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Working Paper

Installment 9 of "Creating a Sustainable Food Future"

AVOIDING BIOENERGY COMPETITION FOR FOOD CROPS AND LAND

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SUMMARY

What is the role of bioenergy in a sustainable food future? The answer must recognize the intense global competition for land, and that any dedicated use of land for bioenergy inherently comes at the cost of not using that land for food, feed, or sustained carbon storage.

The world needs to close a 70 percent gap between the crop calories that were available in 2006 and the calorie needs anticipated in 2050. During the same period, demand for meat and dairy is projected to grow by more than 80 percent, and demand for commercial timber and pulp is likely to increase by roughly the same percentage. Yet three-quarters of the world's land area capable of supporting vegetation is already managed or harvested to meet human food and fiber needs. Much of the rest contains the world's remaining natural ecosystems, which need to be conserved and restored to store carbon and combat climate change, to protect freshwater resources, and to preserve the planet's biological diversity.

A growing quest for bioenergy exacerbates this competition for land. In the past decade, governments have pushed to increase the use of bioenergy—the use of recently living plants for energy (Box 1)—by using crops for transportation biofuels and increasingly by harvesting trees for power generation. Although increasing energy supplies has provided one motivation, the belief that bioenergy use will help combat climate change has been another. However, bioenergy that entails the dedicated use of land to grow the energy feedstock will undercut efforts to combat climate change and to achieve a sustainable food future.

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Box 1 | Definitions

Biodiesel is a type of biofuel that replaces diesel fuel and is derived from vegetable oil or animal fats.

Bioenergy is energy derived from any fuel that comes from biomass.

Biofuel is any liquid fuel that contains energy derived from recently living organisms, mainly plants.

Biomass is any material derived from living or recently living tissue, typically plants.

Cellulosic biomass or feedstock is any feedstock for bioenergy derived from cellulose, hemi-cellulose, and/or lignin. As typically used, the term refers to crop residues or any non-crop plant, such as trees and grasses, even though they may contain some starches.

Ethanol is an alcohol derived via fermentation of biomass, the main sources of which today are maize, sugarcane, and wheat. Ethanol can be used in a pure form but is most often blended with gasoline.

Second generation biofuels is a term typically referring to any cellulosic biofuel.

What are the implications of crop-based biofuels for the supply of food?

Bioenergy challenges a sustainable food future most directly when government policy causes diversion of food crops into ethanol or biodiesel for transportation. Biofuels from food crops today—such as maize, vegetable oils, and sugarcane—provide about 2.5 percent of the world's transportation fuel. Crop needs for 2050 projected by the Food and Agriculture Organization of the United Nations (FAO) assume that this penetration rate will remain roughly the same. Yet even this small share of transportation fuel in 2050 would have substantial implications for the crop calorie gap. If crop-based biofuels were phased out, the 2050 crop calorie gap would decrease from 70 percent to about 60 percent, a significant step toward a sustainable food future.

But the FAO biofuel projection for 2050 is modest. Some of the largest fossil-fuel consuming regions, such as the United States and Europe, have established higher biofuel targets that amount to at least 10 percent of transportation fuel by 2020. If such targets were to go global by 2050, meeting them would consume crops with an energy content equivalent to roughly 30 percent of the energy in today's global crop production. Consequently, the crop calorie gap would increase from 70 percent to about 90 percent, making a sustainable food future even more difficult to achieve.

Overall, phasing out the use of crop-based biofuels instead of meeting an expanded 10 percent target is likely to mean the difference between a 90 percent crop calorie gap and a 60 percent gap. It is therefore a potent strategy for sustainably meeting future food needs.

Would cellulosic biofuels avoid this competition for food?

Cellulosic biofuels (sometimes referred to as "second generation") may use crop residues or other wastes, but most plans for these biofuels rely on planting and harvesting fast-growing trees or grasses. At least some direct competition with food is still likely because such trees and grasses grow best and are most easily harvested on relatively flat, fertile lands—the type of land already dedicated to crops.

Using cropland to grow trees and grasses rather than food crops for biofuels will probably not reduce, let alone eliminate, competition for cropland. Trees and grasses will have a hard time producing more biofuels per hectare than today's crop-based biofuels. For example, a hectare of maize in the United States currently produces roughly 1,600 gallons of ethanol (about 6,000 liters). For cellulosic ethanol production just to match this output, the grasses or trees must achieve almost double the national cellulosic yields estimated by the U.S. Environmental Protection Agency and two to four times the perennial grass yields farmers actually achieve today in the United States.

Alternatively, cellulosic biofuels might rely on harvesting existing forests or producing fast-growing trees or grasses on the world's grasslands or woody savannas. But harvesting standing forests reduces their carbon storage and typically their ability to support biodiversity. Burning the trees for energy results in net carbon dioxide emissions for decades until the trees regrow. Likewise, converting woody savannas to bioenergy sacrifices the ecosystem's abundant carbon storage and biodiversity, while converting pasturelands sacrifices their ability to provide food from livestock.

What about using "degraded" land for bioenergy?

Some researchers argue that growing bioenergy feedstocks on degraded lands would avoid competition for land. The term "degraded lands" has many meanings, but no matter how it is defined, it is hard to find lands that are doing little today for people, climate, or biodiversity and that could produce bioenergy crops abundantly. There are a few possible candidates, such as cleared forests of Indonesia that are overrun by alang-alang grasses. But while some of these lands could support bioenergy plants, the opportunity costs of doing so are high in a world that needs at least 70 percent more crops, livestock, and commercial timber by 2050. Indonesia's alang-alang grasslands, for example, provide a low-opportunity-cost way of meeting rapidly growing demand for palm oil for food. Using these grasslands instead for biofuels could push growers to convert forests to meet food product demands for palm oil.

Some researchers also point to abandoned farmland as a candidate for bioenergy production that avoids competition for land. But abandoned farmlands typically regenerate into forests, woodlands, or grasslands if left alone, which provide climate benefits that are already assumed and counted in climate change assessments. These benefits would be sacrificed by using that land for bioenergy.

By adding irrigation water, some degraded or dry lands might produce biofuels while avoiding this competition with food and carbon storage. Examples might include recirculating water systems or saline ponds that grow algae in the desert. Although this kind of production might eventually be necessary to supply biofuels for applications such as aviation, it is likely to be expensive and should only be employed at scale to reduce greenhouse gas emissions after more cost-effective strategies are fully utilized.

Can increased crop and pasture yields supply bioenergy as part of a sustainable food future?

Crop and pasture yields can increase. Yet to avoid clearing natural ecosystems while still meeting projected food crop and livestock demands, crops and pasture yields overall will have to grow even faster over the coming four decades than they did over the previous four decades. Any yield improvement potential is therefore already needed to meet growing food demands.

What are the implications of wider bioenergy targets?

The push for bioenergy is extending beyond transportation biofuels to the harvest of trees and other sources of biomass for electricity and heat generation. Some organizations have advocated for a bioenergy target of meeting 20 percent of the world's total energy demand by the year 2050, which would require around 225 exajoules of energy in biomass per year. That amount, however, is roughly equivalent to the total amount of biomass people harvest today—all the crops, plant residues, and trees harvested by people for food, timber, and other uses, plus all the grass consumed by livestock around the world.

The world will still need food for people, fodder for livestock, residues for replenishing agricultural soils, wood pulp for paper, and timber for construction and other purposes. To meet these needs at today's level while at the same time meeting a 20 percent bioenergy target in 2050, humanity would need to at least double the world's annual harvest of plant material in all its forms. Those increases would have to come on top of the already large increases needed to meet growing food and timber needs. Even assuming large increases in efficiency, the quest for bioenergy at a meaningful scale is both unrealistic and unsustainable.

Why does a small share of energy require such vast amounts of biomass?

Although photosynthesis is an effective means of producing food, wood products, and carbon stored in vegetation, it is an inefficient means of converting the energy in the sun's rays into a form of non-food energy useable by people. Fast-growing sugarcane on highly fertile land in Brazil, for example, converts only around 0.5 percent of incoming solar radiation into sugar, and only around 0.2 percent ultimately into ethanol. For maize grown in Iowa, the energy conversion rate is around 0.3 percent into biomass and 0.15 percent into ethanol. Even assuming highly optimistic estimates of future yields and conversion efficiencies, fast-growing grasses on productive U.S. farmland would only do slightly better, converting around 0.7 percent of sunlight into biomass and around 0.35 percent into ethanol. Such low conversion efficiencies explain why it takes a large amount of productive land to yield a small amount of bioenergy, and why bioenergy can so greatly increase the global competition for land.

How does bioenergy compare to alternative uses of land to produce energy?

Like bioenergy, solar photovoltaics (PV) convert sunlight directly into energy that is useable by people, but PV's solar conversion efficiency—and therefore its land-use efficiency—is much higher. On three-quarters of the world's land, PV systems *today* can generate more than 100 times the useable energy per hectare than bioenergy is likely to produce in the *future* even using optimistic assumptions. In addition, because electric motors can be 2–3 times more efficient than internal combustion engines, PV can result in 200–300 times more useable energy for vehicle transport than bioenergy per hectare (although fully realizing this potential will require battery production to become more energy efficient). PV can also utilize areas that do not naturally support much (if any) vegetation, such as deserts, dry lands, and rooftops. Overall, PV can contribute to energy security and climate goals with a fraction of the competition for the world's productive land.

Use of bioenergy at a globally meaningful level will push up costs of food, timber, and land, while solar energy costs are likely to become cheaper over time. Although solar power eventually may face storage limitations, promising storage technologies are already emerging, and solar energy could increase multifold to meet more than 20 percent of global energy demand before running into serious storage constraints.

Is bioenergy nevertheless good for climate?

Burning biomass, whether directly as wood or in the form of ethanol or biodiesel, emits carbon dioxide, just like burning fossil fuels. In fact, burning biomass directly emits at least a little more carbon dioxide than fossil fuels for the same amount of generated energy. But most calculations claiming that bioenergy reduces greenhouse gas emissions relative to burning fossil fuels do not include the carbon dioxide released when biomass is burned. They exclude it based on the theory that this release of carbon dioxide is matched and implicitly "offset" by the carbon dioxide absorbed by the plants growing the biomass feedstock. Yet if those plants were going to grow anyway, simply diverting them to bioenergy does not remove any additional carbon from the atmosphere and therefore does not offset emissions from burning that biomass.

For example, in a world without biofuels, farmers grow maize for food and feed (absorbing carbon dioxide) while automobiles run on gasoline (emitting carbon dioxide). When ethanol diverts the already-growing maize to biofuels to run the automobiles, those maize fields do not absorb any additional carbon, and the automobiles still emit roughly the same quantity of carbon dioxide. Maize growth by itself does not reduce greenhouse gas emissions because the carbon dioxide absorption would occur anyway.

Ultimately, plant growth can offset greenhouse gas emissions only to the extent that bioenergy leads to more plant growth than would occur anyway, directly or indirectly. That happens only to a limited extent (see "additional biomass" below) and cannot happen at a meaningful scale because the world's productive land and potential to boost crop, pasture, and timber yields is already needed to meet rising demands for food and timber. Analyses generally attribute greenhouse gas emissions reductions to bioenergy by counting the benefits of plant growth that would occur anyway—thus "double counting" this plant growth.

What accounts for large estimates of bioenergy potential?

Large estimates of bioenergy potential double count biomass, leading to a double counting of carbon. Most of the world's land grows plants each year. Some of these plants are consumed for food, fiber, and timber while others are replenishing or increasing carbon in soils and vegetation. The latter keeps land productive and combats climate change. Like a monthly paycheck, plant growth will occur again once we use it. But because people use this annual growth—just as they use their monthly paycheck—people cannot divert plant growth to some other use except at the expense of what they are already doing with it. To provide bioenergy except at the cost of food, timber, or carbon storage, people must generate additional biomass, which means biomass that is not already growing or being used.

But instead of counting only additional biomass, estimates suggesting that the world has a large potential to produce bioenergy double count biomass and land by assuming incorrectly that bioenergy can freely divert biomass or land that is already in use. For example, the build-up of wood and carbon that is already occurring in some forests is helping to reduce the rate of climate change. If this increasing biomass is harvested for energy, these climate benefits would be lost. Other examples of double counting include counting woody savannas that would lose much of their abundant carbon storage if converted to produce bioenergy, and counting grasslands whose use for bioenergy would sacrifice livestock production.

What types of biomass are additional?

There are some sources of additional biomass that are consistent with a sustainable food future and will therefore reduce greenhouse gas emissions because they do not compete with food production or otherwise make dedicated use of land. This category includes some level of forest and agriculture residues left behind after harvest (some need to remain on the ground to maintain soil fertility); timber processing wastes including sawdust and "black liquor"; and any unused manure, urban wood waste, municipal organic waste, and landfill methane. Another category is biomass grown in excess of what would have grown absent the demand for bioenergy, such as growing winter cover crops for energy and replacing traditional—yet inefficient—fuel wood harvests in some poor countries with wood grown in agroforestry systems and local plantations. Using second generation technologies to convert crop residues into bioenergy has potential and avoids competition for land. But a challenge will be to do this at scale, since most of these residues are already used for animal feed or are needed for soil fertility, and others are expensive to harvest.

Although one or more of these sources may be important in certain local contexts, studies indicate that their potential to meet a sizeable share of energy needs is limited. These feedstocks should therefore be prioritized to energy uses that can probably not be met any other way, such as low-carbon fuels for airplanes.

What should policymakers do?

In light of these findings, phasing out bioenergy that uses crops or that otherwise makes dedicated use of land is a sound step toward a sustainable food future. Doing so will require five policy changes:

1. Governments should fix flaws in the accounting of the carbon dioxide consequences of bioenergy in climate treaties and in many national- and state-level laws.

2. Governments should phase out the varied subsidies and regulatory requirements for transportation biofuels made from crops or from sources that make dedicated use of land.

3. Governments should make ineligible from low-carbon fuel standards biofuels made from crops or from the dedicated use of land.

4. Governments should exclude bioenergy feedstocks that rely on the dedicated use of land from laws designed to encourage or require renewable energy.

5. Governments should maintain current limits on the share of ethanol in gasoline blends.

By concurrently pursuing policies that encourage solar energy development, policymakers can catalyze far more energy growth in a manner fully compatible with a sustainable food future.

BIOENERGY AND FOOD

The world faces a difficult balancing act. As set out in previous papers in this series,[1] it needs to close a gap of 6,500 trillion kilocalories (kcal) per year between the food available in 2006 and likely demand in 2050—roughly a 70 percent increase in needed crop calories from 2006 levels. The world also needs agriculture to contribute to economic and social development, particularly to benefit poor farmers. And it needs agriculture to reduce its impact on climate, water, and ecosystems.

The challenge of meeting food needs while reducing agriculture's environmental impacts results in competition for land. In addition to increased crop production, projections of the Food and Agriculture Organization of the United Nations (FAO) imply the need to increase meat and milk production on grazing land by more than 80 percent by 2050.[2] FAO's estimates of commercial timber demand imply about an 80 percent growth of wood harvest by mid-century as well.[3] Between 1960 and 2006, agricultural land area expanded by roughly 500 million hectares, despite large increases in crop yields and in milk and meat production efficiencies. Because total food demand will grow faster in the next four decades than in the past four decades,[4] producing enough food without expanding agricultural area over the coming four decades will require greater global increases in crop yields and livestock productivity than the world achieved during the past four decades—in fact roughly a one-third greater annual growth in crop yields across all crops.[5] Such growth rates will be particularly challenging because the potential for irrigation and fertilizers—major drivers of yield gains in the past—has already been maximized in many farming regions, resulting in less potential to boost yields in the future.[6]

In the World Resources Report's *Creating a Sustainable Food Future: Interim Findings* (Box 2), we explore an initial menu of solutions that could combine to meet these three needs, focusing both on ways of sustainably increasing crop and other food production and on beneficial ways of reducing the growth in food demand. One item on the menu is to reduce and ultimately eliminate the use of food crops and the dedicated use of land to generate bioenergy. By "the dedicated use of land," we mean the production of bioenergy that sacrifices alternative outputs from land (such as food), but not bioenergy production from wastes or some crop residues (whose benefits and costs we discuss below). This proposed menu item would free up crops and croplands for food rather than for cars and factories.

To what degree can phasing out the dedicated use of land for bioenergy contribute to a sustainable food future by 2050? How desirable is this menu item in light of broader energy and greenhouse gas goals? What policies would be needed to realize this menu item's potential? This working paper addresses these questions.

Box 2 | The World Resources Report: *Creating a Sustainable Food Future*

How can the world adequately feed more than 9 billion people by 2050 in a manner that advances economic development and reduces pressure on the environment?

Answering this question requires a "great balancing act." First, the world needs to close the gap between the food available today and that needed by 2050. Second, the world needs agriculture to contribute to inclusive economic and social development. Third, the world needs to reduce agriculture's impact on the environment.

The forthcoming World Resources Report, *Creating a Sustainable Food Future*, seeks to answer this question by proposing a menu of solutions that can achieve the great balancing act. "Avoiding bioenergy competition for food crops and land" profiles one of these solutions or "menu items," and is an installment in a series of working papers leading up to the World Resources Report.

Since the 1980s, the World Resources Report has provided decision makers from government, business, and civil society with analyses and insights on major issues at the nexus of development and the environment. For more information about the World Resources Report and to access previous installments and editions, visit www.worldresourcesreport.org.

We find that reducing and ultimately eliminating the use of food crops and other dedicated uses of land for bioenergy would satisfy the criteria for a sustainable food future (Table 1). Reducing bioenergy demand for food crops would make more food available for human consumption and should therefore lower food costs and benefit the poor. Reducing bioenergy demand for food crops would also reduce greenhouse gas emissions and help limit further conversion of natural land-based ecosystems to agriculture.

Table 1 | **How "Reducing Bioenergy Demand for Food Crops and Land" Performs Against the *Sustainable Food Future* Criteria**

● = positive ○ = neutral/it depends ⊗ = negative

CRITERIA	DEFINITION	PERFORMANCE	COMMENT
Poverty Alleviation	Reduces poverty and advances rural development, while still being cost effective	●	Reducing bioenergy demand for food crops and land could help lower food prices, which will particularly benefit the poor for whom food purchases are a high share of household expenditures.
Gender	Generates benefits for women	●	By lowering pressure on food prices, reducing bioenergy demand for food crops and land could increase poor families' access to food and reduce household food expenditures. Because women in developing countries are often more vulnerable than men to nutritional problems during times of food scarcity, reducing bioenergy demand could particularly benefit women's food security.
Eco-systems	Avoids agricultural expansion into remaining natural terrestrial ecosystems and relieves pressure on aquatic ecosystems	●	Reducing bioenergy demand for food crops and land would reduce pressure for conversion of natural land-based ecosystems into agricultural fields.
Climate	Helps reduce greenhouse gas emissions from agriculture to levels consistent with stabilizing the climate	●	Reducing demand for bioenergy for food crops and land will on balance reduce greenhouse gas emissions by reducing conversion of land and reducing energy intensive inputs, such as fertilizer. In addition, it might encourage greater resources going toward more effective strategies for replacing fossil fuels, such as solar photovoltaic energy.
Water	Does not deplete or pollute aquifers or surface waters	●	Phasing out the dedicated use of land for bioenergy would reduce agricultural demand for freshwater.

