Fueling a Clean Transportation Future

Chapter 3: Biofuels

Union of Concerned Scientists

Biofuels are an important and rapidly changing part of the nation's fuel supply, the fastest-growing alternative fuel since 2000, and already a key component of our fuel system. While the use of biofuels is likely to continue to grow over time, they are not likely to supply a majority of the overall transportation energy demand in the United States because of intrinsic limitations of land availability and competing uses for crops. Understanding the benefits, risks, and potential improvements for biofuels is critical to mapping a path forward to a future of cleaner transportation fuels and progressively lower global warming emissions.

Ethanol is the most widely used biofuel, while other biofuels such as biodiesel and biomethane are also increasingly important, as are so-called drop-in biofuels. The latter are chemically identical to their fossil fuel analogs and can be blended with gasoline, diesel, or jet fuel at any level and used in the existing fleet of vehicles without modification. For simplicity, this report focuses primarily on different types of ethanol. Many of the issues discussed here apply to other biofuels as well.

In this chapter, we examine the evolving role of ethanol in our gasoline fuel mix and the impact of food-based fuels on agriculture, food production, and land use. We examine more sustainable non-food sources of biofuel as well as opportunities to clean up the biofuels production processes, and we forecast the potential for reducing global warming emissions from biofuels by 2050.

Ethanol Use in Gasoline Blends

Ethanol is often considered as a substitute for gasoline, but its primary role to date has been as a gasoline additive, improving the properties of the gasoline into which it is blended. Ethanol adds oxygen to a gasoline blend, which can reduce air pollution. It also has a higher octane rating than gasoline, which improves the combustion properties of the blended fuel. However, ethanol has lower energy content per gallon than gasoline, making it less valuable when used primarily for energy (for example, as the major component of a vehicle fuel). This has implications for the economic competitiveness of different ethanol blends on the market today and for future blends as well.

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Ethanol made from corn is the most widely used biofuel. While ethanol is a cleaner fuel than oil, increasing corn production affects food prices and increases erosion, water pollution, and habitat loss. For these reasons, additional biofuel sources should be considered.

The primary use of ethanol in the United States today is as a high-octane blending component of gasoline. This 10 percent ethanol blend, called E10, now comprises most of the gasoline sold in the United States.

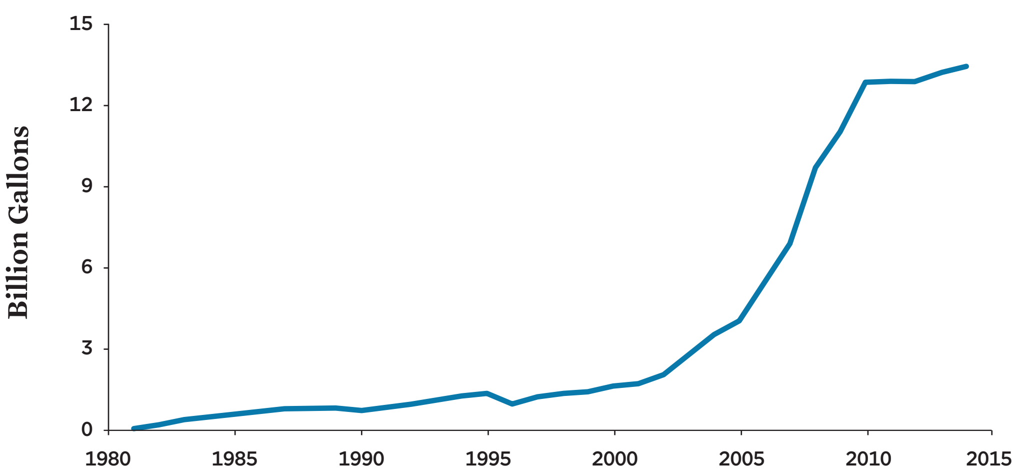
Higher-octane fuels allow engines to function at higher compression ratios without engine knock, which improves their efficiency (Leone et al. 2015). The octane level of gasoline has been increased in several ways over the years, but all of the approaches have serious trade-offs—lead is a neurotoxin and was phased out of gasoline in the 1970s, and methyl tertiary butyl ether (MTBE) was used for both oxygen content and octane, but was phased out due to a concern about groundwater contamination in the 1990s (EPA 1999). Ethanol gained a foothold as a source of oxygen in the post-MTBE era and has grown to become an important octane booster today (EPA 2014b; Kitman 2010; Kovarik 1998). Oil refiners can also generate high-octane blending components internally by additional refinery processes, but these have added costs and other trade-offs.

A variety of policy supports favored ethanol, including tax credits, air-quality rules, and the federal Renewable Fuel Standard that required the steadily increasing use of biofuels. The widespread adoption of E10 occurred relatively quickly, starting in 2002 and accelerating in 2005. By 2010, almost all of the gasoline sold in the United States was a 10 percent blend of ethanol. The E10 transition was facilitated by changes in the relative prices of ethanol, gasoline, and alternative potential high-octane blending components and by public policies (Babcock and Fabiosa 2011). Many of the policies that initially supported the scale-up of corn ethanol—including tax credits for blending ethanol and a tariff on imported ethanol—have ended. The most significant federal biofuels policy, the Renewable Fuels Standard, remains in effect, although its implementation has been mired in controversy and uncertainty. But even in the absence of continued policy support, economic analyses suggest that ethanol will continue to compete effectively against alternative high-octane gasoline blending components, making it likely that ethanol will continue to be blended into gasoline at 10 percent regardless of changes in policy (Irwin and Good 2015; Babcock and Fabiosa 2011).

With ethanol's role in E10 now effectively a settled matter, the key questions are if, when, and how higher blends of ethanol will increase ethanol use beyond E10. There are at least three scenarios for increasing ethanol blending, as well as an increasingly important role in the U.S. transportation fuel mix for other types of biofuels. The benefits of expanding the use of ethanol depend on how the ethanol is made (discussed in the next section) and how the ethanol is used.

