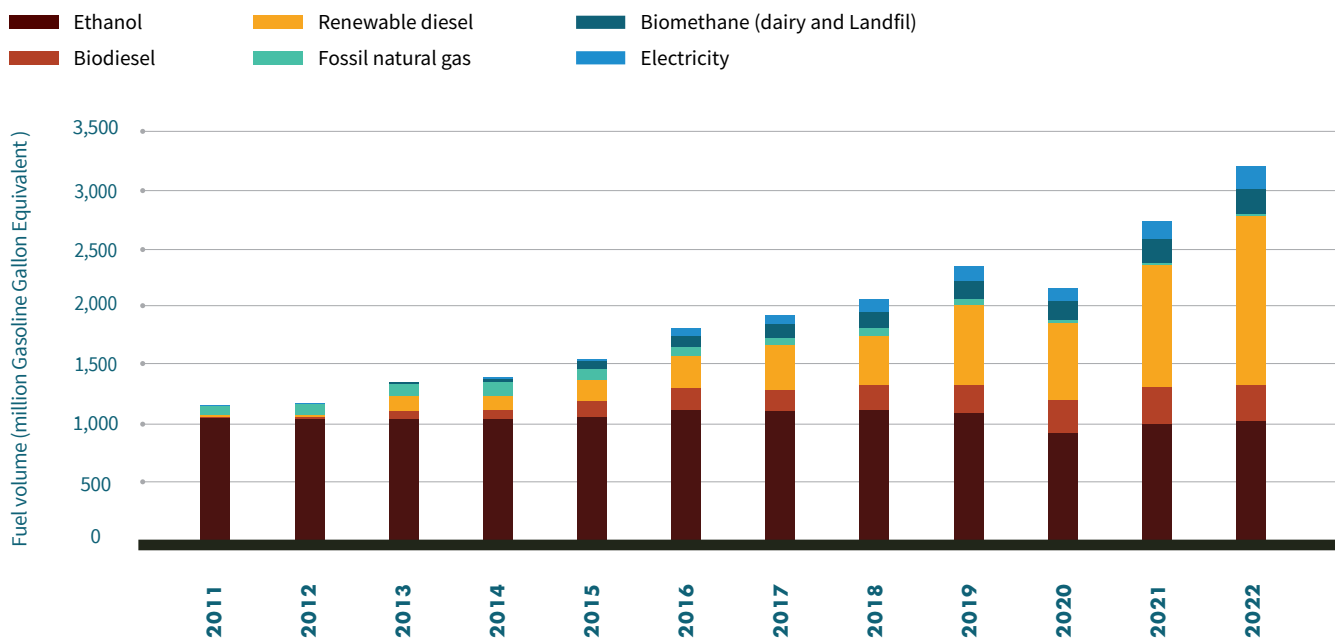


Source: USDA | The California Low Carbon Fuel Standard: Incentivizing greenhouse gas mitigation in the ethanol industry



While the reliance on corn ethanol to comply with the LCFS has been declining, the use of BD and RD has been growing, as shown in [Figure A-6](#). About two-thirds of the renewable fuels consumed in California are BBD (BD and RD), and almost all the RD being produced in the U.S. is being sold in California to comply with the LCFS.¹¹³