Note: This working paper mainly addresses bioenergy's impacts on ecosystems and climate as well as its overall competition with food production. The *Interim Findings* (Searchinger et al. 2013) discusses the impacts on poverty of rising food prices overall. For an analysis of the poverty effects related to food competition from biofuels, see HLPE (2013). For a discussion of the water effects of biofuels, see Mulder (2010). For a discussion of the disproportionate impacts of food scarcity on women, see World Bank, FAO and IFAD (2009).

BIOFUELS AND THE FOOD GAP

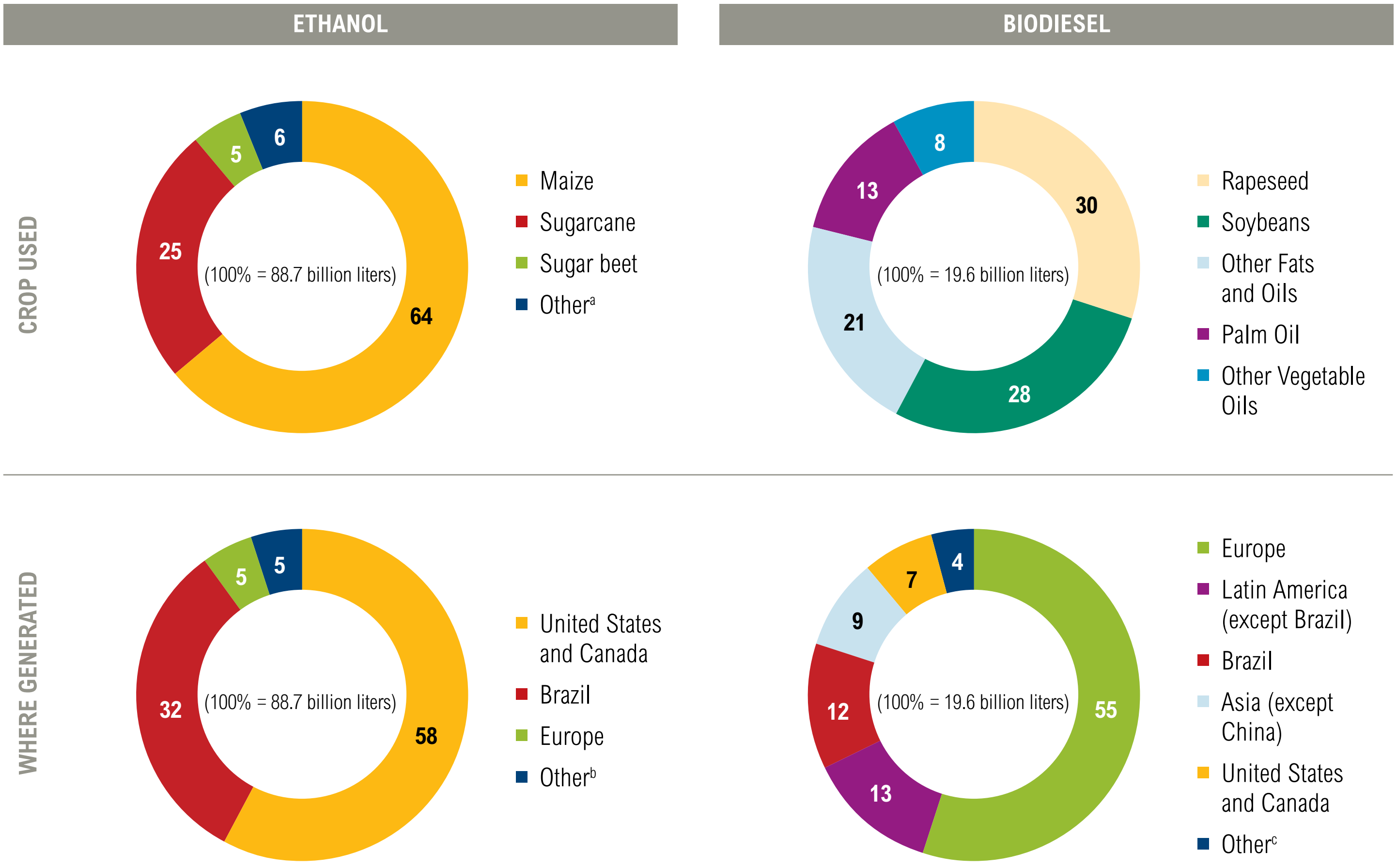
We begin by exploring transportation biofuels and their implications for the food gap.

Impact of biofuels in the 2050 FAO food demand projections

In 2010, biofuels provided roughly 2.5 percent of the energy in the world's transportation fuel (the fuel used for road vehicles, airplanes, trains, and ships).[7] On a net basis, these 108 billion liters of biofuel provided roughly half a percent of global delivered energy.[8] These liters came overwhelmingly from food crops: ethanol distilled mainly from maize, sugarcane, sugar beets, or wheat (88.7 billion liters),[9] and biodiesel refined from vegetable oils (19.6 billion liters). The United States, Canada, and Brazil accounted for about 90 percent of ethanol production, while Europe accounted for about 55 percent of biodiesel production (Figure 1).[10] Overall, excluding feed byproducts, about 3.3 exajoules (EJ)[11] of energy in crops were grown around the world for biofuels in 2010, using 4.7 percent of the energy content of all crops.[12]

The FAO's projected demand for crops in 2050 conservatively assumes that food crops used for biofuels will generate roughly the same share of global transportation fuel as they did in 2010. For the year 2050, that share translates into 990 trillion kcal of food crops for biofuels. Giving up this use of food crops for generating transportation biofuels would reduce the crop calorie gap that exists

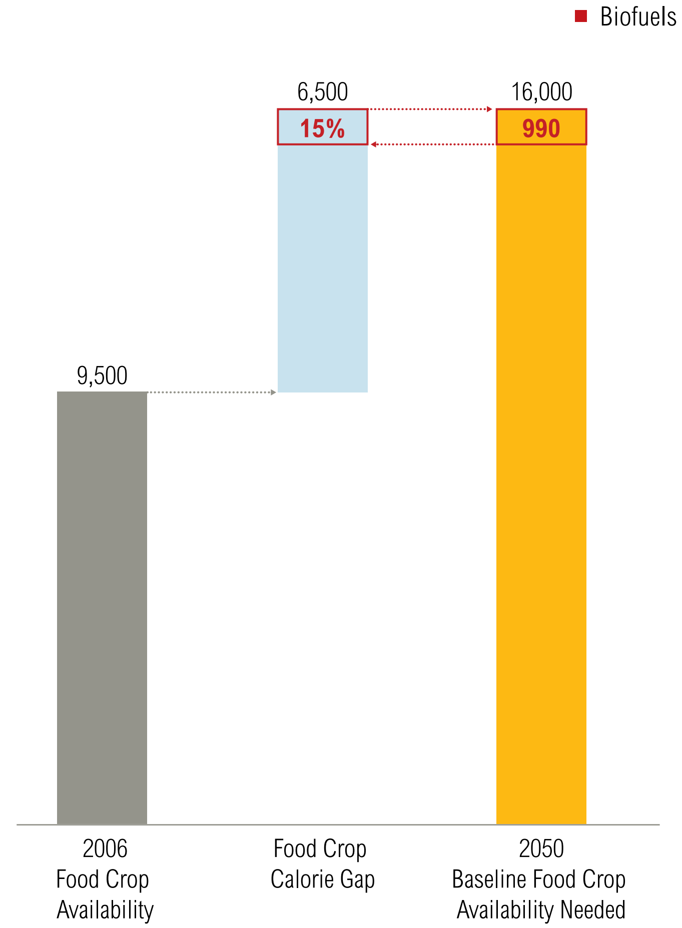
Figure 1 | **Biofuel Production in 2010 Was Concentrated in a Few Regions and a Few Crops** (Percent)



Source: EIA (2014a).
Notes:
a. Includes wheat (4%), cassava (1%), and other feedstocks (1%).
b. Includes China (2%) and other regions (3%).
c. Includes China (2%) and other regions (2%).

between 2006 and 2050 from roughly 70 percent to 60 percent, a 15 percent reduction (Figure 2).[13] This is a substantial amount.

Figure 2 | **Avoiding the Use of Food Crops for Generating Biofuels Would Close the Food Crop Calorie Gap by 15 Percent** (Global annual crop production, trillion kcal per year)



Source: WRI analysis based on Bruinsma (2009) and Alexandratos and Bruinsma (2012).
Note: Includes all crops intended for direct human consumption, animal feed, industrial uses, seeds, and biofuels.

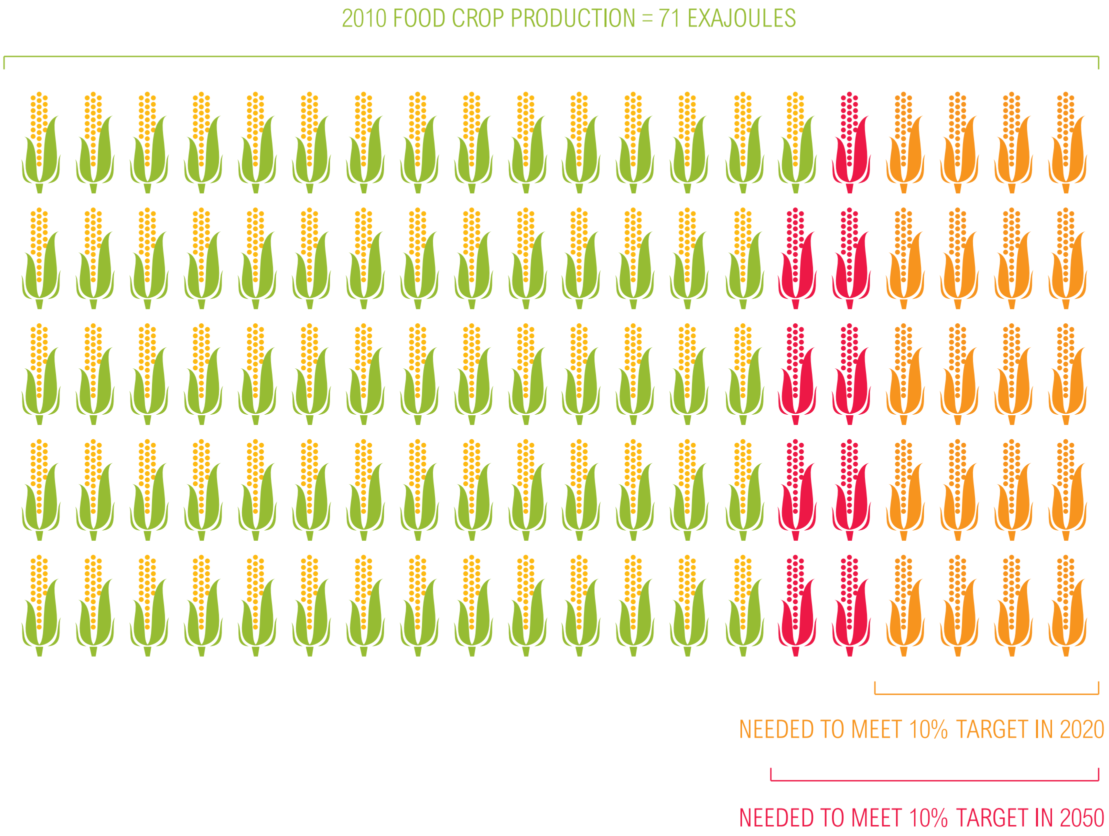
Impact if biofuel targets are met by 2050

This estimated impact of biofuel production on food crops, although meaningful, is highly conservative. The FAO baseline projections assume that biofuels will only maintain roughly their current share of global transportation fuels in the year 2050. But many nations have established, or are establishing, targets and mandates that call for biofuels to make up a greater share of transportation fuel well before 2050 (Table 2). What are the implications of these mandates and targets for the crop calorie gap?

One way to answer this question is to determine the share of the world's existing annual crop production necessary to meet these future biofuel targets, and therefore how much such targets would widen the food crop gap. As Table 2 shows, many of the world's largest fuel consumers have established targets or mandates for biofuels to supply at least 10 percent of their transportation fuel by 2050. Suppose that such a target level went global. The U.S. Energy Information Administration (EIA) projects that global transportation fuel demand in 2020 will be 113 EJ.[14] Meeting 10 percent of this amount with biofuels thus would require 11.3 EJ of energy. To put that figure in perspective, global food crop production in 2010 contained 71 EJ of energy.[15] Even if crop energy could be converted with perfect efficiency into useable transportation fuel, meeting a global 10 percent biofuel target in 2020 would therefore require 16 percent of the energy contained in 2010's global production of food crops.[16] But in practice, given the realistic efficiencies of converting crop energy into biofuels,[17] 19–20 percent is a more reasonable estimate.[18]

Looking ahead to 2050, the EIA projections imply global transportation fuel needs of 168 EJ.[19] Assuming perfect energy conversion efficiency, meeting 10 percent of this amount with biofuels would require about 24 percent of the energy contained in all the world's crops in 2010.[20] Conversion inefficiencies would raise this figure to 29 percent (Figure 3).[21] These calculations ignore the additional, net fossil energy needed to produce biofuels, which means that a 10 percent biofuel target—which would produce roughly 2.5 percent of global delivered energy—would probably produce less than 2 percent on a net basis.

Figure 3 | **A Global 10% Transportation Biofuel Target in 2020 Would Consume 20% of 2010's Food Crop Calories. By 2050, This Target Would Consume 29%.**



Source: Authors' calculations based on EIA (2013a), FAO (2013), and Wirsenius (2000).

If the world were to shift to crop-based biofuels to meet 10 percent of its transportation energy needs by 2050, the world's food crop calorie gap between 2006 and 2050 would widen from about 70 percent to roughly 90 percent.[22] In the other direction, phasing out biofuels altogether would reduce the gap to 60 percent. Many research scenarios envisage far more use of biofuels, but this 30 percentage point spread indicates how even relatively modest biofuel production makes achieving a sustainable food future significantly more difficult.

Table 2 | **Biofuel Targets and Mandates around the World**

COUNTRY	MANDATE/TARGET
Argentina	B7, E5
Australia: New South Wales (NSW), Queensland (QL)	NSW: B5 (2012), E6; QL: E5
Bolivia	B20 (2015), E10
Brazil	B5, E20–25
Canada	B2 (nationwide), B2–B3 (in 3 provinces), E5 (up to E8.5 in 4 provinces)
Chile	B5, E5
China	E10 (9 provinces)
Colombia	B20 (2012), E10
Costa Rica	B20, E7
Dominican Republic	B2 (2015), E15 (2015)
European Union	10% renewable energy in transport[a]
India	B20 (2017), E20 (2017)
Indonesia	B5 (2015), B20 (2025); E5 (2015), E15 (2025)
Jamaica	E10; Renewable energy in transport: 12.5% (2015); 20% (2030)
Japan	500 Ml/year (oil equivalent), 800 Ml/year (2018)
Kenya	E10 (in Kisumu)
Korea	B3
Malaysia	B5
Mexico	E2 (in Guadalajara), E2 (in Monterrey and Mexico City)
Mozambique	B5 (2015), E10 (2015)
Nigeria	E10
Norway	3.5% biofuels, possible future alignment with EU mandate
Paraguay	B1, E24
Peru	B5, E7.8
Philippines	B5, E10
South Africa	2%
Taiwan	B2, E3
Thailand	B5, 3Ml/day ethanol; 9 Ml/day ethanol (2017)
United States	136 billion liters of any biofuel, equivalent to ~12% of total transportation fuel demand in 2020–2022[b]
Uruguay	B5, E5 (2015)
Venezuela	E10
Vietnam	50 Ml biodiesel, 500 Ml ethanol (2020)
Zambia	B10, E5

Source: OECD and IEA (2011). Updated by authors to 2013.

Notes: B = biodiesel (e.g., "B2" = 2% biodiesel blend); E = ethanol (e.g., "E2" = 2% ethanol blend); Ml = million liters.

a. Lignocellulosic biofuels, as well as biofuels made from wastes and residues, count twice and renewable electricity 2.5 times toward the target.

b. The U.S. mandate is for a volume, not a percentage, and this volume may be met either by ethanol or biodiesel, despite their different energy contents. The estimated percentage of U.S. transportation fuel in 2020–2022 is based on the assumption of 34 billion gallons of ethanol and 2 billion gallons of biodiesel and a U.S. Energy Information Administration projection of 2020 U.S. transportation energy demand. The U.S. mandate includes a goal that 16 billion gallons of the 36 billion gallons (136 billion liters) come from cellulosic sources, but that requirement can be waived and all 36 billion gallons could come from crops as long as maize-based ethanol does not exceed 15 billion gallons.

WHAT ABOUT FAST-GROWING GRASSES OR TREES FOR CELLULOSIC BIOFUELS?

Some biofuel proponents suggest that switching biofuels away from food crops to various forms of "cellulose"—sometimes referred to as "second generation" biofuels—would avoid competition with food. Cellulose forms much of the harder, inedible structural parts of plants, and researchers are devoting great effort to find ways of converting cellulose into ethanol more efficiently. In theory, almost any plant material could fuel this ethanol, including crop residues and much garbage. Such "waste" would not compete with food and, in a later section, we discuss the merits, demerits, and potential for its use. Yet the potential for wastes to provide energy on a large scale is sufficiently limited that virtually all plans for future large-scale biofuel production assume that most of the biomass for bioenergy would come from fast-growing trees and grasses planted for energy.[23]

Unfortunately, growing trees and grasses well requires fertile land, resulting in potential land competition with food production. In general, growing grasses and trees on cropland generates the highest yields but is unlikely to produce more biofuel per hectare than today's dominant ethanol food crops. For example, a hectare of maize in the United States currently produces roughly 1,600 gallons (about 6,000 liters) of ethanol. (This level of production per hectare is sometimes understated because any hectare devoted to maize ethanol is also producing a feed byproduct, so the "real" area dedicated to ethanol is not the entire hectare.)[24] For cellulosic ethanol production to match this figure, the grasses or trees must achieve almost double the national cellulosic yields estimated by the U.S. Environmental Protection Agency (EPA),[25] and two to four times the perennial grass yields farmers actually achieve today.[26] Although there are optimistic projections for even higher yields, they are unrealistically predicated on small plot trials by scientists—sometimes only a few square meters.[27] Scientists can devote greater attention to crops than can real farmers, and field trials for all types of crops nearly always produce far higher yields than those that farmers achieve in practice.

There may be specific croplands where grasses or trees have relative yield advantages over food crops. But planting fast-growing grasses or trees on those lands would spare land overall while meeting food supplies only if those food crops shift to other lands in such a way that crop yields overall go up. Otherwise, displacing a hectare of food crops to grow trees or grasses for biofuels in one place would just lead to the conversion of a hectare (or more) of land elsewhere to grow those food crops, at the expense of the plant growth that was already there.