In addition to E10, ethanol is currently sold as a higher blend called E85 (which has an ethanol content between 51 and 85 percent) that is used in specially designed flex-fuel vehicles that accept any ethanol blends, from straight gasoline up to E85. Used to power a flex-fuel vehicle, ethanol is

FIGURE 12. U.S. Ethanol Use



As refiners and fuel distributors switched from using ethanol as an oxygenate in certain markets to using it as a source of octane in E10 nationwide, the quantity of ethanol use increased rapidly. It plateaued in 2010 once most of the gasoline in the U.S. was already being blended with 10 percent ethanol.

SOURCE: EIA 2015B.

primarily a source of energy, rather than a high-octane blending component. Flex-fuel vehicles running on higher ethanol blends get approximately 25 percent fewer miles to the gallon because of the lower energy content of ethanol; therefore, E85 must be sold at a commensurate discount to induce consumers to choose it (Babcock and Pouliot 2013). E15 (a 15-percent blend of ethanol and gasoline) is also sold on a very limited basis, but can in principle be used in many of the cars on the road today. In the future, mid-level blends (between 20 and 40 percent ethanol) may be used in vehicles optimized to take advantage of the high octane and other properties of these blends. Ethanol used in an optimized vehicle would not have the same reduction in fuel economy as a flex-fuel vehicle operating on E85, which makes it more cost-effective to use ethanol in mid-level blends than as E85 (Leone et al. 2015).

However, at the present time, the infrastructure to distribute blends other than E10 is limited. E85 is available at less than 3 percent of gas stations, most of them concentrated in the Midwest, and E15 and other blends are available at far fewer stations (AFDC 2015; NACS 2015). This presents economic and logistical obstacles to the use of higher ethanol blends. Overcoming these obstacles is technically feasible: Brazil has successfully implemented the distribution of ethanol at several blending levels, demonstrating its feasibility and providing useful lessons. But the necessary changes to cars, fuel retail stations, and fuel regulations will require coordination among automakers, fuel producers, refiners, distributors, and retailers, as well as state and federal regulators. Numerous other parties will also be affected directly or indirectly by associated changes in fuel or agricultural markets, adding political complexity to what is already likely to be a technically challenging process.

Ethanol Production and Related Emissions

Biofuels are distinct from oil and electricity as transportation fuels in that they are not just an increasingly important part of the energy and transportation systems, but are also an important part of the U.S. and global agricultural (and therefore food) system. Moreover, as the scale of demand for biofuels increased, so too has the intensity of agricultural production and the footprint of agriculture, both of which have important implications for climate change and other environmental problems. Below, we consider the problems that the rising production of corn ethanol causes in the U.S. agricultural system. We also consider how the expanded production of biofuels in the United States indirectly affects the global footprint of agriculture and what that means for deforestation and climate change. Lastly, we discuss how these and other factors influence the full lifecycle emissions associated with ethanol production and how better sources of biofuels and cleaner production methods can significantly reduce these lifecycle emissions by 2050.

TIMELINE 2. Changes in the Biofuel Industry

1920–1940

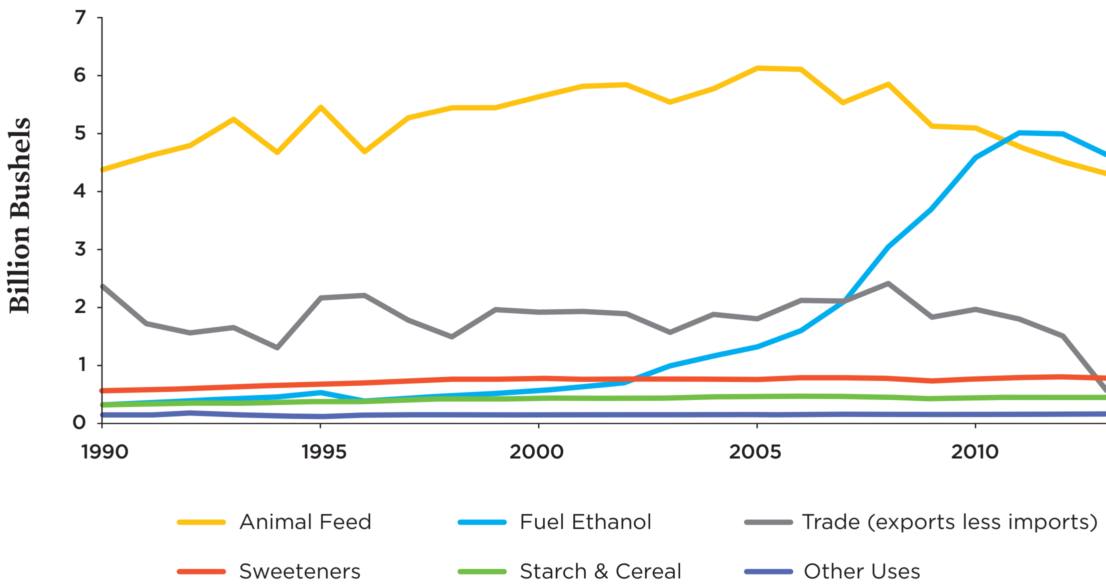
Ethanol is recognized as a potentially attractive fuel for automobiles by automotive pioneers including Henry Ford and Charles Kettering.

1920 1940 1970 1975 1980 1985

1970s

Concern about oil price spikes and shortages lead to renewed policy support for biofuel production, including tax credits supporting blending corn ethanol into gasoline.

FIGURE 13. Uses of U.S. Corn



The use of corn for producing fuel ethanol has increased significantly since 2000, and now competes with animal feed as the number one use of corn in the United States.