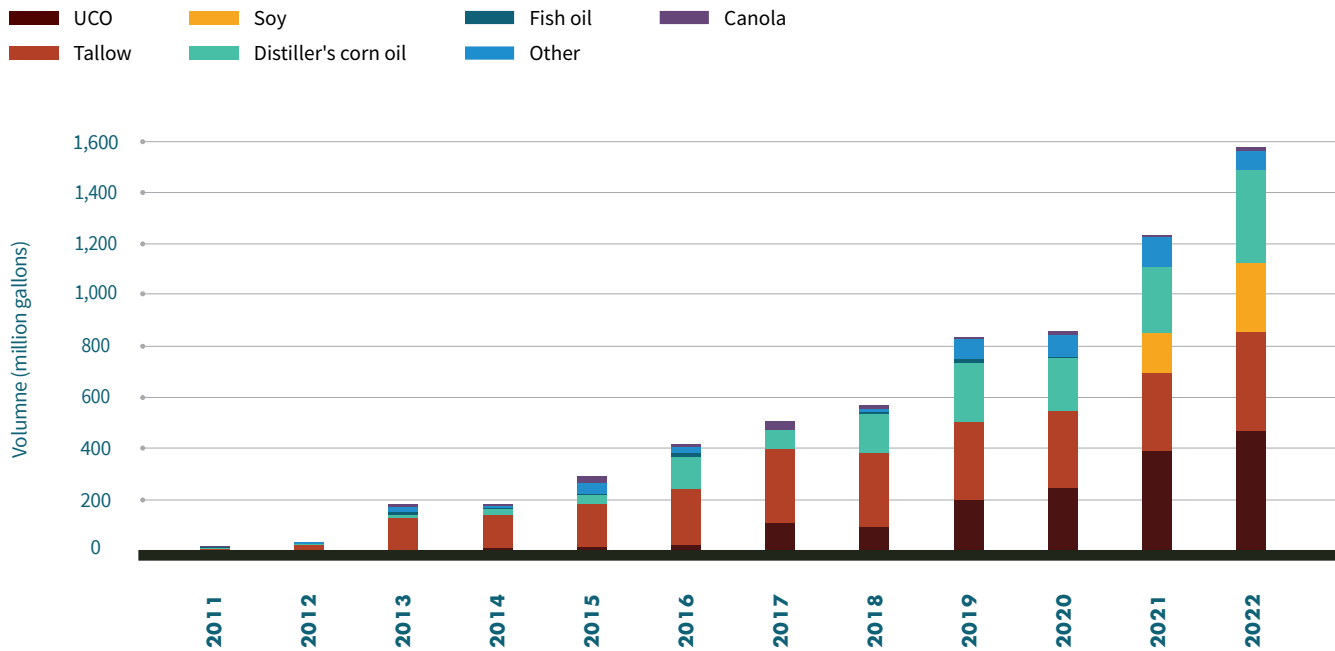
FIGURE A-6. ALTERNATIVE FUELS SOLD IN CALIFORNIA (2011-2021)



Source: California Air Resources Board | Low Carbon Fuel Standard 2023 Amendments: Standardized Regulatory Impact Assessment

113 Renewable Fuels Association | Corn Ethanol’s Energy Balance Continues to Improve

FIGURE A-7. MIX OF FEEDSTOCKS FOR BD PRODUCTION FOR CALIFORNIA (2011–2022)



Source: California Air Resources Board | LCFS Data Dashboard

In the early years after the LCFS was established, the feedstocks of BD and RD were largely wastes and other non-crop-based sources, including UCO, tallow, corn oil extracted from DGS, and oils from fish processing. By 2022, as shown in [Figure A-7](#), the share of soybeans in the BD feedstock mix had grown to about 250 million gallons.

Thus, both the RFS and the LCFS have induced a switch toward BBD but for very different reasons. The RFS has led to BBD uptake because its nested structure has incentivized an advanced biofuel (BD) that offered a lower-cost way (due to the BTC) to meet the volumetric obligation instead of selling higher blends of ethanol (E85) that had higher distribution costs.

he nested structure of the RFS led to a lack of incentives to build demand for higher blends of ethanol by pricing E85 at an energy equivalent level with E10, and it led blenders to blend biodiesel that did not face blending constraints and was a cheaper alternative (due to the BD tax credit) for complying with the RFS. The RFS has imposed an implicit cap of 15 billion gallons of corn ethanol by defining its CI as 20% lower than that of conventional gasoline, even though there is recent research showing that the direct lifecycle CI of corn ethanol has been declining substantially in recent years.¹¹⁴ The categorization of biofuels into conventional, advanced, and cellulosic is based on the characteristics of the feedstock (e.g., from starch or from biomass) and a minimum CI saving requirement. There is no mechanism, for example, to change the classification of corn ethanol to advanced even if its CI were to decrease to 50% lower than that of gasoline.

114 Uisung Lee et al. | Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: Implications for greenhouse gas emission reductions

The LCFS has incentivized BD because of its lower CI relative to corn ethanol and its cost effectiveness (again, due to the BTC) in meeting the standard. Neither the RFS nor the LCFS has been able to incentivize increased demand for ethanol beyond E10. Both policies can be expected to continue to create demand for RD because its consumption is not subject to any blending limits.

Although the LCFS has induced improvements in the production processes of biofuels to lower their CI, it has not yet incentivized improvements in feedstock production pertaining to site-specific farm practices. As discussed in Section 6, practices like planting cover crops in the winter months between the corn and soybean growing seasons has significant

potential to sequester carbon in the soil. Similarly, no-till farming sequesters more carbon compared to conventional tillage practices. However, changes in soil carbon are not included in the CI score of fuels when determining their compliance with LCF programs, and thus there is no mechanism to differentiate payments for feedstocks based on their production practices. Similarly, in Section 6 the RFS has also not created incentives for farmers to lower the CI of corn and soybeans by implementing climate-smart practices due to its threshold-based approach to ensure compliance with the GHG-reduction requirements for the different fuels.



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