For these reasons, most studies of sustainable bioenergy—including biofuel—potential assume that bioenergy crops will not be grown on existing cropland. But yields on poorer, less fertile land tend to be substantially lower.[28]

More fundamentally, using less fertile land for bioenergy still uses land. Land that can grow bioenergy crops reasonably well will typically grow other plants well, too—if not food crops, then trees and shrubs that provide carbon storage, watershed protection, wildlife habitat, and other benefits. In Appendix A, we address various claims of the availability of such non-croplands for bioenergy. We argue that studies that find large bioenergy potential systematically "double count" land for biofuels that is already producing vegetation meeting other important human needs.

Some of the bioenergy literature calls for the use of "marginal" or "degraded" lands, relying on studies that use large-scale maps (see the discussion of abandoned degraded land in Appendix A). However, these areas that appear to be unused and available for bioenergy using a coarse satellite map often turn out to be in *some* use upon closer examination. If millions of potentially productive hectares were truly both unused and not storing carbon, it should be easy to identify them specifically, but thus far no closer examinations have done so.

There are some lands that at any given time are "underutilized," as is probably true of all valuable resources. But the opportunity cost of devoting that underutilized land to bioenergy would still be high because rising food and timber demands mean these lands are also desirable locations for food or timber production.

Perhaps the strongest examples of underutilized lands are deforested lands in Indonesia that are not intensively used and are often partially covered by invasive and flammable "alang-alang" grasses. The World Resources Institute has extensively mapped these areas.[29] Although some have low-intensity agricultural uses, these degraded areas are, from an environmental perspective, highly preferable for siting oil palm production when compared with the most likely alternative, converting native forests into oil palm plantations. Meeting the estimated growth in demand for palm oil will require using these areas for oil palm for food, if barriers to doing so can be overcome.[30] But if oil palm on these relatively degraded lands were instead devoted to bioenergy, then people would need to convert more forests to produce the oil palm needed for food.

As Indonesia illustrates, using land capable of abundant plant production for biofuels will nearly always have a high opportunity cost. Although using grasses or trees for biofuels instead of maize reduces the fertilizer requirements compared to maize, it may not necessarily reduce the demand for land to generate the same quantity of biofuels. It certainly does not fundamentally alter the potential competition between biofuels, food security, and the carbon and biodiversity benefits of forests, savannas, and grasslands.

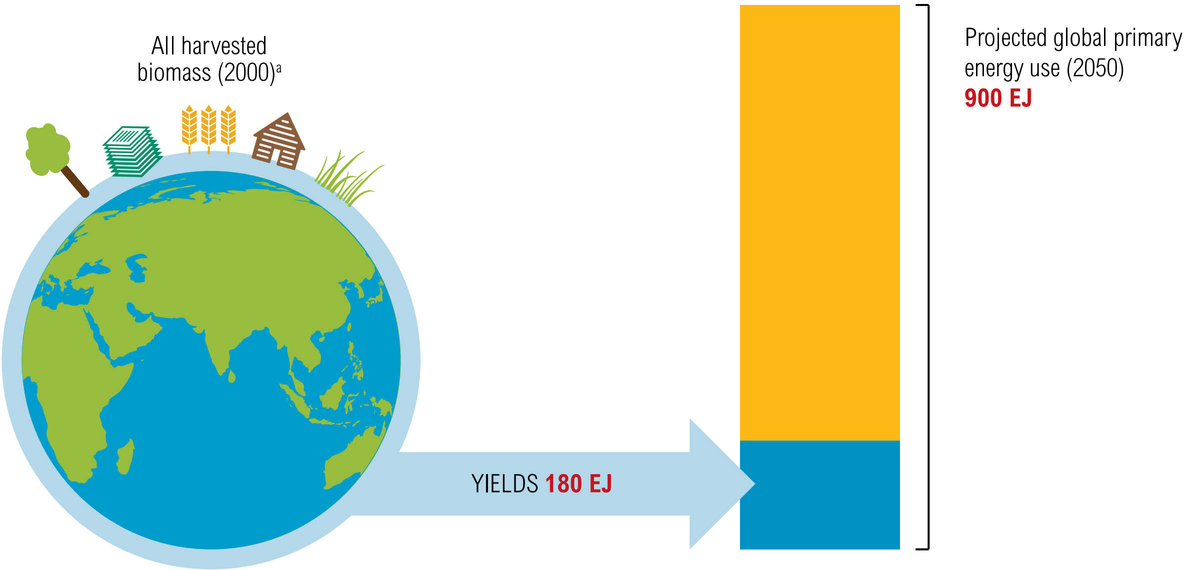
THE IMPLICATIONS OF BROADER BIOENERGY TARGETS

Governments and some researchers are promoting goals related not only to biofuels for transportation, but also to other forms of bioenergy, including the use of wood and grasses for electricity and heat generation. This wood could come from new plantings or even existing forests. The same biomass (and land) that might be used for cellulosic biofuels could also be devoted to meeting this broader bioenergy agenda. What are the implications of these broader bioenergy goals for a sustainable food future?

To answer this question, we make some basic calculations. The International Energy Agency (IEA), among others, has suggested a goal of supplying 20 percent of the world's energy use in the year 2050 from bioenergy.[31] Since the Organisation for Economic Co-operation and Development (OECD) projects global primary energy use in 2050 to be 900 EJ per year, a 20 percent target equates to 180 EJ per year. How much plant material would that require?

To get a sense of how much, consider that in 2000 the total amount of energy in all the crops, plant residues, and wood harvested by people for all applications (e.g., food, construction, paper) and in all the biomass grazed by livestock around the world was roughly 225 EJ.[32] This amount of energy could in theory be liberated by perfect combustion of this biomass. But combustion is not perfect. Factoring in relative energy conversion efficiencies, this 225 EJ of biomass would optimistically replace about 180 EJ of primary energy from fossil fuels.[33] Thus, it would take the entirety of human plant harvests in the year 2000 to meet a 20 percent bioenergy target in the year 2050 (Figure 4).

Figure 4 | **Using All of the World's Harvested Biomass for Energy Would Provide Just 20 Percent of the World's Energy Needs in 2050** (Exajoules per year)



Source: Authors' calculations based on Haberl et al. (2007), IEA (2008), OECD (2011), and JRC (2011).
Note: a. Total amount of crops, harvested residues, grass eaten by livestock, and harvested wood contained 225 EJ, but would replace only 180 EJ of fossil fuels because of conversion efficiencies from biomass to useable energy.

Put another way, meeting this bioenergy target would require not only all of the world's recent crop harvest, but also all of its crop residues, harvested trees, and grass consumed by livestock. And yet the world would still need food for people, fodder for livestock, residues for replenishing agricultural soils, wood pulp for paper, and timber for construction and other purposes. To meet these needs and at the same time meet a 20 percent bioenergy target, humanity would therefore need to double the world's recent annual harvest of plant material. In fact, it would have to do even more than that because humanity also needs to produce about 70 percent more food by 2050.

Today, the best estimates are that agriculture and some kind of forestry use three-quarters of all the world's vegetated land, and agriculture consumes around 85 percent of the freshwater people withdraw from rivers, lakes or aquifers.[34] Seen in this context of land and water scarcity, the quest for bioenergy at a meaningful scale—even assuming large future increases in efficiency—is both unrealistic and unsustainable.

BIOENERGY VERSUS SOLAR ENERGY

What explains these vast requirements of bioenergy for land? The answer is that growing plants for energy is a highly inefficient way of converting the energy in the sun's rays into a form of non-food energy useable by people. Even growing sugarcane, the world's highest yielding crop, on highly fertile land in the tropics converts only around 0.5 percent of solar radiation into sugar, and only around 0.2 percent ultimately into ethanol.[35] For maize ethanol grown in Iowa, the figures are around 0.3 percent into biomass and 0.15 percent into ethanol (even when fully accounting for the feed byproduct).[36] Cellulosic ethanol is unlikely to do much better. Even highly optimistic predictions for future biomass on good farmland in the United States (24 tons of dry matter per hectare per year and 100 gallons of ethanol per ton of dry matter) imply a conversion efficiency of solar radiation into fast-growing grasses of perhaps 0.7 percent, and into ethanol of 0.35 percent.[37]

Solar photovoltaic (PV) systems provide a good and practical point of comparison. Like bioenergy, PV converts sunlight into energy useable by people and its land use needs are often not trivial.[38] But PV's solar radiation conversion efficiency is far greater than that of biomass. Today, the U.S. Department of Energy assumes that new PV cells for homeowners would convert 16 percent of solar radiation into electricity, and on a net operating basis for a home, we estimate an efficiency of 11 percent.[39] This level of efficiency would generate 55–70 times more useable energy per hectare than biofuels even if the solar PV were located in the parts of Iowa or Brazil that produce maize or sugarcane. This level of efficiency would also produce around 30 times more useable energy per hectare than what might be generated by ethanol production on the single most productive potential spot in the United States for producing cellulosic ethanol in the future.[40] (Comparing solar energy to biomass used for electricity results in even larger benefits for solar energy.[41]) In short, producing energy through PV requires far less land.

Because of various spacing factors, a commercial solar PV power system today would be less efficient at converting incoming solar radiation than solar PV mounted on rooftops, but would still be around 30 times more land efficient than bioenergy even coming from Brazilian sugarcane land or Iowa maize land. A variety of factors could make such solar PV systems substantially more land efficient.[42] Looking to the future, this advantage in land efficiency should also improve the costs of solar PV systems relative to bioenergy (Box 3).

These numbers actually understate the real differences in efficiency for three reasons. First, the cellulosic ethanol figures compare solar PV conversion efficiencies in commercial operation today with ethanol production that assumes large future improvements both in growing grasses or trees and in refining them into ethanol.[43] Although progress in cellulosic ethanol has been slow, increases in solar PV conversion efficiencies have actually been proceeding at a rapid rate, and if and when cellulosic bioenergy achieves the efficiencies we cite, PV land-use efficiencies will very likely have grown as well.

Second, solar cells do not require land with plenty of water and good soils. Because of the increases in global demand for food and timber, highly productive lands are already needed for these uses, not for energy generation. On less fertile land, the efficiency of bioenergy drops greatly, but the efficiency of converting the sun's rays to electricity via solar PV is unchanged. And the overall performance and economics of solar PV would even improve if the less fertile land has more solar radiation per square meter than more fertile lands—for example, the U.S. desert west relative to the U.S. maize belt. Even assuming high future cellulosic yields, PV systems available today would generate more than 100 times the useable energy per hectare over a majority of the United States. Moreover, even with reasonably optimistic assumptions for bioenergy, we calculate that PV systems would produce at least 100 times more useable energy per hectare on three-quarters of the world's land—even excluding permanent ice and the driest deserts.[44]

Third, for at least transportation, shifting to solar implies even greater efficiency gains. Internal combustion engines convert at best around 20 percent of the energy in either fossil fuels or biofuels into motion, while electric engines today convert around 60 percent, a three-fold increase.[45] Today, much of that increased efficiency is lost by the high energy needs for building car batteries. But if battery production can become more energy efficient and batteries longer lasting, a combination of solar energy and electric engines could become 200–300 times more land-use efficient than biofuels.

Box 3 | Is Bioenergy Cheaper than Solar Energy?

According to standard accounting techniques, solar PV systems to produce electricity are moderately more expensive than burning biomass to produce electricity in the United States. For example, according to an analysis by the U.S. Energy Information Administration, the cost of producing electricity from a biomass power plant in 2019 will be US$103 per megawatt hour, while that from a PV system will be US$130.[a] Bioenergy is also potentially more valuable because it can be converted into useable energy at any time, while solar PV power depends on the sun shining.

However, as the ethanol experience shows, diverting biomass to energy generation will greatly drive up the price of biomass because land is a finite resource. Land competition drives up prices not only to the energy consumer but also to all those who consume food or timber products. For example, one study estimated that the production of ethanol from maize in the United States in 2010 used roughly 3.4 percent of global crop calories from the major staple crops (after accounting for ethanol by-products) and caused a 20 percent increase in staple crop prices (even over the medium term).[b] According to the study, this increase cost global consumers roughly US$100 billion per year in higher crop prices, yet U.S. maize ethanol provided only about 0.3 percent of global energy.[c] In general, as increases in demand grow larger, the impact on prices grows disproportionately. Because even modest levels of bioenergy would consume large fractions of the world's crops or timber, the potential price impacts are therefore likely to be very large.

Unlike bioenergy, solar PV faces no serious natural resource limitations on its expansion that would drive up prices.[d] In fact, solar PV power costs have steadily declined and are therefore expected to continue to decline.[e]

Notes:

a. EIA (2014b).

b. Roberts and Schlenker (2013).

c. This calculation is based on estimates by the U.S. Energy Information Administration of roughly 398 exajoules of global delivered energy in 2010, U.S. ethanol production of roughly 13.23 billion gallons in 2010, providing roughly 1.2 EJ.

d. Jacobson and Delucchi (2011) analyze the potential of natural resource constraints to impose significant limits on solar production and find no serious restrictions.

e. Goodrich et al. (2012).

Biomass has one major advantage over solar energy: It can be easily stored and therefore can supply energy regardless of whether the sun is shining. When transformed into biofuels, bioenergy is also energy-dense and can be relatively easily used with existing vehicles. To fully replace fossil fuels, solar energy requires further progress on storage technology, both for full electrical grids and in cars. Although there are exciting advances in storage technology, the full extent to which solar power can contribute to a carbon-free energy future therefore remains uncertain.

However, the uncertainty around the potential scale for storage of solar energy is not a justification for bioenergy today for three reasons. First, in the short term, solar energy has enormous capacity to grow even without improved storage. Solar energy currently provides less than 1 percent of global energy. Even without dramatic improvements in storage technology, it should be quite feasible to increase the share of solar energy to 20 percent of energy or more through careful integration into the grid and with good transmission facilities.[46] By comparison, as shown above, achieving this 20 percent share of global energy through bioenergy would require a doubling of the harvest of existing biomass—which is unrealistic.

Second, many new storage technologies are under development for batteries for vehicles, households, and whole electrical grids.[47] Many alternative storage technologies also show promise, including compressed air and thermal storage. By the time solar energy were to face true storage limitations using today's technology, there is at least good reason for hope that advances in technology would have eased those limitations.

Third, regardless of the limits to expansion of solar PV, the inherent inefficiency of biomass means that it cannot provide a meaningful quantity of energy without large competition for the use of productive land for food, timber, watershed protection, biodiversity, and carbon storage. Solar power's far greater land use efficiency and its ability to use dry and otherwise unproductive land and rooftops make it the only option that could use direct solar radiation to meet a sizeable portion of the world's energy needs.

THE GREENHOUSE GAS IMPLICATIONS OF USING BIOMASS FROM DEDICATED LAND FOR ENERGY

Whether phasing out bioenergy from the dedicated use of land meets our climate criterion for a sustainable food future (Table 1) depends on the greenhouse gas implications of bioenergy use. Bioenergy supporters believe that bioenergy reduces greenhouse gas emissions, so significant impacts of bioenergy on biodiversity and water are to be accepted in the interest of combating climate change. We agree that there are some sources of waste biomass that probably can help reduce greenhouse gas emissions if used as a bioenergy feedstock, but devoting land to produce plants for bioenergy will rarely, if ever, do so—at least without sacrificing food or timber. Large, positive estimates of global bioenergy potential are based on an incorrect belief that biomass, like solar and wind, is inherently a carbon-free source of energy despite the fact that burning biomass emits carbon. That view is based on an accounting error that "double counts" biomass, carbon, or land that is already in use.

The accounting error: double counting biomass

The world's lands are already growing plants every year and these plants are already being used. The most common uses involve the production of food, fiber, and timber, which people directly "consume." Other uses include replenishing or increasing carbon in soils and in vegetation, which together contain four times as much carbon as the atmosphere.[48] Failing to maintain these carbon stocks by adding more carbon from new plant growth as microorganisms consume old plant tissue would increase atmospheric carbon dioxide concentrations and contribute to climate change. Bioenergy cannot supply energy except at the expense of these other valuable uses of plants, unless bioenergy uses or results in some additional source of biomass.

Additional biomass primarily means plants that grow "in addition" to what otherwise would grow. Additional plant growth would occur, for example, by growing bioenergy crops on fields that otherwise would remain fallow. Additional biomass can also mean waste biomass that is captured and used for bioenergy and that otherwise would have decomposed without meeting human needs. Crop residues that farmers would otherwise have burned in the field are an example.

Large estimates of bioenergy's greenhouse gas reduction potential have overlooked this need for additional biomass production and have treated biomass (or land) that is being diverted from other valuable human uses as "available for bioenergy."[49] For example:

- Today's principal biofuels, which use maize or sugarcane, simply divert crops from the food supply into the energy supply. By itself, this does not generate additional biomass and directly comes at the expense of food. (We discuss the indirect effects below.)
- In 2001, the Intergovernmental Panel on Climate Change assumed that bioenergy crops could grow on any unused "potential croplands" without sacrificing their carbon storage, even though those lands consist of forests, woody savannas, and the wetter and more productive grazing lands that store carbon, benefit ecosystems, and—in the last case—already help meet food needs.[50]
- More recent analyses accept the need to protect forests, but have assumed that those tropical woody savannas that are wet enough to produce crops are "carbon free," even though they too store abundant carbon, and provide abundant biodiversity and ecosystem services.[51]
- Many additional bioenergy estimates also count large quantities of grazing lands as "carbon free," ignoring the fact that they produce forage for livestock or ignoring the enormous growth in meat and dairy demand that these grazing lands will be needed to help meet.[52]
- Some analyses assume that people can harvest trees as "carbon-free" sources of energy so long as they only harvest the annual growth of that forest. The thinking is that as long as the forest's carbon stock remains stable, the harvest for bioenergy has not added carbon dioxide to the atmosphere. But this theory ignores the fact that any forest that has such annual growth already would have added biomass and have stored additional carbon if it had not been harvested for bioenergy.[53] The loss of one ton of such a carbon dioxide "sink" has the same effect on the atmosphere as a one-ton increase in carbon dioxide emissions to the atmosphere. Overall, despite the loss of forests in the tropics, the world's forests are accumulating carbon and providing a large carbon sink, which holds down climate change and is critical to future strategies to reduce climate change. In general, harvesting forests for energy reduces the quantity of carbon that forests store more than it displaces emissions of carbon from fossil fuels (at least for decades).[54]

All of these estimates are a form of "double counting" because they rely on biomass or the land to grow that biomass that is already being used for some other purpose. Because bioenergy analyses assume these other purposes continue to be met, they are in effect counting the biomass and land again. Although there might be some ways to add to some land's functions for bioenergy, such as by planting winter cover crops during fallow seasons on some cropland, in general the same biomass or tract of land cannot serve two purposes at the same time.

This double counting of biomass also double counts carbon and therefore erroneously accounts for greenhouse gas effects. Bioenergy is a means of replacing fossil carbon—and the energy it stores in its chemical bonds—with biomass carbon and its chemical energy. But unless bioenergy uses additional biomass, the carbon it uses just comes at the expense of carbon storage or some other human use of biomass. All of the above examples of double counting biomass are therefore also double counting carbon. Appendix A discusses these double counting errors in more depth.