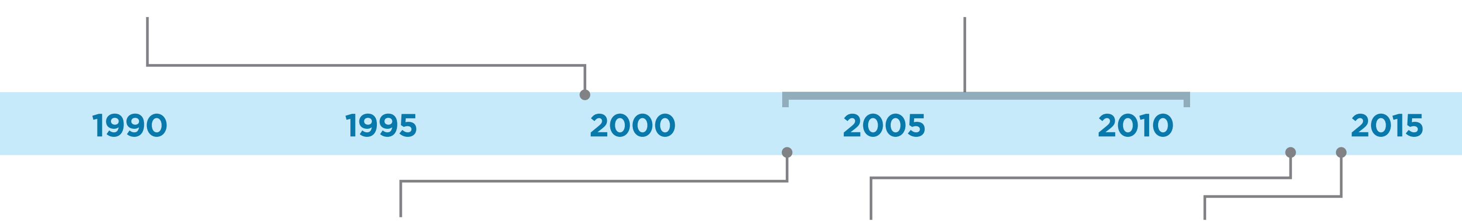
SOURCE: ECONOMIC RESEARCH SERVICE 2015.

1999

A blue ribbon panel convened by the Environmental Protection Agency (EPA) recommends reducing the use of MTBE as an oxygenate in reformulated gasoline because of water pollution concerns, leading to a series of state and federal policy changes that encouraged ethanol use as a replacement.

2003–2010

Between 2003 and 2010, the scale of the corn ethanol industry grows rapidly to 13 billion gallons per year. This rapid growth of an industry dependent on a crop also used for food and animal feed raises concerns about food price spikes, environmental problems associated with corn farming, and agricultural expansion in the tropics leading to deforestation.



2003

The U.S. ethanol industry produces fewer than 3 billion gallons of corn ethanol using 10 percent of the U.S. corn crop, primarily for use in reformulated gasoline. Lifecycle carbon emissions from ethanol produced at facilities powered by coal were higher on an energy-equivalent basis than those for gasoline.

2013

Ethanol production is becoming more efficient, and the share of facilities using coal as a power source is falling, leading to lifecycle emissions per gallon of about 20 percent lower than that of gasoline.

2014

The first commercial-scale cellulosic ethanol plants open in the Midwest, producing biofuel from agricultural residues like corn stalks and cobs. This cellulosic ethanol has the potential to avoid competition with other uses of corn and cut emissions, compared to corn ethanol, by more than half.

EXPANDED USE OF CORN FOR FUEL CAUSES SERIOUS PROBLEMS

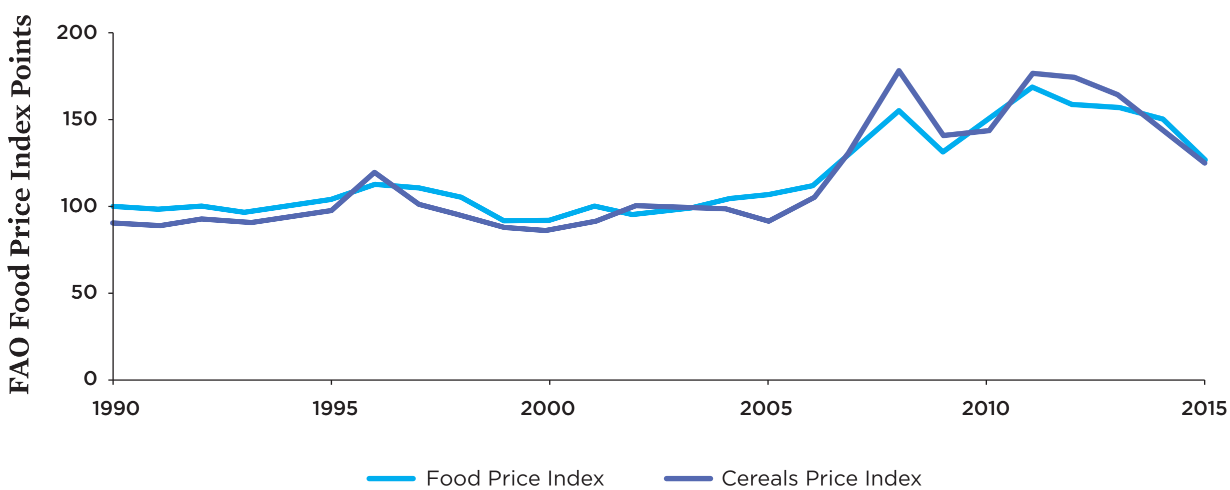
Ethanol can be created from a wide variety of sources including sugar, starch, biomass, and even natural gas, but the vast majority of the ethanol produced in the United States today is made from corn starch. As corn ethanol use has scaled up in the last decade, so has the demand for corn. Ethanol grew from being a minor use of corn (in 2000 more corn was used to make sweeteners than ethanol) to becoming one of the largest domestic uses of corn. Animal feed is still the largest use of corn on a net basis, since most corn exports are used for animal feed and about 30 percent of the corn grain used for ethanol production is returned to animal feed markets after the starch has been utilized. On a net basis, ethanol accounts for about one-quarter of U.S. corn consumption and has accounted for virtually all growth of corn consumption in the United States since 2000.

The very rapid increase in the utilization of corn for fuel put pressure on markets for corn, particularly because the increase in ethanol use happened rapidly, occurred while global demand for corn and other grain was rising, and coincided with major droughts in important grain-producing regions like Australia in 2008, Russia in 2010, and the U.S. Midwest in 2012. While the expansion of biofuel use was certainly not the only factor affecting food prices, it was one of several important factors leading to significant price increases for corn and other cereal grains (Babcock and Fabiosa 2011). Higher and less stable commodity grain prices had a relatively minor impact on U.S. consumers—mostly reflected in slightly higher prices for meat, eggs, and dairy—but basic commodity prices account for a small share of total U.S. food budgets. The impact was greater for people living in extreme poverty globally, for whom basic cereal crops make up a larger part of the diet and food constitutes a much larger share of families' incomes.

Ethanol use in fuel stabilized after 2010. Crop prices started to come down as farmers in the United States and around the world increased corn production to satisfy the additional demand and rebuilt stocks depleted by the simultaneous droughts and ethanol expansion. Recent assessments of the impact of biofuels on food markets have been more nuanced than reports published at the height of the food crisis and have suggested that biofuel expansion can either increase poverty or play a productive role in the food system if biofuels are produced at appropriate scale and supported by more flexible policies that stabilize crop prices and put food needs first (Chakravorty, Hubert, and Ural Marchand 2015; Graziano Da Silva 2015; Ivanic and Martin 2014).

But while corn production can rise to simultaneously address demand for food and fuel, this rising production has costs—both direct environmental impacts of more intense corn

FIGURE 14. Ethanol Use Can Affect Food Prices



Rapid increase in the use of corn for ethanol between 2005 and 2010 together with other factors contributed to a major global spike in food prices. The price shock affected those in poverty most severely, because they rely on cereal grains for a larger share of their diet. The Food and Agriculture Organization (FAO) Food Price Index is a measure of the monthly change in international prices of a basket of food commodities. It consists of the average of five commodity group price indices, weighted with the average export shares of each of the groups for 2000–2004. Prices are in real terms normalized to 100 for 2002–2004.

SOURCE: FAO 2015.

BOX 8.

More Intense Corn Production Is Hard on Land, Water, and Wildlife in the United States

While total cropland acreage in the United States has fallen slightly since the late 1970s, demand for ethanol has increased acreage used for corn at the expense of other crops (Economic Research Service 2015; Nickerson et al. 2011). Corn is especially hard on the environment, intensifying erosion, water pollution, and habitat loss more significantly than other crops. The rising demand for corn ethanol exacerbates these problems.

- **Erosion.** Corn farming leaves land vulnerable to erosion from heavy rains. Increased demand for corn versus other crops has increased the share of land planted to corn and exacerbated existing problems (Cox, Hug, and Bruzelius 2011).
- **Water pollution.** Corn farming as it is typically practiced in the U.S. Midwest includes the intensive application of nitrogen and phosphorous fertilizer. This fertilizer causes serious pollution problems for ground and surface water in the Midwest, and the pollution flows down the Mississippi River to the Gulf of Mexico, where it causes a "dead zone." Corn farming is the largest source of this pollution, and the extra acreage of corn devoted to ethanol production set back efforts to reduce this pollution (UCS 2011b).
- **Habitat loss.** Growing demand for corn has expanded the Corn Belt into states such as North and South Dakota, where it has resulted in the conversion of some of the last remaining grasslands—an important habitat for birds and other wildlife—into cropland (Lark, Salmon, and Gibbs 2015).

production in the United States (see Box 9, p. 9) and indirect impacts as crop production around the world increases to replace the crops made into fuel in the United States, in part at the expense of tropical forests that store a great deal of carbon.

EXPANDING THE SCALE OF GLOBAL AGRICULTURE HAS CONSEQUENCES FOR FORESTS AND CARBON IN THE TROPICS

The United States is one of the world's largest agricultural exporters, and changes in crop prices and consumption in the United States are felt around the world. Therefore, as the United States has devoted a greater share of its agricultural output to fuel production, other agricultural producers around the world, in particular, those in Brazil, Indonesia, and other tropical countries, have increased production of the crops that might otherwise have been imported from the United States. This international expansion of agriculture has come through a combination of farming existing land more intensively and expanding the area used for crop production, often at the expense of forests, the primary source of new agricultural land in recent decades (Babcock and Iqbal 2014; Gibbs et al. 2010). Deforestation releases huge amounts of carbon stored in trees and soils, causing environmental damage and undermining the carbon benefits of using biofuels in place of fossil fuels.

The international expansion of agriculture has come through a combination of farming existing land more intensively and expanding the area used for crop production, often at the expense of forests.

But deforestation is not an inevitable consequence of rising crop production. While some countries, such as Indonesia, still have massive emissions from the expansion of palm oil plantations at the expense of forests and carbon-rich peat soils, other tropical countries such as Brazil have significantly reduced deforestation even as production of soybeans and beef, for example, have risen rapidly (Boucher et al. 2014). This complex link between increased agricultural production and deforestation has important implications for the lifecycle analysis of biofuels, discussed in Box 9.

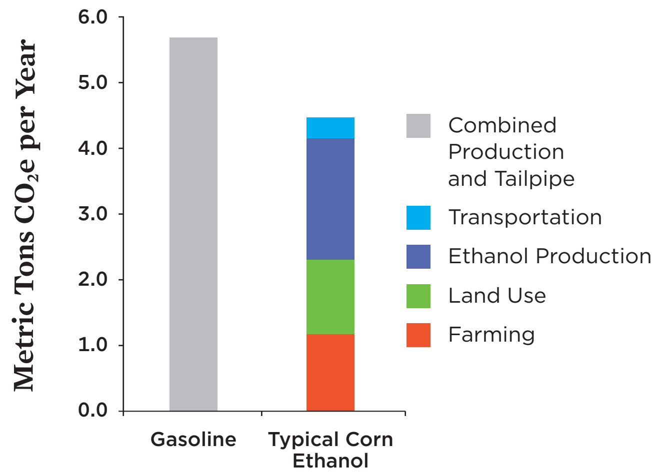
ETHANOL PRODUCTION HAS DIFFERENT EMISSIONS DEPENDING ON CROP CHOICE AND PRODUCTION METHODS

Global warming emissions associated with ethanol production fall into three major categories: 1) those resulting from crop production, including fertilizer production and use; 2) emissions from land use change, an indirect consequence of expanding the footprint of agriculture to accommodate fuel production while continuing to produce food; and 3) the production of ethanol itself, especially emissions from fossil fuels used for power and heat.