Understanding the accounting error by tracing flows of carbon

One additional way to understand the accounting error is by tracing the flow of carbon to and from the atmosphere. This is because bioenergy could only mitigate climate change if it either reduced the flow of carbon to the atmosphere or increased the flow of carbon from the atmosphere to the earth. Unfortunately, burning biomass, whether wood or ethanol, emits carbon in the form of carbon dioxide just like burning fossil fuels. (In fact, because biomass chemical bonds contain more carbon for each unit of energy than fossil fuels, bioenergy must emit at least a little more carbon dioxide than fossil fuels for the same amount of energy.) Because the vehicle or power plant still emits at least as much carbon dioxide, bioenergy can only lead to reductions of carbon dioxide in the air if somewhere else either more carbon dioxide is absorbed from the atmosphere or less carbon dioxide is emitted.

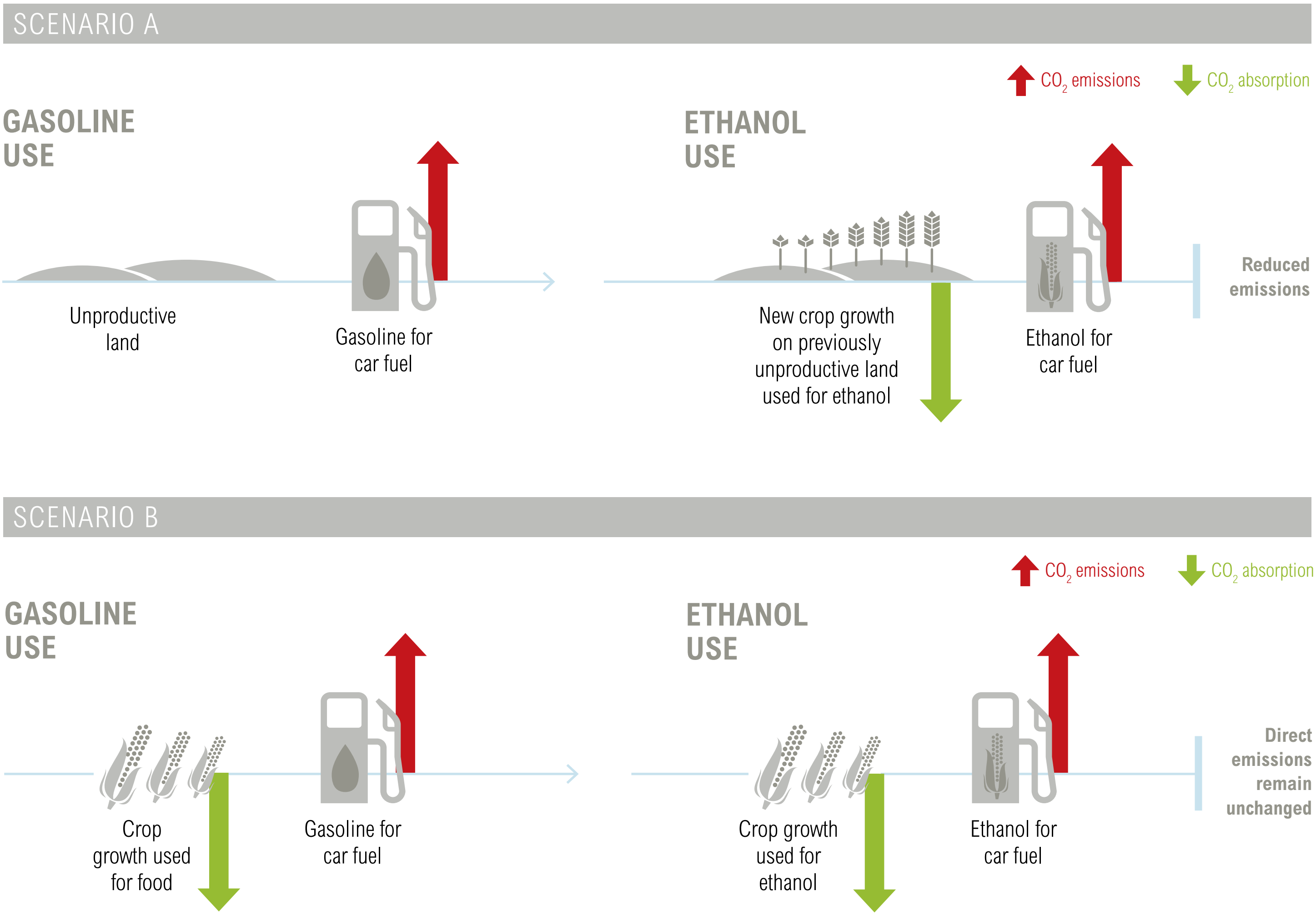
Most calculations that claim bioenergy reduces carbon dioxide emissions relative to burning fossil fuels do not count this carbon dioxide released when the biomass is burned.[55] They do so on the theory that the carbon dioxide emitted is matched and implicitly offset by the carbon dioxide absorbed by the plants producing the biomass. (Although bioenergy is not typically called an "offset," that is the physical theory and the only physical mechanism by which bioenergy can reduce carbon dioxide in the atmosphere.) But if those plants were going to grow anyway, just diverting them to bioenergy does not absorb any more carbon dioxide from the atmosphere. For example, diverting maize that farmers would grow anyway to biofuels does not absorb any additional carbon dioxide to offset the carbon dioxide emitted when the ethanol is burned. Only additional biomass, which means either additional plant growth or reduced waste, provides a valid offset. Figure 5 illustrates scenarios where bioenergy can lead to net greenhouse gas emission reductions and where it does not. Appendix B provides more illustrations that show proper accounting of greenhouse gas emissions associated with bioenergy.

The principle of "additionality" here is the same as for a regulatory offset. In regulatory systems, power plants are sometimes allowed to offset their emissions from burning coal by planting a new forest elsewhere on the theory that the carbon absorbed and stored by the additional trees offsets the carbon released from the coal. But a power plant cannot claim an offset by pointing to a forest that would grow anyway. Only *additional* forest growth counts for a forest-planting offset; the same principle is true for bioenergy. In effect, a forest-planting offset uses the additional plant growth to store more carbon in trees to offset fossil-based energy emissions, while bioenergy uses the additional plant growth to replace fossil fuels and leave more carbon underground. The concept of "additional" is the key to both forms of offsets.

Although increasing plant growth can lead to genuine greenhouse gas emissions reductions from bioenergy, it does not help just to replace crops, or even pasture, with faster growing grasses or trees. Although energy crops may generate more biomass per hectare than food and forage crops, land somewhere still needs to be devoted to growing food and forage crops if the world wants to continue to eat. Growing these food and forage crops elsewhere displaces that other land's existing ecosystem and thus its existing carbon storage or ability to sequester new carbon. For bioenergy to reduce greenhouse gas emissions not at the expense of food or forest products, it must lead to increased plant production in total over the entire landscape. This implies increased crop, pasture, or timber yields in response to the pursuit of bioenergy.[56]

The principle of additionality does not rule out retirement of agricultural land. There are situations where use of land for agricultural purposes is probably squandering its productive capacity, and planting trees on the land to store carbon makes more sense. Badly managed, steep

Figure 5 | **Why Greenhouse Gas Reductions from Bioenergy Require Additional Biomass**



These illustrations show the flows of carbon dioxide with fossil energy use on the left and bioenergy use on the right. Scenario A shows a theoretical way of producing bioenergy to reduce greenhouse gas emissions by growing bioenergy crops on unproductive land. The greenhouse gas emissions reduction results from the new (additional) plant growth.

Scenario B, in contrast, shows the typical bioenergy scenario. Here, demand for bioenergy merely diverts plant growth (e.g., maize) that would have occurred anyway and therefore does not directly reduce greenhouse gas emissions.

Appendix B provides additional scenarios and also shows the accounting for the potential indirect effects of diverting crops, such as reduced crop production, increased crop yields, or conversion of forests into croplands.

pastures in the Atlantic rainforest region of Brazil provide an excellent example because their existing and potential food production is small while their potential to sequester carbon is vast. Yet lands like these with steep slopes are also hard to cultivate for bioenergy crops, which is why reforestation would be their best use.

Not all analyses of biofuels explicitly double count. The interest in algal biofuels is based on the belief that they can substantially increase total biomass production while avoiding fertile land. Moreover, some modeling analyses discussed below claim additional carbon storage due to increased crop and pasture yields in response to rising crop prices, which in turn were triggered by biofuel demand. We discuss the potential of algae and the claims of such modeling analyses below. But all of the large estimates of bioenergy potential discussed above count biomass and carbon twice.

Box 4 | The Legal Origins of the Bioenergy Greenhouse Gas Accounting Error in the Kyoto Protocol's Accounting Rules

Under the United Nations Framework Convention on Climate Change, countries report their national emissions from using energy in one account and from cutting down trees or making other land use changes in another account. That means that if trees are cut down or other land use change occurs to make bioenergy, the carbon released during the process is counted. But the scientists who encouraged this system recognized that it had the potential to count emissions from bioenergy twice. If the carbon in a tree is counted as an emission in the land use account as soon as the tree is cut, counting that same carbon in the energy account when it is burned for electricity would count it again. To prevent this form of double counting, scientists suggested that such carbon should only be counted in the land use account. In national accounts, therefore, governments can ignore the carbon emitted from power plants when burning biomass, but only because governments must count that carbon in the land use account. Far from implying that biomass is free of carbon emissions, this approach means that this carbon must be counted and in fact is counted in national reporting.

For example, if the United States cuts down trees and uses them to replace coal in power plants, it reports fewer emissions from coal but more from cutting down trees. This system also works globally. If trees are cut in the United States and burned in Europe, the carbon from the trees is counted in the United States and therefore is reflected in a global account, even though the real emissions occur in Europe. Similarly, if the United States diverts crops to biofuels, and the crops are replaced by converting land somewhere else in the world to crop production, those land use change emissions are counted somewhere.

The error occurs when applying these principles to accounting only in the energy sector, such as the emissions from smokestacks and exhaust pipes. When governments are evaluating whether shifting a power plant from coal to wood would reduce carbon emissions, the principle implies that they can only ignore the carbon released by burning wood if they count the reductions in carbon in the forest. For the same reason, they can only ignore the carbon released by burning ethanol if they count the carbon from all the land use change that occurs due to producing that ethanol. Unfortunately, when governments adopted rules for the Kyoto Protocol, which established a cap on total national energy emissions, they erred by allowing biomass carbon to be ignored from the energy account *without requiring* that it be counted in the land use account.

As long as the cap did not apply globally to both energy and land use emissions, governments should have changed the accounting rule. As a result, any forest could in theory be clear-cut (and even never allowed to regrow) with the wood used to replace coal in Europe, and European governments would count that as a 100 percent greenhouse gas reduction compared to burning coal. Governments and researchers made the same error in many policies and scientific papers regarding bioenergy.

Although this error followed from the misinterpretation of a rule designed to avoid double counting, the error has become a form of double counting. It leads governments and researchers to count as greenhouse gas emissions reductions the mere diversion of biomass or land to energy in situations when that biomass is already being used for food, timber, or carbon storage, or the land is already being used to produce these other benefits. As explored further in Appendix A, this kind of double counting is the basis for all large estimates of bioenergy potential.

For more on this accounting error, see Searchinger (2009).

The sources of the accounting error

How did the idea develop that biomass is inherently carbon-free? Box 4 explains the legal origins, which arose from a misapplication of international scientific guidance and turned rules designed to avoid double counting carbon dioxide emissions from biomass into rules that did not count biomass emissions at all. But the idea also arose from a common intuition that anything renewable is carbon-free. That idea is based on thinking like the following: "If the world uses plant growth for energy and the plants grow again, it cannot cost the world any carbon."

The analogy of a monthly paycheck illustrates the error in this thinking. Like annual plant growth, a paycheck is renewable in that a new check should come every month. But just because the money is "renewable" does not mean it is free for the taking for alternative uses. People cannot spend their paycheck on something new like more leisure travel or energy without sacrificing something they are already buying, like food and rent, or without adding less of that money to their savings. To afford more leisure travel or energy without sacrificing other benefits, people need a bigger paycheck or they must cut some source of wasteful spending.

Analogously, people use annual plant growth and the carbon it absorbs for food and forest products, and they leave some of the carbon to be stored in vegetation and soils, thereby limiting climate change. That annual plant growth and carbon is not free for the taking by bioenergy. The cost of using the carbon in plants to replace the carbon in fossil fuels is not using that carbon to eat, to build a house, or to replenish or increase the carbon in vegetation and soils. To be richer in carbon, one cannot merely divert plants from one use to another; one needs more plant growth or elimination of some plant waste. In other words, one needs "additional biomass."

Modeling studies

Nearly all studies of bioenergy potential, even those that project large potential, accept that demand for cropland needed for food is likely to grow and therefore exclude existing cropland from the category of potential land for bioenergy (see Appendix A). Yet present biofuel policies not only allow but also encourage biofuels to use crops from existing croplands. In doing so, they can find some support from a few modeling studies. In fact, most modeling studies analyzing the greenhouse gas implications of using crops for biofuels find little or no emissions reductions so long as they estimate the conversion of forests and grasslands to replace the forgone food production. But some studies find potential greenhouse gas emissions reductions of 50 percent or more for biofuels from some crops.[57] Given the broad consensus among studies of bioenergy potential that existing cropland is unavailable, what explains these more favorable modeling results? Do the merits of biofuels depend on which model is correct?

The complexity of these models is intimidating, but they estimate three responses that could produce greenhouse gas benefits. Although the level of each response can be debated, the more important point is that none of the outcomes modeled is ultimately socially or environmentally desirable.

First, some models estimate that much of the food crops diverted to biofuels are not replaced. That means people do not have to clear more land to replace the forgone food crops. More directly, when people eat crops, they release that carbon, mostly through respiration (and a little through their wastes). If crops are not replaced, then people or livestock eat fewer crops and breathe out less carbon dioxide. Economic models used by the European Commission and the state of California have estimated that from a quarter to a half of the food calories (and therefore roughly that much carbon) diverted to biofuels is not replaced, and these reductions play a critical role in their findings that biofuels can generate small greenhouse gas emissions savings.[58]

Unlike taxes imposed on high-carbon foods such as beef or on overconsumption of food by the wealthy, biofuels increase wholesale crop prices for basic commodities and for the rich and the poor alike. Biofuels therefore are most likely to reduce both the quantity and quality of food consumption by the poor, who have less capacity to absorb the higher costs.[59] Even if these models are correct, such a strategy to reduce greenhouse gas emissions by reducing food consumption of the poor does not contribute to a sustainable food future.

Second, some models estimate that farmers replace crops or cropland diverted to biofuels largely or primarily by increasing their crop or pasture yields on existing agricultural land.[60] These yield gains avoid clearing more land to replace the food production area lost to biofuels. The theory is that because these diversions increase crop prices, farmers have more incentive to add fertilizer or otherwise improve management on existing agricultural land. Some yield response is possible, but the evidence is weak because global yield growth has shown remarkably consistent trends that fluctuate little or not at all in response to annual changes in price.[61] Unless yield gains rather than expansion of cropland replace nearly all the crops diverted to biofuels, the greenhouse gas reductions from biofuels relative to gasoline and diesel would at best be modest because the emissions from clearing more land would negate them.[62]

Perhaps more importantly, for biofuels grown on cropland or pasture to make even a modest contribution to energy supplies by 2050 without sacrificing food production or clearing more land, farmers would have to increase crop or pasture yields overall far more than they already need to do just to meet rapidly rising food demands on the same agricultural footprint. Precisely because that seems highly unlikely, most global biofuel potential studies exclude existing cropland. As our *Interim Findings* calculated, meeting FAO's projections for food demand in 2050 without expanding harvested crop area would already require that global average crop yield growth per hectare per year expand roughly one-third more between 2006 and 2050 than it expanded over the previous 44 years. Relying on yield gains in excess of these levels would be reckless: there is no convincing economic evidence to demonstrate farmers will in fact achieve such levels of yield gains over the next several decades. Farmers have never before faced such rapidly rising demands nor the kinds of physical constraints the world now faces, such as climate change and limitations on expanding irrigation (Box 5).[63]

Box 5 | Are Concerns About Bioenergy Based on Inappropriately Pessimistic "Malthusian" Concerns About Food Production?

Since Thomas Malthus, many thinkers have periodically warned that food production will reach its limits and that the world will face massive starvation. History has proven them wrong. Some supporters of bioenergy believe that concerns about bioenergy are based on these "Malthusian" concerns and similarly underestimate human capacity for innovation. Bioenergy supporters sometimes point to various studies showing technical capacities to increase crop yields greatly if all "yield gaps" were eliminated. But these perspectives miss several key distinctions:

- The challenge is not merely feeding the world, but doing so while conserving natural areas, preserving their carbon, and otherwise protecting natural resources. From 1961–2006, despite the Green Revolution and stunning gains in yield and livestock productivity that managed to more or less feed the world, agricultural production still cleared nearly 500 million hectares of land. Increasing agricultural production also came at high environmental costs from fertilizer and pesticide use, diversion of water from rivers and lakes, and drainage of wetlands. As food growth needs in the next comparable period are even larger, the challenge of both feeding the world and also avoiding these environmental impacts is much larger. This series of working papers explores a menu of solutions to this challenge: If the challenge can be met, sustainable ways of holding down that growth in demand are likely to be necessary.[a]

- Estimates of technical potential have only so much significance. For example, estimates of the technical potential of wind energy, even restricted to areas of high wind speed, are more than 100 times total human energy demand—and the technical capacity of solar PV is even greater.[b] Yet in few human endeavors is technical capacity the critical limitation, and that includes bioenergy and agriculture.

- Even if agricultural productivity or other strategies could free up agricultural land for other uses, that does not mean that bioenergy is the land's best use. Left to its own devices, abandoned agricultural land nearly always regrows into forests or grasslands, which themselves absorb carbon and thereby reduce atmospheric greenhouse gas concentrations. (They also provide watershed protection and biodiversity conservation, among other benefits.) Bioenergy only helps to reduce greenhouse gas emissions if and to the extent its displacement of fossil fuels saves more carbon than these lands would otherwise sequester. Allowing lands to reforest is likely to provide greater benefits for decades, and even where bioenergy might provide net benefits, those benefits would be small.[c] Alternative strategies for displacing fossil fuels, such as solar PV and wind, would both reduce fossil fuel use and permit these lands to sequester carbon and provide habitat, providing a double benefit.

- Finally, if land were to become available for energy, solar PV or other forms of solar energy on that land would produce far more energy per hectare. The "not merely optimistic" but "technically efficient" future is to use these energy sources on less fertile land, and to save the fertile land for growing food, producing timber and pulp, and storing carbon.

Notes:
a. Searchinger et al. (2013).
b. Jacobson and Delucchi (2011).
c. Righelato and Spracken (2007).

Third, some models can find greenhouse gas emissions reductions because, in various ways, they claim that much of the land that will ultimately be pressed into production is "degraded" in the sense that it has little carbon cost. In effect, the models claim that the market will select land that studies on bioenergy potential find hard to locate. Some models, for example, assume that farmers will expand food production primarily by using idle land or by reclaiming abandoned agricultural land, which the modelers assume would not otherwise substantially regrow forest or grass and sequester much carbon.[64] Neither assumption has direct evidentiary support, and neither makes economic or physiological sense.[65] In another example, some modelers claim that oil palm for biofuels in Indonesia expands primarily onto already deforested land, which the modelers assume will neither reforest nor be used to meet expanding agricultural demands.[66] Again, although there is evidence that much oil palm expansion does follow deforestation, that scenario relies heavily on unsupported assumptions that all cutover forest would never reforest nor produce food or other valuable benefits. Regardless, as discussed above, to the extent potentially productive yet currently low-carbon degraded lands do exist, they are already needed to meet expanding food demands (including oil palm for food products) without clearing other lands.

To summarize, there is broad acceptance in global bioenergy studies and other assessments that biofuels cannot sustainably use existing croplands because those croplands will be needed to meet food needs. Yet modeling analyses that result in favorable estimates of greenhouse gas impacts of biofuels implicitly project that biofuels can use existing cropland because (a) some of the crops for biofuels come out of the crops currently available for people; (b) some of the crops for biofuels come from land that is "freed up" by yield gains in crops or pasture on existing agricultural land; or (c) some crops for biofuels come from the use of marginal land. But the vast majority of global projections for 2050, including this working paper series, agree that both existing food production *and* the potential to increase food production on existing agricultural and marginal lands are already needed to meet the food needs of the world's growing population in a sustainable manner. Because studies that evaluate the net effect of directly converting forests, woody savannas, or grasslands to biofuels also find little or no emissions reductions for decades,[67] they concur that no significant amount of land could be beneficially dedicated to bioenergy.

WHAT "ADDITIONAL" SOURCES OF BIOMASS ARE AVAILABLE?

To reduce greenhouse gas emissions without reducing the production of crops, timber, and grasses that people already use, bioenergy must come from a feedstock that either would be wasted or is grown in excess of what would have grown absent the demand for bioenergy. In addition, to meet our other sustainability criteria (Table 1), bioenergy must not trigger conversion of natural ecosystems (which would also rarely, if ever, pass the "additional" biomass and carbon test for greenhouse gas emissions reductions). Forms of waste or residue that might meet these criteria under certain conditions include:

- Crop and forest residues left behind after harvest;
- Municipal solid waste and urban wood waste;
- Unused manure;
- Timber processing wastes including sawdust and black liquor—an organic waste from paper production; and
- Methane from the decomposition of organic matter in landfills.

Estimates of the technical potential to produce energy from these wastes vary. Some are as high as 125 EJ per year, which would be enough to generate almost 25 percent of global primary energy demand today and 14 percent in 2050.[68] Unfortunately, these high estimates rely heavily on crop residues in unrealistic ways. They start by ignoring the existing heavy use of such residues for livestock feed and bedding.[69] After accounting for residues that are already harvested for animal feed or other purposes, the best estimate is that harvesting half of the remainder could generate roughly 14 percent of present world transportation fuel, or almost 3 percent of today's delivered energy.[70] But even that estimate does not take into account the need for most crop residues to replenish soils. This need is particularly great in parts of the world such as Africa where soil fertility is low.[71] Even in high yielding locations that produce huge quantities of residues, such as maize production in Nebraska, a recent paper suggests that the loss of soil carbon from harvesting residues for ethanol cancels out the benefit from replacing fossil fuels for at least a decade.[72]

This "technical potential" also unrealistically assumes that biofuel producers would harvest half of the crop residues from every crop and every field in the world. But the economics of harvesting and hauling such a bulky, non-energy-dense source of biomass would probably restrict the harvest to limited areas with highly concentrated, highly productive crops that have large quantities of residues. Therefore, crop residues overall are likely to be only a limited source of sustainable "low carbon" biomass for modern bioenergy.

Turning to wood residues, Sweden provides an example of potential beneficial sources of forest waste. Its commercial forestry industry generates large quantities of residues that would otherwise decompose. Relying overwhelmingly on this "additional" biomass because it would otherwise decompose quite quickly,[73] Sweden generates roughly one third of its energy from bioenergy.[74] But Sweden serves as a special case. It has a small population, a large forestry sector, and a large need for energy for heating, which is the most efficient use of biomass. We estimate global forest residues of roughly 10 EJ per year assuming that all could be collected.[75] At least some of these residues should be left to maintain soil fertility.

Studies sometimes group with forest residues other wood wastes including sawdust, wood processing waste, and post-consumer waste wood. Adding these sources brings wood residues and wastes to a total of 19–35 EJ per year according to one review,[76] although much of the processing wastes are already used for bioenergy. Municipal solid waste might add roughly another 10 EJ per year.[77] In the real world, only some of this material could realistically and economically be collected and used, so the practical potential to use this material is uncertain.

What potential exists to grow biomass in excess of what would have grown absent the demand for bioenergy? One possible source would be cover crops that are planted after harvest of the main crop in order to reduce soil erosion and help replenish soil fertility. In the United States, for example, some farmers plant rye or a legume to plow into the soil to add nitrogen, while others use cover crops to reduce weeds, minimize erosion, or break up compacted soil layers. These practices are rare, however. The potential to harvest cover crops for bioenergy, instead of adding them to their soils, might encourage more cover cropping, but their economic viability has yet to be proven.

Algae are sometimes viewed as a bioenergy feedstock that does not compete with fertile land and is therefore "additional" and "sustainable." Algae are potentially capable of far faster growth rates than land-based plants and some algae have higher oil production, too. Algae fall into two categories: microalgae, which float loosely in the water and have high protein content, and macroalgae, which are essentially seaweeds. Seaweeds currently must be grown in nearshore waters, which are increasingly supporting other uses such as fish farming. Although some papers have urged greater focus on seaweeds, even if all the world's cultivated brown seaweeds were presently used for energy, they would supply at most 0.06 percent of just the United Kingdom's energy needs.[78] There is a lot of ocean, however, and if there is some way to tap the broader ocean, seaweeds might become an energy source that does not compete with land, although their uses for food and animal feed would be valuable alternatives.

Microalgae, although a focus of much interest, face even larger limitations in providing a natural resource advantage. As a recent U.S. National Research Council report concluded, using microalgae to meet just 5 percent of U.S. transportation fuel demand "would place unsustainable demands on energy, water, and nutrients with current technologies and knowledge."[79] In addition to many technological obstacles that need to be overcome to bring costs down, water requirements are likely to be large. One estimate found that twice the present use of U.S. irrigation water would be needed to produce enough biofuel from microalgae to supply 28 percent of present U.S. oil consumption for transportation.[80]

Even if other problems were resolved, land requirements for algae ponds are likely to remain formidable. One recent optimistic estimate concluded that "only" 49 percent of total U.S. nonarable land would be needed to replace 30 percent of U.S. oil demand with algae, even assuming no water, nutrient, or carbon dioxide constraints.[81] This is not an encouraging figure. And most technologies assume extra injections of carbon dioxide to maintain high rates of algal growth, which would typically require a neighboring fossil-fuel power plant to supply the carbon dioxide. Because such algae production only works if coupled with the use of fossil fuels and because that carbon dioxide is eventually released when the algae are burned, the maximum reduction of total greenhouse gas emissions per unit of biofuel would only be around 50 percent.[82] Another issue with the use of algae for bioenergy is that it fails to take advantage of the high protein content of many algae or the special properties of algal fats. Although technological breakthroughs might change the prognosis, algal production holds larger potential to produce fish oil substitutes and high protein animal feeds, which take advantage of these properties of algae.[83]

Although these limitations constrain algae's potential to be a large source of biofuels, much of the limitation is cost. If produced in the desert with closed-loop systems or in saline ponds, as some entrepreneurs are pursuing, algae would be able to produce biofuels without competing with carbon storage or food, but at a cost. They might therefore eventually contribute to the supply of low-carbon aviation fuels, but are not likely to be cheap. They are therefore possible energy strategies for the future rather than strategies to pursue at scale today.

An entirely different category of modern bioenergy would be fast-growing trees, agroforestry products, or possibly some oil-bearing crops to supply or replace traditional fuel wood. Global studies nearly all claim that traditional uses of wood and crop residues for cooking and charcoal provide about 10 percent of global energy use (although the original basis for this estimate is hard to find, and it conflicts with FAO fuel wood figures).[84] Whatever the real number, traditional fuel wood use is substantial, and this harvest of trees for firewood or charcoal is a major source of forest degradation in some parts of the world.[85] This traditional use of firewood and charcoal is also highly inefficient. Shifting away from all wood sources of fuel would be desirable in most places from a purely environmental perspective. But such a dramatic shift is not going to happen soon in the many poorer parts of the world that rely heavily on firewood or charcoal. In the meantime, replacing inefficient traditional fuel wood with biomass that is grown, processed, and burned more efficiently would provide net environmental benefits. Such bioenergy production would make dedicated use of land, but not in excess of that which exists today and is likely to continue to exist in many fuel-wood-dependent societies.

Table 3 segregates biomass feedstocks that require the dedicated use of land (and thus are not advisable) from feedstocks that are potentially beneficial to climate. Some of the feedstocks in the right-hand column of Table 3 have the potential to meet a modest part of human energy demands, but expectations for potential should be limited. Box 6 profiles Brazilian sugarcane ethanol.

Table 3 | **Advisable and Unadvisable Sources of Biomass for Energy Use**

FEEDSTOCKS THAT REQUIRE DEDICATED USE OF LAND (UNADVISABLE)	FEEDSTOCKS THAT DO NOT MAKE DEDICATED USE OF LAND (ADVISABLE)
■ Food crops ■ Fast-growing trees or grasses purposely grown on land dedicated to bioenergy ■ Harvests of standing wood from existing forests	■ Some forest slash left behind after harvest ■ Black liquor from paper making ■ Unused sawdust ■ Municipal organic waste ■ Landfill methane ■ Urban wood waste ■ Crop residues that are otherwise not used, are not needed to replenish soil fertility, do not add substantial carbon to the soil, or the soil functions of which are replaced by additional cover crops ■ Cover crops that would not otherwise be grown ■ Unused manure ■ Wood from agroforestry systems that also boost crop or pasture production ■ Intercropped grasses or shrubs for bioenergy between trees in timber plantations in ways that maintain timber yields ■ Tree growth or bioenergy crop production that has higher yields and is more efficiently burned than traditional fuel wood and charcoal (and that replaces these traditional fuels in societies that continue to rely on them)

Box 6 | Sugarcane Ethanol in Brazil

Should Brazilian sugarcane ethanol be an exception to the recommendation to avoid bioenergy that makes dedicated use of land? Sugarcane is a high-yielding, perennial crop with relatively modest nitrogen use. Its byproducts are burned to generate the energy to ferment the sugars and often generate excess electricity. Even so, if sugarcane for ethanol directly converts Cerrado or Amazonian forest, it will likely release enough carbon to cancel out all or much of its greenhouse gas benefits for many years.[a] The case for sugarcane ethanol rests largely on the observation that Brazil has already deforested about 175 million hectares for pasture, and that most sugarcane expansion results primarily in the conversion of this pasture, yielding quick carbon payback periods.

If that ended the story, sugarcane ethanol could be considered an unqualified carbon success. However, in at least some years, roughly one-third of sugarcane expansion has displaced other crops, and those crops must in turn be replaced.[b]

In addition, the big question is whether the conversion of pasturelands to sugarcane encourages new conversion of forest land elsewhere to pasture, whether in the Cerrado, the Amazon, or in another country. On the one hand, Brazil's total net pasture area has not been increasing while its beef production has been rising, which suggests that intensification is providing the growth in production.[c] Since 2005, Brazil has also greatly reduced deforestation in the Amazon by enforcing many long-standing environmental laws. And Brazil has enormous capacity to boost beef production further without more pastureland expansion.[d]

On the other hand, Brazilian pastureland has still been expanding on a gross basis into both the Amazon and the Cerrado. This expansion is just offset, according to the data, by the abandonment of pasturelands elsewhere, presumably because they have become too degraded for use. That gross expansion should, at least according to economic theory, still respond to the price of meat and therefore to displacement of meat production on pasture by sugarcane. There are competing studies using very different methods, each with strengths and weaknesses, about whether expansion of crops into Brazilian pastures is spurring clearing of forest to replace the pasture.[d, e, f] Displacement of Brazilian pasture could also contribute to the pasture expansion that continues to occur in other countries, such as in Paraguay's Chaco Forest. In addition, diversion of sugar to ethanol does not require that Brazil alone supply the new sugar fields planted to replace sugar in the human food supply chain. For example, high sugar prices have been encouraging efforts to convert carbon-rich, highly sensitive ecosystems in Africa to sugarcane.[g]

Although immediate greenhouse gas consequences of sugarcane ethanol are therefore hard to pin down, opportunity costs still explain why even these biofuels should not be a part of a sustainable food future. Put simply, the favorable prospects for intensifying pasture and crop yields in general in Brazil do not alter the tight global land budget to meet food and timber needs. In fact, the potential to increase pasture and crop yields in Brazil increases the opportunity cost of devoting them to biofuels.

Because of natural endowments, its investment in agricultural research, and the massive clearing of land in past decades, Brazil is now in a unique position to help the world close the 70 percent crop calorie gap and 80 percent gap in meat and milk output from pasture without clearing more land. For instance, Brazil now accounts for around 15 percent of global beef production. Even if Brazil doubles its beef production on existing grazing land without reducing pastureland area, that by itself would increase global beef production by only 15 percent and meet around one-fifth of the increased global demand for beef by 2050.[h] Increasing production from pasture in other countries without clearing more land will be more difficult. It would therefore be more socially and environmentally valuable for Brazil to contribute *more* than one-fifth of the additional beef needed than to divert potentially productive grazing land to bioenergy.

In addition, if Brazil diverts pastureland to biofuels, it may not even contribute 15 percent more beef to the world. If productivity on one hectare is doubled, but a comparable hectare is turned into ethanol, overall beef production remains the same.

On a global basis, pastureland only becomes available for non-grazing use at the point that the global need for intensification is exceeded, and the best estimate of that intensification need by 2050 is 80 percent—already a significant challenge. Even if pastureland area can be globally reduced, any spared land that could be used for sugarcane could also be used to produce food crops. Bioenergy remains an inefficient way to turn solar radiation into energy, even in Brazil. Brazil is in a unique position to help feed the world, and from a global perspective, that is the optimal use of its enormous natural and human agricultural resources.

Notes:

a. Fargione et al. (2008) found a 17-year payback period for Cerrado and a 100-year payback period for conversion of Amazonian forest. Payback periods are the length of time it takes for the greenhouse gas emissions saved by replacing fossil fuels with biofuels to start exceeding the emissions released from converting a tract of land into that biofuel production.
b. Pacca and Moreira (2009).
c. Lapola et al. (2013).
d. Lapola et al. (2010).
e. Arima et al. (2011).
f. Nasser (2010).
g. Royal Society for the Protection of Birds (2014).
h. Searchinger et al. (2013).

RECOMMENDATIONS

Using land to produce bioenergy is likely to compete with food production and carbon storage. This competition makes feeding the planet more difficult, likely triggers conversion of natural landscapes, and increases greenhouse gas emissions. We therefore recommend phasing out the dedicated use of land to generate bioenergy, including biofuels, while reserving some efforts to generate bioenergy from true wastes. Doing so will require changes in several types of policies:

- **MANDATES AND SUBSIDIES.** Biofuels have expanded in part due to mandates that a nation's or region's transportation fuel supply incorporate a target share of biofuels, as summarized in Table 2.[86] Governments have supported these mandates or targets with a range of tax credits and other financial support not only for biofuels themselves, but also for the construction of biofuel production facilities.[87] Countries and regions that already have such policies in place should phase out these mandated targets and financial support packages. Countries and regions that are contemplating such policies should refrain from establishing them.

- **LOW-CARBON FUEL STANDARDS.** Countries should also phase out low-carbon fuel standards or at least make ineligible the use of biofuels grown on land dedicated to biofuel production. These laws—in California, British Columbia, and the European Union—require that the carbon-intensity of all the transportation fuels sold by a company decline by a small percentage relative to gasoline and diesel, typically by 10 percent.[88] Proponents originally hoped that these laws would provide incentives to incorporate environmentally preferable biofuels, particularly those from cellulose, at a time when thinking about the greenhouse gas consequences of biofuels ignored land use implications. California regulators then recognized the importance of land use and made efforts to incorporate emissions from land use change into their analyses of crop-based biofuels. But like other efforts to do so, California's analysis incorporated the forms of double counting discussed above. In particular, the state credited biofuels for the greenhouse gas reductions that its model estimated would result from reduced food consumption.

  The ability of low-carbon fuel standards to drive the desirable transformation in transportation fuel sources is debatable. Today, fuel-shifting even to electricity provides only modest greenhouse gas benefits and is therefore an expensive mechanism for achieving immediate emissions reductions because that electricity generation still relies heavily on fossil fuels. The major reason to promote fuel-switching is not to reduce emissions today but instead to reduce emissions in the future when electric or possibly hydrogen fuel-cell cars will be combined with electricity or hydrogen fuel made from solar, wind, or other low-carbon energy sources. Such a shift will require technology-forcing strategies, not immediate "performance standards." In addition, low-carbon fuel standards apply to gasoline and diesel wholesalers, so they cannot meaningfully motivate the manufacturers, electric utilities, and consumers whose actions are most necessary for big fuel shifts. In fact, tax credits—rather than a low-carbon fuel standard—are responsible today for helping to encourage purchases of electric cars in California.

  Governments should either switch from low-carbon fuel standards to other measures of encouraging purchases of electric or hydrogen cars, or at a minimum they should disqualify biofuels grown on dedicated land from contributing to low-carbon fuel standards.

- **RENEWABLE ENERGY STANDARDS.** As adopted by the European Union and many U.S. states, renewable energy standards require or encourage electric utilities—and in the case of Europe, whole energy sectors—to obtain a minimum share of their annual power from renewable resources.[89] That is a good strategy for encouraging solar and wind power generation, but most standards also treat the burning of wood as a qualifying source of renewable energy. The result has been rising harvests of trees for electricity and the construction of large facilities in the United States and Canada for manufacturing and shipping wood pellets to Europe.[90] As many papers have now shown, burning whole trees or wood pellets increases greenhouse gas emissions for decades.[91] These standards also threaten to create a significant increase in the global harvest and degradation of forests for relatively little energy impact; doubling the world's tree harvest and using that additional harvest for energy would at most supply around 5–6 percent of global energy today and less in the future.[92]

One solution would be to exclude whole trees from the list of eligible resources. Another solution would be to qualify the eligibility of wood with proper greenhouse gas accounting. Massachussetts, for example, requires proper accounting of the greenhouse gas consequences of harvesting whole trees and, based on that, requires biomass to result in a minimum level of greenhouse gas emissions reductions compared to the use of fossil fuels. As a result, for wood-based feedstocks, the Massachussetts renewable energy standard provides incentives only for forest residues.[93] This approach leaves electric power plants free to use forest residues—although the potential scale of such residues is small.