Lifecycle analysis is used to calculate these emissions, but it is worth noting that precise lifecycle analysis results depend to some degree on how the analysis is conducted. For example, a lifecycle analysis based on a particular ethanol facility or set of facilities operating today will be conducted differently and produce different results than the lifecycle analysis of a projected industry operating at some future date. Methodological differences and uncertainties are even more significant when the indirect land use emissions are considered (see Box 9). As a consequence, a more meaningful comparison of results is possible within a single lifecycle analysis approach than is possible between different studies. In this report we have drawn most of our comparisons from lifecycle analysis conducted by the California Air Resource Board. This analysis is attractive because of the breadth of fuels compared using a consistent analytical framework and because of the extensive public process of stakeholder engagement and expert consultation (CARB 2015a; CARB 2015c; and associated rulemaking documents). The results are used below, converted into tons of CO2e emissions associated with driving a 25 mpg car 12,000 miles in a year. As discussed above, ethanol is typically blended with gasoline rather than used by itself, so the conversion is based on the amount of energy in the fuel, although typically this energy is provided by a mixture of gasoline and ethanol. This approach captures ethanol's contribution to the overall fuel blend on an energy-equivalent basis.

- **Emissions from farming.** Growing corn typically involves significant use of chemical fertilizers, which create emissions during their production and use. Other emissions come from fuel to drive tractors and other farm equipment. Together, these add up to about 1.18 tons CO_2e per year for a 25 mpg car—or, as often expressed in the literature, 20 grams (g) CO_2e per megajoule (MJ).
- **Emissions from land use change.** Expanding the use of corn to make ethanol increases the demands on the global agricultural system as a whole. Some of that demand is met by the expansion of cropland onto acres previously occupied by forests or used for other purposes, which can release carbon that has been stored in plants and soils into the atmosphere. Estimating these indirect land use change (ILUC) emissions is complex and subject to considerable uncertainty (see Box 9), but CARB calculates emissions for corn ethanol from ILUC at about 1.14 tons (20 g/MJ).
- **Emissions from ethanol production.** Energy is needed to convert corn into ethanol; in particular, a great deal of heat is needed to distill the ethanol from something like beer, the initial product of fermentation, into the pure ethanol (200 proof) that is blended into gasoline. A typical ethanol facility today uses natural gas as a source of heat and has production emissions of 1.85 tons (32 g/MJ), but these emissions vary a great deal from one facility to another depending on the energy source and efficiency of the operation. Some older facilities use coal for heat, which can increase production emissions by as much as one ton, while other facilities use more efficient processes or lower-carbon sources of fuel, such as biomethane, which can reduce emissions by a similar amount.

FIGURE 15. Ethanol Is Cleaner than Gasoline



Major components of the lifecycle emissions for ethanol include farming, land use change, and ethanol production.

Note: TThe global warming emissions of gasoline represents the metric tons of CO_2e associated with the production and consumption of fuel required to power a typical car (getting 25 mpg) for a year (driving 12,000 miles). This is compared with the energy equivalent amount of ethanol.

SOURCE: CARB 2015A.

The Future of Biofuels

Biofuels in general, and corn ethanol in particular, have been put forward for decades as a solution to oil shortages and more recently offered as a way to reduce carbon pollution from cars. Corn ethanol also promised to create stronger demand and raise prices for corn at a time when corn prices were very low. Since 2000, the United States has made remarkable progress on many of these goals, so much so that new challenges have emerged on several fronts, including the need to:

- balance the demand for biofuels with the competing uses of crops and land, including food production and forest protection;

BOX 9.

Emissions from Indirect Land Use Change

Expanding the scale of agricultural production to produce both food and increasing amounts of fuel has important implications for the size and intensity of the global agricultural system. When cropland expands at the expense of other non-crop land uses like pastures, grasslands, and forests, carbon sequestered in trees and soils is released into the atmosphere. These land use changes are not generally the result of directly converting forests to the crops used to make biofuels, but are linked to expanded biofuels production indirectly through global markets for agricultural commodities. This phenomenon has come to be called indirect land use change (ILUC), and it is both technically challenging and hotly contested by advocates for or against biofuels. Initial estimates of ILUC by Searchinger et al. were so high that those authors concluded that using crops for fuel was, under almost any circumstance, far more polluting than gasoline (2008).

However, the link between shifting Midwestern corn from feed to fuel markets and deforestation across the globe is complex and depends on many factors. Since Searchinger's initial 2008 paper, academic researchers and environmental regulators around the world have been using a variety of global agricultural economic models to quantify these connections and estimate ILUC emissions. Estimates from more recent analyses have been lower than those in the initial Searchinger et. al study, but remain subject to a high degree of uncertainty. By its nature, ILUC analysis is technically challenging and produces results that depend on detailed data for land use in the major agricultural areas around the world, soil carbon stocks in forests and other ecosystems, and specific economic parameters (called elasticities). Results also depend upon model structure and even value judgements such as how the analysis treats reduced food consumption associated with crop price increases (Plevin et al. 2015).

Taken as a whole, the literature provides strong evidence that land use change is a significant component of the emissions of crop-based biofuels, although not so high as to make all crop-based biofuels necessarily worse than fossil fuels, as suggested by the initial Searchinger et al. study. Using land to grow fuel is neither always a climate disaster nor always a climate solution, but has practical limits and environmental consequences that must be carefully balanced against other considerations (Martin 2015).

- avoid environmental problems caused by more intensive farming of existing agricultural land; and
- address distribution and marketing obstacles to the expanded use of advanced biofuels at levels higher than our current vehicles and infrastructure were designed to easily accommodate.

While most biofuels in use today are made from corn starch, sugar, and vegetable oil, biofuels can be made from non-food sources including various types of wastes and more environmentally friendly crops.