- **REFORMED ACCOUNTING OF BIOENERGY.** As discussed more in Appendix A, flawed greenhouse gas emissions accounting provides another spur for bioenergy.[94] The Kyoto Protocol sets limits on greenhouse gas emissions by the countries that have agreed to it, but it incorporates the accounting error of ignoring all carbon dioxide emitted by burning biomass. The implications of this error are large. Taking an extreme example to illustrate, European countries could turn the Amazon basin into a parking lot, use the felled wood to replace coal, and count these actions as a 100 percent reduction in greenhouse gas emissions compared to burning that coal. Europe incorporated the same erroneous accounting into its emissions trading system for power plants and large industries. This accounting error should be fixed, both in any successor to the Kyoto Protocol and in the various policies and programs to limit greenhouse gas emissions established by individual countries.

- **BLEND WALL LIMITATIONS.** All of these changes would go a long way, but they may not go far enough. A number of studies have found that maize ethanol has now become a cost-effective replacement for gasoline when oil prices are high and maize prices are low.[95] Although studies disagree on the precise level, estimates are that oil prices of US$100/barrel make ethanol competitive until maize prices reach US$6 to US$7 a bushel. The latter is a higher cost than the long-term cost of expanding maize production today, according to virtually all estimates (although fast growth in demand can lead to higher prices for a few years until farmers can boost production to catch up). That means, in effect, that high oil prices could lead to a continuous expansion of maize-based ethanol at the rate at which farmers can expand maize production and still keep maize below these “breakeven” prices with oil. Because the expansion of maize will displace other crops, this expansion of maize ethanol would also increase the prices of other crops. The result could be continuing and large pressures to expand agricultural area globally and consistently high crop prices.

If oil prices are high enough, other limitations will be necessary to hold down ethanol expansion. The most significant of these is the so-called blend wall. In the United States, because few cars can use more than a 10 percent blend of ethanol for technical reasons, gasoline wholesalers have refused to install equipment to sell blends with a higher share of ethanol. The U.S. Environmental Protection Agency has approved the use of 15 percent blends for new cars, but in recent years it has refused to impose expanded ethanol requirements for existing vehicles that might force gasoline wholesalers to install new equipment. In the past couple of years, the blend wall has effectively blocked expansion of ethanol in the United States and, not surprisingly, brought down the price of maize dramatically.[96] It is important that this blend wall be maintained.

Over the long term, if oil prices are high, the blend wall may not be enough to prevent at least some steady expansion of ethanol production. If that occurs, affirmative limits or disincentives would be necessary to limit ethanol production.

CONCLUDING THOUGHTS

Much of the case for bioenergy is grounded in technological optimism. But a more realistic optimism must recognize the inherent limitations in photosynthesis by plants that will keep bioenergy's land-use efficiency low, even under the most optimistic scenarios. There are also inherently large opportunity costs to using fertile land to grow plant-based energy. Those costs are only going to grow as the world demands more food and wood products, and as the world needs more land to store carbon to combat climate change. Fortunately, a competitor to most applications of bioenergy, solar PV, is already more than 100 times more efficient per hectare at converting sunlight into energy on most of the world's land, including the less fertile land that can plausibly be spared from being used to meet other human needs. And solar energy is gaining in efficiency and reducing costs at a rapid rate. Solar energy still needs large quantities of land, but because of its efficiencies, it is the only plausible means of using land to produce large volumes of energy. For the technological optimist, the lesson should be to bet on the horse that is both already far ahead and the only one capable of reaching the finish line.

The belief in bioenegy has flowed in large part from the implicit view that land and plant material are "carbon free" assets, so their use comes with no forgone opportunity cost for reducing atmospheric carbon dioxide levels. That would be true if people could easily create more land, but they cannot. Although there is capacity to increase plant production on each hectare people already manipulate—by increasing yields or by enhancing use of lands that are degraded—that capacity is already needed to meet rising demands for food and wood products while preserving ecosystems and their carbon. There are some biomass feedstocks that avoid the competition for land, namely various forms of wastes and residues. In the long run, such wastes might contribute modestly toward replacing some of the hardest-to-substitute uses of fossil fuels, such as fuel for airplanes.

Phasing out the dedicated use of land to generate bioenergy, particularly biofuels, would reduce the food gap and, perhaps even more importantly, keep it from greatly expanding. It is therefore a valuable menu item for creating a sustainable food future.

APPENDIX A. FORMS OF DOUBLE COUNTING

Nearly all of the large estimates of bioenergy potential double count either biomass or land. By "double count" we mean that either the biomass or the land on which the biomass feedstock would be grown is already meeting some other human need or storing carbon—which is critical for combatting climate change. Recent bioenergy potential analyses—both by IPCC[97] and IEA[98]—are based on this double counting. There are five forms of such double counting:

1. Double counting existing forests and savannas. In 2001 the IPCC estimated future bioenergy potential to be roughly equal to the world's total energy consumption at that time, even as it projected that world cropland would need to expand by more than 400 million hectares by 2050.[99] To obtain this estimate, the authors assumed that all potential world cropland not otherwise needed for food production could be devoted to bioenergy at high yields. Unfortunately, the world's unused potential cropland consists mostly of forests, grasslands, and woody savannas wet enough to produce crops. Converting this land to bioenergy production would release immense stores of carbon. The analysis did not calculate these losses and appeared to assume that unused potential cropland consisted of more than a billion hectares of potentially productive but bare land.

2. Double counting net forest growth. Many studies assume that the biomass accumulating in the world's forests also provides a carbon-free source of bioenergy.[100] The world's forests are accumulating biomass for two basic reasons.[101] One is from the regrowth of forests on abandoned agricultural lands in some regions or on previously logged forests. For the most part, this regrowth is just balancing out new cutting on a global basis.[102] The other reason forests are accumulating biomass is that they are growing faster overall. This increase in growth is believed to result in part from more nitrogen deposition from the air, but also in part from the increase in carbon dioxide in the atmosphere from human sources. This "carbon dioxide fertilization effect" spurs trees to grow faster. As a result, even undisturbed, interior forests are accumulating biomass and carbon. This fertilization effect from carbon dioxide is built into standard calculations of the global warming effect of carbon dioxide emissions through an estimate that roughly one-quarter of all that carbon dioxide is reabsorbed through additional forest growth over 100 years. If that were not the case, then the warming effect of carbon dioxide emissions would be 50 percent more than it is today.[103]

The fact that forests are accumulating carbon is exactly the reason why their use as bioenergy does not reduce emissions. The biomass and carbon being stored in forests is already limiting the rise in carbon dioxide in the atmosphere. Consuming this biomass instead for bioenergy does not reduce emissions compared to using coal or natural gas for electricity because any gain from reductions in emissions in fossil carbon is lost through the reduction of the forest carbon sink. In fact, because of inherent inefficiencies in harvesting, transporting, and burning that forest carbon, the loss of carbon storage due to the replacement of coal or natural gas with wood far exceeds the reduction in emissions from fossil fuels for many years until and unless the forest grows back.[104]

The only ways to generate additional biomass from forests would be either to plant more forests or to spur existing forests to grow more. Cutting mature forests can spur more rapid growth, but that will only generate greenhouse gas emissions benefits after many years when additional growth (and saved fossil emissions) compensates for the original loss of carbon storage in the forest.[105]

3. Double counting abandoned agricultural land. Many large estimates of bioenergy potential rely on abandoned agricultural land.[106] Some estimates assume that bioenergy can freely use land that is abandoned each year because of the shifting of cropland from one location to another, even as overall cropland area expands. For that reason, some studies estimate that bioenergy potential will actually grow as climate change itself causes more cropland shifts. However, as our *Interim Findings* showed, the regrowth of forest on abandoned agricultural land already plays an important role in holding down global net deforestation and therefore global net greenhouse gas emissions. If that land were converted to bioenergy, the net loss of forests and carbon would be much larger. As these lands are already serving to sequester carbon and hold down climate change, they cannot simply be accounted for again.

Other estimates hypothesize that potential agricultural intensification can reduce the need for agricultural land on balance and thereby free up land for bioenergy. Nearly all studies estimate, however, that agricultural area is likely to grow,[107] and our *Interim Findings* explain why. Regardless, even these estimates are at least partially double counting. Unless the pursuit of bioenergy is the cause of this great expansion in agricultural intensity, intensification would occur anyway. And any freed-up former farmland would revert to forests, savannas, or grasslands, which would sequester carbon anyway. Using these lands instead for bioenergy would sacrifice this alternative carbon sequestration. Using abandoned agricultural land for bioenergy could only yield greenhouse gas benefits if and to the extent that using this land for bioenergy would reduce fossil fuel emissions of carbon dioxide more than this land alternatively would sequester carbon dioxide in regrown natural vegetation. In many contexts, allowing a forest to grow will do more to reduce carbon dioxide in the atmosphere for decades than producing bioenergy. At the very least, the net benefit from using the land for bioenergy compared to a forest will reduce the potential avoided emissions from bioenergy.[108]

One paper focused on abandoned land that did not explicitly double count tried to estimate the world's abandoned agricultural land that has not reforested.[109] Arriving at this estimate was a challenging enterprise. Even today's land use maps contain many errors, and there were no satellites able to map global land use 100 years ago. Some of the land that appears abandoned is likely to be only a result of these inconsistent maps, and that is borne out by the fact that the authors estimated millions of hectares of abandoned, non-forested land in Western Europe that no analyst in Western Europe has actually identified on the ground. Regardless, most of the land identified was dry, abandoned grazing land, which provides an unlikely target for the economic production of biomass. And even if all this globally identified abandoned land were fully used for bioenergy up to its maximum technical potential, the authors estimated that it would provide only 5 percent of today's total energy supply.

4. Double counting savanna, woodlots, and grazing lands. Some papers exclude existing forests, agricultural lands, and protected areas and estimate bioenergy potential from the remaining lands. In reality, these estimates assume that use of the world's less intensively managed pastures somehow comes without a carbon opportunity cost. Other supposedly "carbon-free" lands include tropical savannas and sparser woodlands.[110] In fact, as we show in the *Interim Findings*, even if some of the world's grazing land is inefficiently managed, the world needs to produce roughly 80 percent more milk and meat between 2006 and 2050 on pasture. (It also needs to increase the production of milk and meat that relies on crops by roughly the same amount.) To avoid further conversion of natural ecosystems to livestock grazing, productivity improvements in existing grazing lands are needed—not conversion of those grazing lands into biofuel production.

Conversion of savannas to biofuel production is also not carbon free. The tropical savannas wet enough to support bioenergy contain extensive woody vegetation, shrubs, and deep-rooted grasses that store carbon. Converting these savannas to bioenergy therefore carries heavy carbon costs. One study found that producing bioenergy on most tropical savannas would not generate any net greenhouse gas emissions reductions within ten years, even assuming extremely high biomass yields.[111] Correcting a single, incorrect assumption in the study doubles that period to 20 years.[112]

5. Double counting biomass as part of bioenergy with carbon storage. One reason some researchers continue to promote bioenergy is that current strategies for holding down emissions enough to hold global warming to 2 degrees Celsius no longer seem plausible and "carbon-negative bioenergy" seems like a way out. Carbon-negative bioenergy could only result if bioenergy first uses a source of biomass that truly did not lead to greenhouse gas emissions because the biomass feedstock was additional. To become carbon negative, the biomass must then be burned in power plants and manufacturing facilities equipped with systems that capture the carbon dioxide emitted before it leaves the smokestack and store it underground. This is a form of "carbon capture and storage." Viewed from a life-cycle perspective, the aspiration is that bioenergy feedstock plants would absorb carbon dioxide from the atmosphere, the plants would be combusted to generate energy, and the associated carbon dioxide emissions would be intercepted and stored underground. This combination of bioenergy and carbon capture and storage is known as "BECCS." The net result would be a gradual reduction in carbon dioxide concentrations in the atmosphere.

Some researchers interpret this aspiration as a rationale for supporting bioenergy today. In reality, the logic works the other way.

First, despite this vision, carbon capture does not transform non-additional biomass that cannot generate carbon savings into additional biomass that can. The only way to generate carbon-negative energy is to start with additional biomass. Although carbon capture and storage can reduce this carbon, it can do the same for coal and natural gas, so there is no more benefit in applying carbon capture and storage to non-additional biomass than to fossil fuels. Our earlier analysis explains why there is only limited opportunity for additional biomass. Modelers who estimate large potential benefits from BECCS rely on the same estimates of biomass potential that are based on double counting (see above).

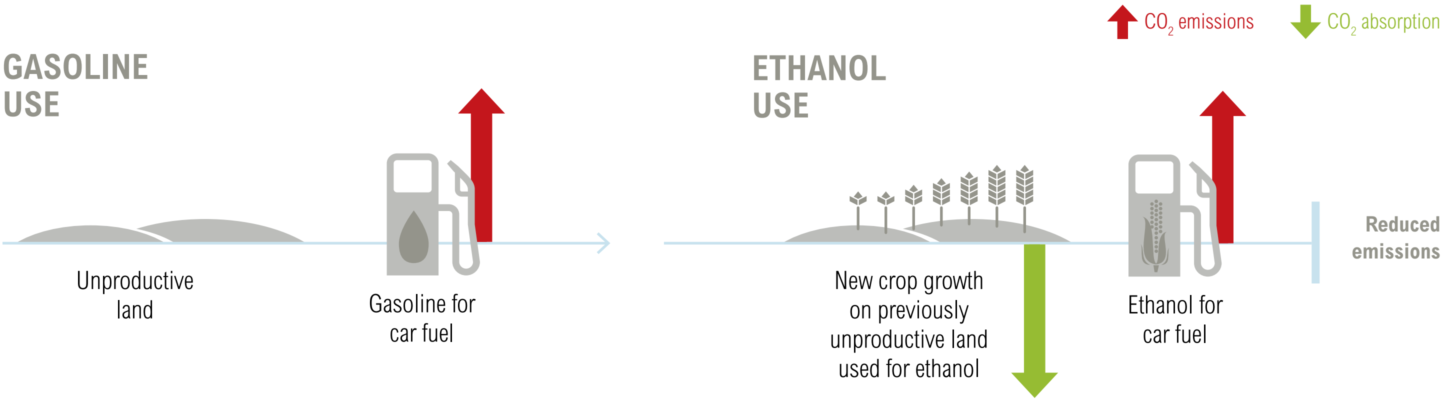
Second, there is no benefit to applying carbon capture and storage even to additional biomass until all fossil fuel emissions have been eliminated or captured and stored. Generating one kilowatt hour of low-carbon energy through additional biomass in one location and applying carbon capture and storage to the burning of coal in another location generates precisely the same amount of greenhouse gas benefit as BECCS that uses wastes or other truly additional biomass. Only once coal and other fossil emissions have been eliminated does the prospect of low-carbon biomass combined with carbon capture and storage provide an added opportunity, but not until then.

Third, even if there were a special benefit from BECCS, this is not a reason to use biomass today without carbon capture and storage. It would instead be a reason to hold on to biomass and use it only later, once carbon capture and storage technologies have presumably become feasible and cost-effective and would be used with additional biomass.

APPENDIX B. PICTORIAL REPRESENTATION OF BIOENERGY GREENHOUSE GAS ACCOUNTING

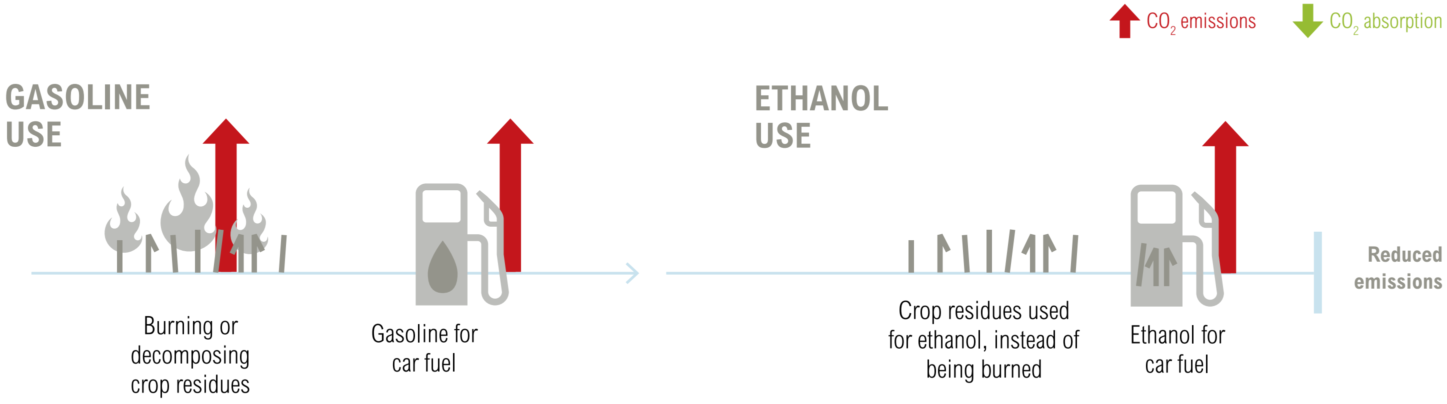
Most greenhouse gas accounting that has found emissions reductions arising from bioenergy has started with the assumption that the actual carbon dioxide emitted by burning biomass "does not count" because those emissions are negated or offset by the carbon dioxide absorbed by the plant growth that produced the biomass. This negation of emissions is only true if the biomass grown is additional to what otherwise would have occurred, or if alternative demands for that biomass (e.g., food, timber) is at the same time reduced. "Additional biomass" is biomass that results from additional plant growth in response to the demand for bioenergy or biomass that would not otherwise be used for human benefit—essentially some kind of waste. The illustrations below (Figures B1–B6) show several scenarios of greenhouse gas emissions related to bioenergy use, with vertical arrows indicating carbon dioxide uptake and emissions. The length of the arrows in each figure is illustrative.

Figure B1 | **Scenario: Additional Plant Growth for Bioenergy Reduces Greenhouse Gas Emissions**



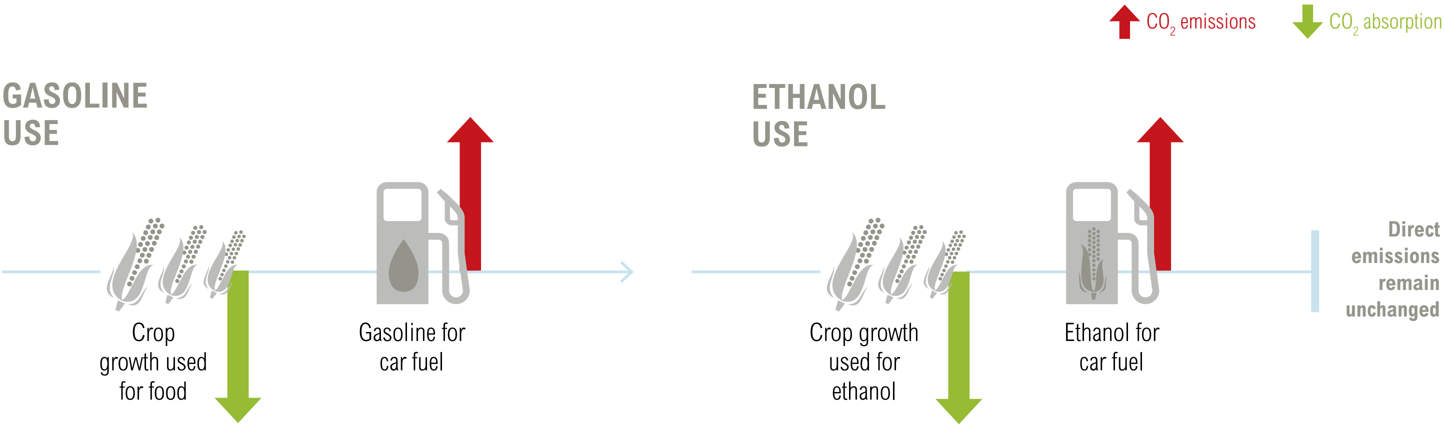
Bioenergy made from "additional" plant growth can reduce greenhouse gas emissions relative to fossil fuel use. On the left, a tract of land is unproductive and vehicles use gasoline. On the right, vehicles use biofuels grown on the previously unproductive land. On the right, vehicle emissions continue unchanged, but the "additional" plants absorb carbon dioxide from the atmosphere, offsetting emissions from biofuels.