FUELS MADE FROM WASTES, RESIDUES, AND AGRICULTURAL BYPRODUCTS

Making biofuels from wastes, agricultural residues, and agricultural byproducts avoids the need to expand crop production and the associated emissions and also reduces land use change. Thus, these biofuels can have low total lifecycle global warming emissions. Wastes come from many different sources including food production, town and city residents (municipal solid waste and wastewater), industry, and agriculture (e.g., manure). Agricultural residues include corn stalks, wheat straw, and forest residues like slash piles of branches left by logging operations. Agricultural byproducts like inedible corn oil or animal fats can also be made into fuels. Some wastes and byproducts used to make biofuel today include:

- methane gas collected from landfills, manure digesters, and water-treatment facilities, which can power heavy-duty vehicles (UCS 2015b); and
- used cooking oils and fats that can be made into biodiesel.

Other technologies are coming on line now, or will in the near future, that open up new pathways to make clean fuels from other waste streams, including:

- agricultural residues like corn stalks that can be made into ethanol at cellulosic ethanol facilities; and
- municipal or industrial wastes that can be used to make ethanol or other biofuels.

One of the largest potential sources of agricultural residues in the United States is corn stover: corn stalks, husks, and cobs. Three commercial-scale facilities producing cellulosic ethanol from corn stover are starting up in the Midwest. A recent UCS analysis found that up to 155 million tons of agricultural residues can be available to make biofuel by 2030, enough to make more than 12 billion gallons of cellulosic ethanol; this would almost double ethanol production in the United States without the cultivation of any additional cropland (UCS 2014a). Using agricultural residues for energy, however, requires changes to agricultural practices and must be limited to a level that protects the soil from erosion and prevents the loss of carbon from the soil (English et al. 2013). Excessive or poorly managed residue removal can lead to reduced soil carbon, which would lower the climate benefits of the fuel and the productivity of the agricultural land (Murphy and Kendall 2015). But with appropriate agricultural practices, such as reduced plowing and the planting of cover crops, corn stover can produce ethanol with low net carbon emissions (Pratt et al. 2014).

Technologies are also being developed to turn waste gases from steel mills into ethanol or ordinary household garbage into jet fuel. Turning trash into valuable clean fuels is an important opportunity to expand the production of clean fuels.

SMART AGRICULTURE, BETTER CROPS, AND MULTI-FUNCTIONAL LANDSCAPES

The most promising opportunity to scale up biofuels comes from cellulosic biofuels made from perennial crops that not only can produce high yields of very low-carbon fuels, but can simultaneously address existing environmental problems with the agricultural sector.

Perennial crops are attractive as a source of biofuels because of their potential to produce high yields of very low-carbon biofuel on land that is less suitable for other crops

BOX 10.

Cellulosic Biofuels

The process of making starch or sugar into ethanol has been known for millennia, but new cellulosic biofuel facilities are making ethanol from the tough fibrous parts of plants' cell walls that human beings cannot digest. These fibers are composed of cellulose, hemicellulose, and lignin. Cellulose and hemicellulose, like starch, are long chains composed of sugars, except that in cellulosic biomass the sugars are bound more tightly than in starch, which make them more difficult to break down and digest. Bacteria in the digestive tract of ruminant animals like cows can digest these tough fibrous parts of plants, and recent developments in biotechnology are creating industrial systems of enzymes that can break down cellulosic material into sugars that are subsequently fermented into ethanol. Lignin, another component of cellulosic biomass, can be burned to generate the heat and power needed to run the fermentation and distillation processes, reducing a facility's need for natural gas or sources of heat and power and thereby reducing the emissions associated with the biofuel production process.

Extension Farm Energy Community of Practice/Creative Commons (Flickr)

After corn grain is harvested, the corn stover (stalks, husks, and cobs) is left behind. Some of this material must be left behind to protect the soil, but in many cases some of it can be used to make ethanol. Here, corn stover is seen baled for harvest.

(Dwivedi et al. 2015). Moreover, perennial crops offer tremendous environmental advantages over annual crops because they are planted once every 5 to 10 years (or more) and harvested many times. By providing year-round cover and deep root systems these crops reduce erosion and water pollution, build soil carbon, enhance biodiversity (creating habitat for pollinators, birds, and other species), and provide many other valuable ecosystem services (Liebman and Schulte 2015; Asbjornsen et al. 2014; Werling et al. 2014; Smith et al. 2013). Some land is relatively more suitable for perennials than corn in terms of both yield potential and environmental performance. When the specific part of the landscape that offers the greatest benefits can be targeted, perennials can enhance the overall sustainability of the agricultural system while expanding production of low-carbon biofuel. While it will take time to develop an efficient large-scale supply chain for perennial grasses, they offer the potential for up to 400 million tons of sustainable low-carbon biomass per year by 2030, enough to produce more than 30 billion gallons of ethanol, more than twice as much as corn ethanol produced in 2014 (UCS 2012b).

> ***Perennial crops are attractive as a source of biofuels because of their potential to produce high yields of very low-carbon biofuel on land that is less suitable for other crops.***

Perennial crops offer the opportunity to simultaneously cut oil use and improve agriculture, but realizing this dual benefit will require smart policy coordination that recognizes and supports both benefits. Shifting to perennial crops has costs for farmers, while the environmental benefits of such a shift, such as reduced water pollution and greater carbon sequestration, accrue to society at large; therefore, time and effective policy support will be necessary to realize potential benefits (Housh, Khanna, and Cai 2015). By expanding the production of biofuels made from environmentally preferable perennial crops that function as a complimentary part of the agricultural system—rather than exacerbating the harsh tradeoffs associated with corn ethanol—we can ultimately increase the potential scale of low-carbon biofuel that can cut oil use and global warming emissions throughout the U.S. transportation sector.

BOX 11.

Too Much Waste-based Biofuel Can Turn a Solution into a Problem

Waste-based biofuels reduce the environmental impact of fuel production but are by definition a niche market, creating a new use for a waste or a higher use for a low-value product than previously existed. If waste-based biofuels expand too much and outgrow their niche, their benefits can be reduced or they can create other problems. For example, if a farmer has a sustainable management plan that benefits from removing a portion of her corn stover, then using that stover for fuel is an opportunity for the farmer and can increase clean-fuel production. But if too much stover is removed from a field, the harm to the environment undermines the benefit. Another example is biodiesel made from used cooking oil. Most of the potential waste-based biodiesel feedstocks have at least some existing uses; for example, used cooking oil or animal fat is also often used as animal feed or to make soaps and detergents. Making biodiesel from these feedstocks creates additional opportunities to find good uses for these low-value products, but if demand for waste-based biodiesel outstrips the available supply, existing users of these substances will need substitutes, and some may even switch to using new vegetable oil. Once this shift begins, further expansion of waste-based biodiesel is no longer avoiding expanded production of vegetable oil, and the theoretical benefits are not matched in the real world. The scale of waste-based biofuels production needs to be matched to the sustainable supply of waste feedstocks to deliver the maximum potential benefits.

Conclusions and Recommendations

While today's biofuels offer limited benefits and significant challenges, the potential for cleaner biofuels is substantial. Ethanol is cutting oil use and emissions as part of gasoline blends today, and over the long term biofuels are especially valuable for parts of the transportation sector that are particularly challenging to power with electricity, such as avaiation. Biofuels are cleaner now than they were 10 years ago, and they can become much cleaner still.

There are already many types of biofuels in production today, and many more are in development. In this chapter, we focused primarily on three types of ethanol that exemplify important trade offs: 1) corn ethanol representing the progress and problems with first-generation biofuels made from major commodity food crops; 2) corn stover ethanol representing the next generation of biofuels made from waste materials and agricultural residues; and 3) cellulosic ethanol made from perennial grasses representing the potential for environmentally friendly crops that also enhance the sustainability of the agricultural system. Rather than offering speculative estimates of potential future emissions for each source of biofuel, we conclude by considering the three major sources of emissions from their production—agriculture, land use change, and biorefineries—which provides a useful framework within which to understand opportunities to improve these fuels.

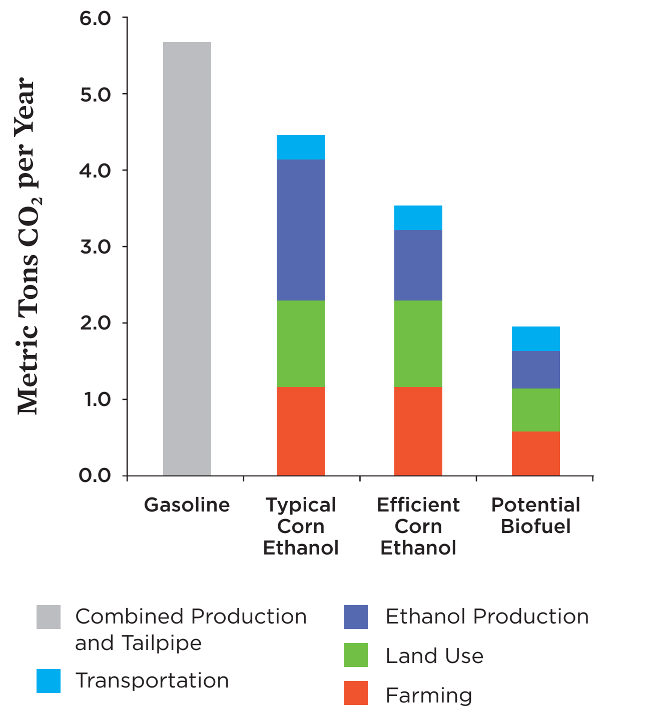
EMISSIONS FROM FOSSIL FUEL USED IN BIOFUELS PRODUCTION MUST BE REDUCED

One of the key reasons for corn ethanol's limited climate benefits is the extensive use of fossil fuels in the process of making it. Smart engineering can reduce or eliminate these fossil inputs in a variety of ways, paving the way for cleaner biofuels. Lower-carbon fuel choices and more efficient processes at biorefineries can reduce emissions from biofuel production. The most efficient corn ethanol facilities in the Midwest have reduced production emissions by as much as 50 percent by adopting advanced technologies including using combined heat and power systems, using biogas from anaerobic digesters as a source of process heat, and co-locating with feed lots, which eliminates the need to dry the co-product of ethanol production before feeding it to livestock (CARB 2015d; EPA 2010).

A byproduct of cellulosic biofuels is lignin, which can be burned to generate heat, completely replacing the fossil fuels needed to power the biofuel production process and even providing extra heat or electricity that can offset fossil fuel use at adjacent biorefineries or put power onto the grid. The reduced use of fossil fuels for heat and power is a major reason that cellulosic ethanol generally has much lower carbon emissions than corn ethanol.

As the biofuels industry matures, it will have substantial additional opportunities to cut carbon emissions from biofuel production. Like other large-scale industrial process, corn ethanol production has become more efficient as it scaled up over the last decade; the industry has taken advantage of countless small opportunities to improve, from more efficient enzymes, to reduced energy and water consumption, to a more diversified product portfolio optimized for local markets. The most efficient corn ethanol facilities have already cut production emissions by half, and with the potential for further optimization and the use of lignin as a process fuel, significant additional progress is achievable. In our judgement, emissions at biorefineries can realistically be reduced to an average of 0.5 ton per 25 mpg car by 2050.

FIGURE 16. Efficiency and Non-food-based Feedstocks Can Make Biofuels Even Cleaner



While improvements have been made to ethanol production, the potential exists to reduce emissions throughout the entire lifecycle of biofuels. Emissions reduction strategies include using biogas from anaerobic digesters as a source of process heat and switching from corn to wastes, residues, or perennial grasses.

Note: The global warming emissions of gasoline represents the metric tons of CO_2e associated with the production and consumption of fuel required to power a typical car (getting 25 mpg) for a year (driving 12,000 miles). This is compared with the energy equivalent amount of ethanol.

SOURCE: CARB 2015A; CARB 2015D; UCS ANALYSIS.