Figure B2 | **Scenario: Reduced Crop Residue Burning Reduces Greenhouse Gas Emissions**



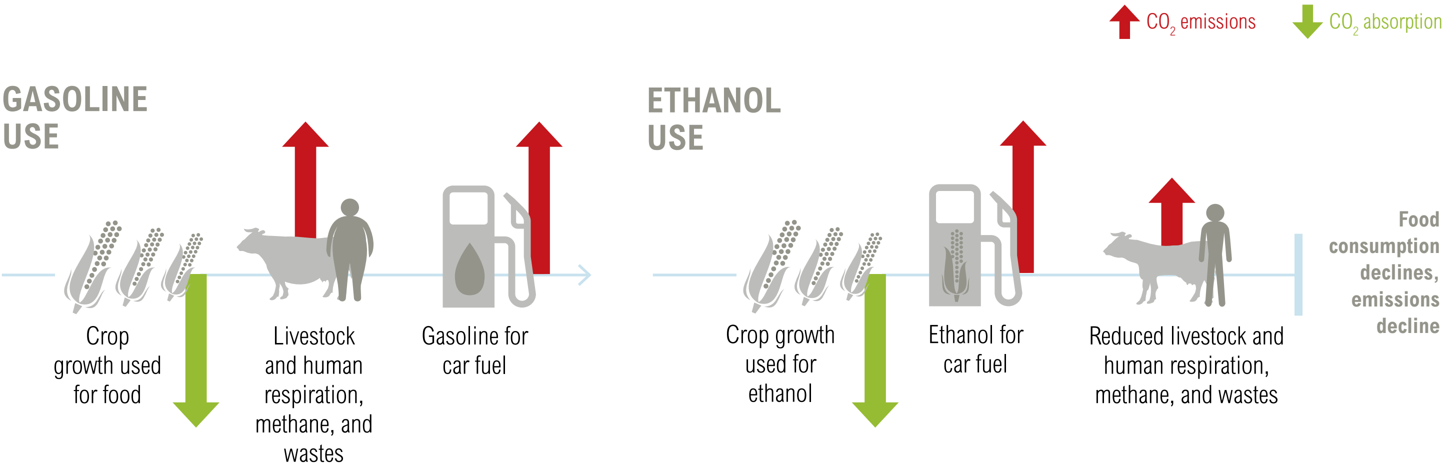
When crop residues are burned, they add to carbon dioxide emissions. If these residues are instead turned into ethanol, vehicles would continue to emit the same quantity of carbon dioxide as if they used gasoline, but emissions from the field would be reduced. Since these residues would otherwise be burned, storing no carbon, this biomass can be considered "additional."

Figure B3 | **Scenario: Food Crops are Diverted to Biofuels, Emissions Remain Unchanged**



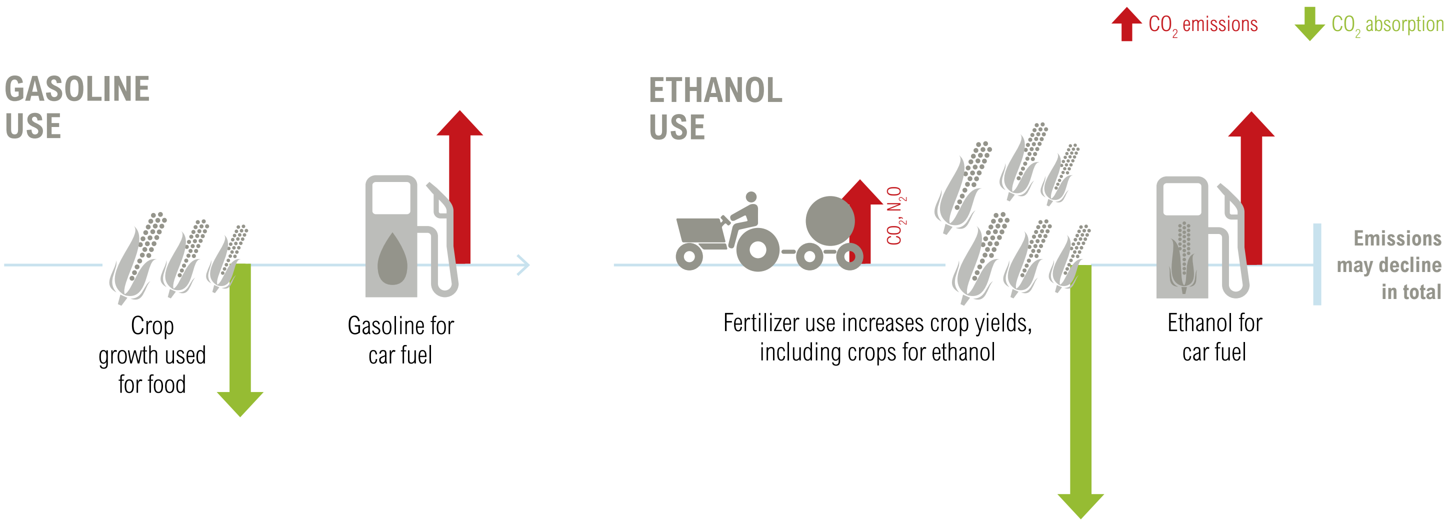
Whether vehicles use gasoline or ethanol, they emit carbon dioxide. And whether maize is used for food or fuel, it absorbs carbon dioxide as it grows. On the left, maize grown for food and feed absorbs carbon dioxide as vehicles using gasoline emit it. On the right, maize diverted to ethanol absorbs the same amount of carbon dioxide, while ethanol-fueled vehicles emit it. These effects alone fail to justify using biofuel to limit greenhouse gas emissions.

Figure B4 | **Scenario: Food Crops are Diverted to Biofuels, Food Consumption Declines, Emissions Decline**



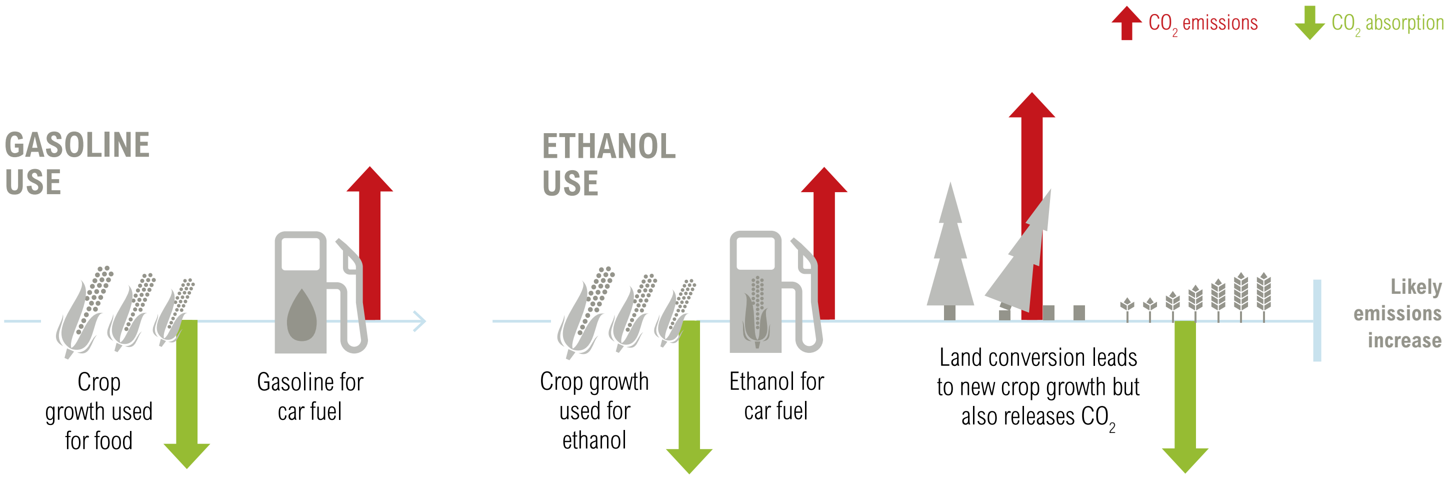
Higher demand for biofuels could trigger changes in food consumption. On the left, cars use gasoline and people and livestock eat maize; all emit greenhouse gases. On the right, when maize is diverted to biofuels, greenhouse gas emissions from human and livestock consumption decline, but at the expense of having less food. Increased demand for maize for ethanol drives up food and feed prices.

Figure B5 | **Scenario: Food Crops are Diverted to Biofuels, Fertilizer Use and Crop Yields Increase**



Higher prices for maize driven by biofuel demand could prompt farmers to increase maize crop yields by using chemical fertilizers. While additional crop production absorbs more carbon dioxide, fertilizer use can add to greenhouse gas emissions. To the extent crop yields increase, greenhouse gas emissions overall are likely to decline. However, for these improved crop yields to be part of a sustainable food future, they must be greater than the increase in crops needed to feed people with the same land by 2050—which is unlikely, given the projected increased demand for food by mid-century.

Figure B6 | **Scenario: Food Crops are Diverted to Biofuels, Farmers Convert Natural Ecosystems to Cropland, Emissions Increase**



Diverting maize to biofuels could also encourage farmers to convert forest or grassland to cropland. These additional crops would absorb carbon dioxide, but the land conversion would release vast amounts of carbon dioxide previously stored in the converted ecosystems. This conversion also sacrifices any continued carbon storage that would have occurred in the forest or grassland. Land conversion is likely to increase the net carbon dioxide flow into the atmosphere for many years.

ENDNOTES

1. Visit www.worldresourcesreport.org and see Searchinger et al. (2013).
2. Searchinger et al. (2013).
3. FAO (2009) finds annual increases in timber demand of 1.4 percent for sawnwood and 3 percent for paper and related products and projects such increases through its projection period of 2030. Even a 1.4 percent growth rate translates into an 84 percent increase over 44 years, corresponding to our period of analyses for this series of reports (2006 to 2050).
4. See the discussion in Searchinger et al. (2013). Put simply, the amount of additional food needed in 2050 compared to 2006 is larger than the amount of additional food needed between 1962 and 2006. In the underlying FAO study, there is a suggestion that the growth in food demand going forward is a lesser challenge, because the compound growth rate of food demand is declining over time. However, because crop yields grow at linear growth rates, the impact of food demand on land use is most directly explained by its linear—not compound—growth rates. Expressed in terms of linear growth rates, crop yields will need to grow more quickly between 2006 and 2050 than they did between 1962 and 2006 (a period that encompassed the Green Revolution).
5. See Searchinger et al. (2013) for the underlying calculations.
6. Searchinger et al. (2013).
7. EIA (2013a).
8. Authors' calculations based on estimates of global delivered energy in EIA (2013a).
9. EIA (2013a).
10. EIA (2013a).
11. 1 exajoule = 238,902,957,619,000 kilocalories.
12. Authors calculations based on biofuel production estimates from U.S. Energy Information Administration, published information from diverse sources of feedstocks for ethanol and biodiesel in different countries, standard conversion factors for estimating energy in different crops, and data from FAOSTAT on total 2010 crop production. These calculations do not include the portion of food crops that produce useable byproduct.
13. Authors' calculations from data provided by FAO. The growth in biofuels contributes roughly 11 percent of the increase in demand for crop calories estimated by FAO from 2006 to 2050. When combined with the crops used for biofuels already in 2006, the total amounts to 15 percent.
14. EIA (2012a).
15. This figure counts the higher heating value of crops based on conversion factors in Wirsenius (2000). Higher heating values assume perfect combustion and are therefore higher than typical calculations of kilocalories from food consumption for people. This figure counts only the sugar portion of sugarcane and not the remaining part of the plant, which becomes bagasse. We exclude this portion to provide a fairer comparison of food energy to bioenergy. When we calculate the total amount of primary energy that crops could provide in total, we count the bagasse, which raises this figure to 75 EJ. Each of these calculations provides a more favorable perspective for bioenergy.
16. 11.3 EJ/71 EJ = 0.16.
17. For example, in practice, Bremer et al. (2010), Table 1, indicated that 66.6 percent of the energy in maize went toward ethanol and 33.4 percent went toward feed byproduct. But of the 11.6 megajoules (MJ) of energy per kilogram of maize that are devoted to ethanol and not byproducts, only 8.84 MJ are converted into ethanol if conversion efficiencies are 0.419 liters per kg and 21.1 MJ/l lower heating value (Liska et al. 2009). That implies a ratio of 11.6/8.84 of energy in starch devoted to ethanol to energy out in ethanol. For every MJ of energy in ethanol from maize, therefore, 1.31 MJ of energy in maize are used excluding the energy that goes to byproducts. (The authors thank Adam Liska of the University of Nebraska for assistance in these calculations.) Somewhere in the system, the remainder is lost.
18. Authors' calculations. This calculation is based on the present mix of crops for biofuels (dominated by sugarcane and maize) projected into the future and on common energy conversion efficiencies.
19. Extrapolations from EIA (2013a).
20. That is a simple calculation of 16.8 EJ of biofuels divided by 71.1 EJ from all crops calculated using total crop production from FAOSTAT for 2010 and dry matter and energy conversion figures from Wirsenius (2000).
21. Authors' calculations. This calculation is based on the present mix of crops for biofuels (dominated by sugarcane and maize) projected into the future and common conversion efficiencies and excludes byproduct of biofuel production that remain to supply food or feed. We calculated the tons of biofuel crops required to produce 16.8 EJ of biofuels using the present mix, and then calculated the HHV of these crops using the same energy and water content coefficients from Wirsenius (2000) we used to calculate the total energy production of all 2010 crop production. The estimated crop energy needed is 20.9 EJ, which is 29 percent of 71.1 EJ, the total crop production in 2010.
22. Our crop gap is based on 2006 production because that was the baseline used by the FAO study of Alexandratos and Bruinsma (2012). The quantity of biofuel crops in the 2050 FAO scenario already includes 5.8 EJ, which equals 8.5 percent of the total crop energy in 2006. That implies that a 10 percent transportation fuel target would require an increase in ethanol crop production of 15.1 EJ, which would require an increase in crop production equal to 22 percent of 2006 crop production. That would increase the calorie gap from 2006 to 2050 to 8,675 trillion kcal per year, or from 69 to 91 percent of 2006 calorie production. If we directly translated the crop needs into digestible kilocalories using the calorie conversions used in the underlying spreadsheets for Alexandratos and Bruinsma (2012), the gap would rise to 100 percent.
23. Haberl et al. (2010).
24. This calculation assumes 395 bushels of maize per hectare (equivalent to about 160 bushels per acre), 2.8 gallons of ethanol per bushel, and thus 1,106 gallons per hectare. It also assumes that 30 percent of the maize traditionally enters the animal feed supply chain as an ethanol byproduct. This implies that 0.7 hectares produce the 1,106 gallons, and thus a full hectare would produce 1,580 gallons, which rounds up to 1,600 gallons.
25. The yields used by EPA are described in Plevin (2010).
26. To match the yields of maize ethanol, perennial grasses must achieve yields of 16 metric tons of dry matter per hectare per year (t/ha/yr), and very high conversion efficiencies of 100 gallons (376 liters) per metric ton. Hudiburg et al. (2014) estimates that replacing maize and soybean rotations with switchgrass in the United States would achieve yields of 9.2 tons/hectare and miscanthus would achieve yields of 17.2 tons/hectare. EPA estimated average switchgrass yields of 8.8 t/ha (Plevin 2010), and average switchgrass yields today are 4.4 t/ha/year to 8.8 t/ha (Schmer et al. 2010). Although miscanthus might achieve slightly higher yields than maize, among its challenges, it reproduces rhizomatically, so that new rhizomes must be dug up and separated from existing plants and replanted elsewhere.