AGRICULTURAL EMISSIONS CAN BE REDUCED THROUGH BETTER FARMING AND CROPS

Emissions from the cultivation of crops are a significant part of the total emissions of biofuels. While it is difficult to draw meaningful generalizations across a wide variety of crops, soils, and practices, there are significant opportunities to reduce emissions from agriculture using a wide range of strategies. The largest share of biofuels' emissions are from chemical fertilizer production and use, and improved crop varieties and crop rotations can reduce or eliminate the need for these fertilizers. While it is unrealistic to expect the total elimination of fertilizer use or emissions, to say nothing of emissions from tractors and combines, we expect that further improvements between now and 2050 could reduce agricultural average emissions associated with biofuel production by half.

EMISSIONS FROM LAND USE CHANGE MUST BE REDUCED

The impact of biofuels on land use change emissions is challenging to quantify now, and even more difficult to predict far out into the future. However, some general conclusions are clear. First, fertile land is a scarce resource with multiple competing uses, so using more of it to produce fuel means using less of it for other purposes. Recent analysis has focused primarily on how much expanded biofuels production contributes to emissions from deforestation. Several decades from now, it may be more appropriate to consider how biofuels production compares to using more land for growing forests that sequester carbon. In either case, there is a significant opportunity cost to using land for biofuels production that cannot be ignored in considering the climate costs and benefits of biofuels. However, land use emissions can be reduced.

Increasing the productivity of fuel production on a given parcel of land directly reduces land use change emissions per unit of energy, since the energy obtained increases while the land use stays the same. Therefore, emissions per unit of fuel production can be reduced through achieving higher crop yields, harvesting multiple crops per year, using a portion of the crop residues, or growing high-yielding perennial crops. Also, not all land is equally suitable for all crops. Crops that are adapted to less fertile land will reduce competition with other crops and associated land use change. Finally, the way in which biofuel crops are integrated into our agricultural system can make a big difference, with strategic integration of perennials in cropping systems providing the opportunity to increase production of cellulosic biomass with only minor reductions of conventional crop production while improving environmental outcomes at the same time.

Taken together, the potential exists to reduce the land-use emissions of biofuels by improving yield and efficiency and targeting the most appropriate crops and land. In our judgement, with well-considered policy support, land use emissions per unit of fuel can be cut in half by 2050.

TRANSPORTATION EMISSIONS ARE LIKELY TO REMAIN ROUGHLY CONSTANT

Moving crops and fuels around the country is a small but significant part of the biofuels emissions profile. We do not anticipate significant changes in these emissions because, while operational efficiencies and scale can certainly reduce emissions per ton, biomass-based fuels may require more transportation of bulky feedstocks like corn stover than is currently the case for grain-based fuels like corn ethanol.

BIOFUELS CAN GET MUCH CLEANER, BUT THERE ARE LIMITS

Lifecycle assessments for potential future cellulosic biofuel production are often more optimistic than our projection; some even suggest that biofuels can have net negative emissions, reducing carbon in the atmosphere. These results are a function of credits added to the lifecycle analysis for activities external to the fuel production process such as cogeneration of power, soil carbon sequestration, or other factors. While these credits may be reasonable in a particular lifecycle analysis framework, they can obscure the fact that biofuels will continue to have real emissions. Farming and fuel production generate emissions that can be substantially reduced but cannot realistically be entirely eliminated. Using land for fuel production has an opportunity cost that can be reduced by strategic integration of biofuel feedstocks into the agricultural system at an appropriate scale, but this cost also cannot be entirely eliminated.[2]

Biofuels have the potential to be much less polluting than they are today, to scale up significantly, and to play a more constructive role in the U.S. agricultural system. But realizing this potential is by no means automatic, and expanding production of corn ethanol will deliver limited global warming emissions reductions at mounting costs in other areas. However, with innovative technology, significant investment, and smart policies for both transportation fuel and agriculture, biofuels can be a core element of our clean-fuel future.

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A NOTE ON THE FEBRUARY 2017 CORRECTED VERSION

The original release of this report made an incorrect inference based on preliminary research. The error became apparent upon subsequent publication of the final analysis, so we have removed the specific claim and the reference to the preliminary analysis. The revised report reflects the literature available at the beginning of 2016, when this report was originally published. Subsequent analysis will be reflected in future publications.

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2 *We have not considered credits for carbon sequestration in soil carbon, biochar, or geologic sequestration in our forecast. These strategies can lead to dramatically lower or even negative lifecycle emissions. Carbon sequestration has potential application not just in conjunction with biofuels but for electricity and oil as well. Carbon sequestration is potentially very significant, but it raises complex accounting questions that are beyond the scope of this report.*

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Fueling a Clean Transportation Future

Smart Fuel Choices for a Warming World

> ***Cutting oil use dramatically is essential to avoiding the worst impacts of climate change, but to achieve a clean transportation future, we must ensure that all of our fuels are as clean as possible.***

The use of biofuels in the United States has expanded dramatically since 2002. This expansion has cut oil use significantly. In 2009, oil's share of transportation energy fell below 95 percent for the first time since 1958, largely because of increased biofuel use. Ethanol now accounts for about 10 percent of every gallon of gas. But the rapid increase in the use of corn for fuel also put pressure on crop prices and highlighted trade-offs and limitations with food-based biofuels in general, and corn ethanol in particular. Fortunately, advanced biofuels made from non-food resources offer a better path to continue to cut oil use and emissions.

The ethanol being blended into gasoline today reduces emissions by about 20 percent compared with gasoline. Ethanol produced in today's most efficient ethanol facilities has emissions reduced by another 15 percent. Advanced biofuels made from wastes—including cellulosic ethanol made from agricultural residues—are coming to market now, and environmentally friendly perennial grasses offer further opportunities to expand biofuel production while complementing food production and enhancing the sustainability of the U.S. agricultural system. The potential scale of biomass resources is vast. Biofuel production can triple while protecting our food system and environment. By seizing these opportunities, global warming emissions from biofuels can be cut by more than 60 percent compared with gasoline on an energy equivalent basis.

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