27. Searle and Malins (2014).
28. Searle and Malins (2014).
29. See <http://www.wri.org/resources/maps/suitability-mapper>.
30. Corley (2009) includes estimates of land likely needed for oil palm under different scenarios, the lowest of which would require the vast majority of land mapped by WRI as potentially suitable for oil palm.
31. IEA (2008). Although ambiguous, the IEA report encourages this goal on top of any traditional uses of biomass for fuel wood. OECD (2011) projects global primary energy use in 2050 to be 900 EJ per year.
32. The energy in biomass is derived by multiplying the harvested biomass estimated in Haberl et al. (2007), provided by the authors of that paper, by an average energy content of 18.5 GJ per ton of dry matter.
33. The amount of energy in fossil fuels that bioenergy would replace depends on the form in which the bioenergy or fossil fuel is used. Primary energy measures the energy in the original fuel, e.g., wood or crude oil. Delivered energy is the energy in a useable form, such as electricity, gasoline, or ethanol. There is substantial loss of energy in the conversion process because of the energy needed to mine, produce, or refine feedstocks into liquid fuel, or the energy lost (primarily through waste heat) in turning a fuel into electricity. Our assumption is that the conversion of biomass into delivered energy would overall occur at 80 percent of the efficiency of fossil fuels, which is optimistic for bioenergy. This calculation looks at the total amount of useable energy generated, such as the energy in ethanol, versus the total biomass and fossil energy used to generate it. For calculations of the relative efficiency of converting crude oil and biomass into useable energy forms, see JRC (2011), chapter 9.
34. Haberl et al. (2012), Erb et al. (2007).
35. Authors' calculations. These numbers require information only about the solar radiation received in an area of production, the crop or biomass yields, the quantities of biofuels per ton of crop, and the energy of the biofuel. Brazilian sugarcane ethanol numbers assume average solar radiation of 2,000 kilowatt hours per square meter per year in Brazilian sugarcane producing areas based on SolarGIS global solar radiation map, which yields 72,000 GJ/ha/yr. (Map available at <http://solargis.info/doc/_pics/freemaps/1000px/ghi/SolarGIS-Solar-map-World-map-en.png>). It also assumes a yield of 80 metric tons of sugarcane per hectare/yr, dry matter content of 27 percent, and an energy content of 17 GJ/tDM, for 367.2 GJ/ha/yr. If sugarcane is produced every year, then it generates a 0.51 percent efficiency of the energy in sugarcane relative to solar radiation, but if it is produced only seven of eight years to factor in replanting, the efficiency is 0.45 percent. Assuming 75 liters per ton of sugarcane and 23.4 MJ/l, that results in 140 GJ/ha/yr of energy in ethanol. The result is 0.19 percent assuming both annual production and 100 percent of fossil fuels used in production are offset by an electricity energy credit from burning sugarcane bagasse. The energy in the biomass other than sugar, the bagasse, is therefore counted in this net calculation.
36. These figures, calculated for Iowa, assume 9.7 tons per hectare (180 bushels per acre) of maize, 487 liters of ethanol per ton (2.8 gallons per bushel), a 35 percent reduction in land use estimates to recognize feed byproduct, 23.4 MJ/liter of ethanol, and solar radiation of 1,600 KWH per square meter per year (~57,500 GJ/hectare/yr). The calculation also assumes optimistically that the net energy yield of maize ethanol is 50 percent after accounting for all the energy used in its production.
37. Authors' calculations assuming production in Iowa. Shifting the production to less good, generally drier, land would typically decrease the efficiency even if these yields could be achieved, and reduce the probability of achieving these yields.
38. For example, one paper estimated land use demands to meet existing electricity production in the United States in 2005 as varying from 1 percent to 9 percent for states east of the Mississippi in the United States (Denholm and Margolies 2008). This figure would obviously need to expand to meet the greater electrical generation needs of 2014. But it would decline if power were imported from the sunnier, drier, and less populated states in the U.S. West, as PV conversion efficiencies grow (and they have grown greatly even since 2008) and as costs come down, which permit more dense packing of PV cells in tilted configurations.
39. Calculations of rooftop solar and for solar farms differ. This figure for rooftop solar assumes a 16 percent photovoltaic cell, a 20 percent loss in actual operation of a rooftop solar installation, including losses from conversion of DC power to AC power and a further 11 percent cost for paying back the energy used to construct and install the system. Photovoltaic efficiencies and payback times are from Fthenakis (2012), and the 20 percent efficiency loss is based on typical conversion cost figures using the PVWatts calculator website (National Renewable Energy Laboratory of the U.S. Department of Energy 2014).
40. This figure is based on the highest projected future switchgrass yield at any point in the United States in Geyer (2013), and the assumption of 100 gallons per ton of dry matter in biomass, compared to our calculation of 11 percent efficiency of PV.
41. Our cellulosic ethanol assumptions imply a 50 percent conversion of energy in biomass to ethanol. Converting biomass to electricity typically occurs at roughly a 25 percent efficiency.
42. Calculations for a solar farm differ somewhat from calculations for rooftop solar. This calculation assumes at least a 16 percent efficient solar PV cell, a 10 percent loss in efficiency for DC/AC conversion, a 50 percent "coverage factor," and a 10 percent payback cost for the energy involved in construction and installation, yielding an overall efficiency of 6.5 percent, which is more than 30 times the net solar conversion efficiency of sugarcane into ethanol in Brazil (0.2 percent) and maize into ethanol in the United States (0.15 percent). The "coverage factor" represents the average spacing that commercial solar PV systems commonly have between solar cells to avoid shading when they tilt cells to maximize the reception of sunlight (Ong 2013). The 10 percent loss in DC/AC efficiency is based on NREL estimates for average effects (personal communication with Paul Denholm, September 11, 2014). The biggest loss of land use efficiency in this example is the coverage factor. Technically, there is no problem to achieving almost a 100 percent coverage factor but the cost per cell will rise because of the lack of tilt to maximize solar radiation per cell. The cheaper solar cells become, the more economically worthwhile it is to sacrifice tilt for greater energy per square meter.
43. Searle and Malins (2014) provide a good summary of the scientific basis for projections of cellulosic energy crops.
44. This figure is based on a global GIS (geographic information system) analysis by Asa Strong and Susan Minnemeyer of WRI, comparing the net energy output of potential bioenergy production against the output of photovoltaics. The area analyzed excluded area covered permanently by ice and the driest deserts. The bioenergy production assumed that biomass production in all areas would match the net primary production (NPP) of the original native vegetation based on use of the LPJmL model provided by Tim Beringer of the International Institute for Applied Systems Analysis. (NPP of native vegetation is one common measure of maximum likely potential biomass production because agricultural biomass production rarely exceeds that of native vegetation (Field et al. [2008], Haberl et al. [2013].) This analysis further assumed

production of 100 gallons of ethanol (379 liters) per metric ton of biomass, and that all energy used to produce and transport biomass and refine it into ethanol would be either provided by the biomass itself or offset by electricity byproducts. (Using ethanol, these assumptions imply that around 48 percent of the gross energy in the biomass becomes useable energy. If we were to assume use of this biomass to produce electricity instead of ethanol, the net energy yield of bioenergy would decline by more than half [representing a typical conversion efficiency of less 25 percent of the energy in biomass into electricity minus the energy used to produce the biomass], and the advantage of photovoltaic energy over bioenergy would increase.)

For PV production, this analysis used a global data set of horizontal radiation available from the U.S. National Renewable Energy Laboratory. Efficiency ratings of PV are based on a particular formula that is a function of radiation and temperature, and we adjusted our estimated net efficiency of PV (see note 39) down from 11 percent to 10 percent to reflect the possible differences between this measure of radiation and the formula estimating efficiency of PV.

This analysis calculated that on 73 percent of the world's land, the useable energy output of PV would exceed that of bioenergy by a ratio of more than 100 to 1. For the remaining 25 percent of the world's land, the average ratio is still 85 to 1 and the lowest ratio is 40 to 1. This relatively "better" land for bioenergy consists primarily of areas whose native vegetation would have been dense forest, and which today includes the world's densest remaining tropical forests and the North American and European areas of the world's best farmland. This land is therefore the land most valuable for carbon storage, food, and timber. If energy production chose from the top 25 percent of land with the highest efficiency advantage for PV, the minimum ratio of PV to bioenergy production would be 5,000 to 1.

Redoing our analysis with the assumption that biomass production would exceed that of native vegetation by half, 40 percent of the world would still have a PV advantage of more than 100 to 1, and in the remainder, PV would have an average advantage over bioenergy of 69 to 1.

This analysis should be viewed only as illustrative. At finer resolution, much land would neither be suitable for biomass production nor PV, such as some steeply sloped land.

For similar calculations, Geyer (2013), using optimistic estimates of potential biomass yields, estimated that PV would produce more than 80 times the electricity of bioenergy per hectare of land, using a PV rated efficiency of 9 percent common in 2005, over most of the United States. Adjusting that figure to the commercial typical PV cell today of 16 percent would raise that increased efficiency to a multiple of over 140 for most of the United States. For other estimates, see MacKay (2009); Fthenakis and Kim (2009); and Edwards et al. (2010), Table 9.2. Fthenakis and Kim (2009) performed a land use analysis for electricity production using a life-cycle approach, which means that they calculated not just direct land demands but also indirect land demands, such as the land used in mining materials or disposing of materials. They estimated solar energy from PV from a power plant to be roughly 250 square meters per gigawatt hour, depending on the type of solar energy system (e.g., a solar thermal tower was the highest land user, a sophisticated PV system was the lowest, and rooftop PV had almost no land use). By comparison, the most efficient form of biomass-generated electricity in the most efficient location using fast-growing willows required more than 12,600 square meters per gigawatt hour, even assuming high yields of 15 tons of dry matter per hectare per year. For the most efficient bioenergy location in the United States, PV would generate 50 times more energy per hectare.

45. U.S. Department of Energy, Renewable Efficiency & Renewable Energy, <http://www.fueleconomy.gov/feg/evtech.shtml>. The California Energy Commission lists the efficiency of internal combustion engines at 15 percent. California Energy Commission, "Energy Losses in a Vehicle." See <http://www.consumerenergycenter.org/transportation/consumer_tips/vehicle_energy_losses.html>.
46. International Energy Agency (2014) surveys the opportunities for incorporating solar and wind energy, which are "intermittent sources," into energy grids that must supply power on demand. The report concludes that integrating 40 percent of such energy is achievable at only a 10 percent added cost for integration. The report also noted that improvements in the costs of generating solar and wind should save these added integration costs. Although this estimate focuses on the supply of wind and solar for electricity, and not other energy needs such as heating or transportation, progress in electric cars could easily allow a nearly full electrical transportation fleet, which could be charged during periods of high solar and wind generation.
47. For a discussion of the potential of lithium sulfur batteries for cars, see Manthiram et al. (2013). For one company that has started to ship a relatively cheap battery back that could be used for grids or households, see Fehrenbach (2014).
48. Mahli et al. (2002).
49. Searchinger (2010).
50. IPCC (2001).
51. Papers relying on these sources are summarized in Searchinger (2010).
52. See Searchinger et al. (2013).
53. Globally, forests are increasing their biomass and sequestering carbon, which plays a critical role in limiting the amount of warming that occurs as human activities release more carbon dioxide into the atmosphere (Pan et al. 2011). Much of this growth is due to faster forest growth that results from higher concentrations of carbon dioxide, and is in fact a beneficial feedback of the release of carbon dioxide that is already factored into the estimate of the warming effect of carbon dioxide. Reducing the sink in these forests cannot reduce the total quantity of carbon in the atmosphere.
54. Researchers have made this finding while analyzing a broad range of forest types and a broad range of harvesting regimes. See for example Holtsmark (2012), Hudiburg et al. (2011), Manomet Center for Conservation Sciences (2010), Mitchell et al. (2012). The basic reason harvesting forests for bioenergy leads to a carbon debt is that each ton of carbon in a forest that is harvested only leads to a quarter to a third of a ton of carbon savings in its typical use for electricity generation. This is because (a) some of the live carbon in roots and branches is left behind to decompose, and (b) burning wood is less efficient than burning fossil fuels to generate electricity. In addition, young or middle age forests, which are most frequently harvested in commercial operations, would typically grow faster and therefore accumulate more carbon for at least some years than a newly regrowing forest, which starts with seedlings or natural regeneration. That factor increases the carbon debt of using trees for energy. Eventually, forests that are not cut reach slow rates of growth, and regrowing forests will start to catch up. Eventually, the greenhouse gas reductions from reduced fossil fuel use will equal and ultimately exceed the increase in carbon in the air from the transfer from the forest. At that point, there are greenhouse gas benefits. But

governments that have explicitly recognized and addressed this accounting have generally agreed to account for these bioenergy impacts in periods of 20 or 30 years, up to which bioenergy leads to likely emissions increases.

One source of confusion in this analysis lies in the difference between the rate of uptake in any given year and the total carbon stored. Cutting a mature forest will increase the rate of carbon uptake (at least over a couple of decades as a new forest grows), but at the expense of a large initial loss of carbon. And it will still result in a net release of carbon from the forest, and even a net release of carbon for decades, even when accounting for the reductions in fossil carbon emissions from the bioenergy use.

55. Searchinger (2009), Haberl et al. (2012).
56. Technically, such a strategy must result in increased pasture and crop output per unit of carbon released by using the land for agriculture. In theory, therefore, achieving the same yields on less carbon-rich land could produce additional carbon. In general there is no reason to believe that will happen. While there are degraded lands that are underutilized, their improved use is already needed to meet rising food and timber demands, and otherwise could be used to sequester carbon by allowing forests to regrow on them.
57. For two comparisons, see Decara et al. (2012) and Edwards et al. (2011).
58. Searchinger (2013).
59. HLPE (2013), Dorward (2012).
60. See the discussion in Searchinger (2013) of the IFPRI model, and the discussion in Berry (2011) of the GTAP model. Berry (2011) also includes a good discussion of the limited real economic evidence that higher demands spur yield growth.
61. Berry (2011), Berry and Schlenker (2011).
62. Searchinger (2013) discusses the IFPRI model used by the European Commission, which is structured so that the vast majority of increases in crop production to replace crops diverted to biofuels results from additional yield increases by farmers. Even so, estimated greenhouse gas reductions from grain-based biofuels are modest.
63. See Searchinger et al. (2013) for a discussion of the various physical constraints from the standpoint of water, fertilizers, and changing climate faced by farmers.
64. Dumortier et al. (2011), for example, assumed that expanded cropland in the United States and much of the world would first use idle cropland, which is the equivalent of assuming that expanded crop production would come from an increase in cropping intensity (the percentage of cropland cropped in a given year).
65. As we discuss in Searchinger et al. (2013), world cropland shifts and truly abandoned cropland regenerate carbon. There is also a category of land that comes in and out of crop production in part in response to fluctuations in demand and yields and in part in response to physical limitations on crop growth every year. Those fluctuations will continue to exist in a future with more biofuels, and that means there will always be this kind of cropland that comes in and out of production. The argument that biofuels will use this cropland confuses a structural change in demand with the effect of annual fluctuations in the demand for cropland. E4tech (2010) made similar assumptions for European biofuel production.
66. This assumption, for example, was implicitly built into the regulatory analysis by the U.S. EPA for its biofuel greenhouse gas regulations, and was also part of the assumptions in E4tech (2010). It derives from satellite studies that identify extensive “savanna” in Indonesia, while the savannas in Indonesia are in fact originally forest that has been cut and is typically in some kind of mosaic use if not at some stage of reforestation.
67. Papers analyzing food crops include Fargione et al. (2008) and Gibbs et al. (2008). Few papers analyzing potential cellulosic ethanol crops actually calculate the carbon losses of converting lands, but those that do find large payback times. See Beringer (2011).
68. Haberl et al. (2010).
69. Haberl et al. (2010) discusses the various estimates.
70. The Haberl et al. (2011) estimate is of 25 EJ of unused residues, which could generate 12.5 EJ of transportation biofuels according to high conversion efficiency estimates.
71. Smil (1999) provides a compelling analysis of the uses and needs for crop residues worldwide. Even in the United States, Blanco-Canqui and Lal (2009) found that at least in a part of the U.S. maize belt, the removal of residues resulted in substantially negative effects on maize yields.
72. Liska et al. (2014). Many studies have estimated conditions under which the removal of residues might not reduce soil carbon, but the more salient factor is the difference in soil carbon with and without the residues. If the residues would add to soil carbon, then their removal reduces carbon sequestration.
73. Surendra (2014).
74. Andersson (2012).
75. Authors’ calculations based on data from FAOSTAT and assumption that all tops and branches are available and equal 30 percent of harvested roundwood.
76. Haberl et al. (2010).
77. Haberl et al. (2010).
78. Hughes et al. (2012).
79. National Research Council (2012), p. 2.
80. Wigmosta et al. (2011). The water challenge exists in large part because algal biofuel production is expensive (estimated at US$300–US$2,600 per barrel in 2010, in Hannon et al. [2010]), and strategies to achieve a reasonable cost require production in open ponds from which much water evaporates. Although some other estimates of potential water use are lower, nearly all still estimate large quantities needed, according to the National Research Council (2012). One possibility might be to use saline waters, but the National Research Council (2012) concluded that some freshwater would be necessary.
81. Moody et al. (2014).
82. In effect, if power plants transfer their carbon dioxide to algal production and the gas is entirely absorbed into algae, then that carbon dioxide is still released when the algal biofuels are consumed. The benefit is that roughly twice the energy is produced for the same release of carbon dioxide, which means a maximum reduction in emissions of only 50 percent. In reality, the reduction is probably less due to the energy and other requirements of producing the algal biofuels.
83. Waite et al. (2014).
84. Although FAO has cited this 10 percent figure in some publications, its own published estimates of global fuel wood amount to only about 3 percent. For example, the 2008 fuel-wood harvest reported in FAO (2011) amounted to 1.87 billion cubic feet, which by conventional conversion factors should contain roughly 17.5 EJ, relative to 2010 global energy demand of around 500 EJ.
85. Kissinger et al. (2012).
86. See also HLPE (2013).
87. Steenblik (2007), Koplow (2007), Koplow (2009).
88. Sperling and Yeh (2010).

89. Kitzing et al. (2012).
90. IEA (2013), Brack and Hewitt (2014).
91. Bernier and Paré (2013), Holtsmark (2012), Hudiburg et al. (2011), McKechnie et al. (2011), Mitchell et al. (2012), Manomet Center for Conservation Sciences (2010), Zanchi et al. (2012).
92. Authors' calculations using FAOSTAT. This figure is calculated by using the FAO's total reported timber harvest, using conversion factors to estimate their energy content, and comparing them to estimates of global energy consumption. This figure refers to all tree harvest. Focusing only on commercial tree harvest, which ignores traditional firewood, 5–6 percent of global energy would require roughly a four-fold increase.
93. Massachusetts regulations can be found at <http://www.mass.gov/eea/docs/doer/rps-aps/rps-class-i-regulation-225-cmr-14-00.pdf>. The approach properly calculates both the savings in fossil fuel carbon and the reductions, and therefore emissions, from harvesting trees and calculates the balance over a period of 20 years.
94. Searchinger (2009).
95. For different estimates, see Mallory et al. (2012), Tyner (2010), Abbott (2012).
96. Abbott (2012).
97. Chum et al. (2011).
98. Bauen (2009).
99. Moomaw et al. (2001), Table 3.31.
100. Bauen et al. (2009), Smeets and Faaij (2007).
101. Pan et al. (2011).
102. Richter and Houghton (2011).
103. Because only half of every ton of carbon dioxide emitted to the air is assumed to remain in the atmosphere, and one half of the carbon dioxide that is reabsorbed occurs because it spurs the forest carbon sink (Solomon et al. 2009), then eliminating that forest carbon sink (one-quarter of that emitted ton) would turn that half a ton into three-quarters of a ton.
104. See the studies cited in note 54 above. The precise years of increases in emissions depend on the nature of the forest, the efficiency of the electrical plant, and the type of fuel being replaced. The same would be true for the harvest of wood for ethanol, as some of the live wood must be left behind in roots and at least some residues, and as the conversion efficiency for transforming energy into cellulose into ethanol is unlikely to be more than 50 percent.
105. The studies cited in note 54 above evaluate the harvest of mature forests as well as middle-aged or younger forests.
106. Hoogwijk et al. (2005), Bauen (2009).
107. For example, see Smith et al. (2010).
108. The math is simple. If a hectare could generate enough biomass for energy to avoid four tons of carbon from fossil fuels per year for 20 years but alternatively would regrow as a forest and sequester two tons of carbon per year, then the maximum savings that bioenergy could have compared to fossil fuels would be 50 percent, assuming no fossil emissions involved in the production and use of bioenergy.
109. The same analysis was presented in two separate papers: Campbell et al. (2008), Field et al. (2008).
110. Hoogwijk et al. (2005), de Vries et al. (2007).
111. Beringer (2011).
112. This study assumed that every ton of carbon in biomass avoids one ton of carbon in fossil fuels when used for bioenergy. In fact, due to energy losses in the conversion process for cellulosic ethanol, the figure is less than half. Ultimately this study identified most of the bioenergy potential existed in shrublands in Asia and in temperate zones. By visual inspection, this analysis is likely to be capturing many regrowing forests, and the study did not estimate carbon losses from the forgone sequestration of such lands if forests were allowed to regrow.

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity and human well-being.

Our Challenge
Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision
We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach
COUNT IT
We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT
We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT
We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.