ENVIRONMENTAL IMPACTS OF BIOFUEL PRODUCTION AND USE

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Introduction

The 2007 Energy Independence and Security Act (EISA) required a significant increase in the production and use of renewable fuels. Given the current state of technology and infrastructure, nearly all of the projected volume of biofuel consumption over the foreseeable future is expected to be made up of three types of biofuel: corn-based ethanol, cellulosic-based ethanol, and biodiesel. The vast majority of the current volume of biofuels is in the form of corn-based ethanol, with lesser amounts of biodiesel from virgin vegetable oils, animal fats, and used cooking oils. Projections for future energy sources anticipate the development of processes to convert cellulosic biomass into ethanol or other biofuels to meet the target of 36 billion gallons of renewable fuels by 2022. The production and use of biofuels will result in different environmental impacts than petroleum fuels. In some cases, these changes will be positive, but in others, the changes could be negative. It is important to understand the adverse environmental impacts associated with the full biofuel supply chain, from field to wheel, to enable the long-term, beneficial development of biofuels.

Non-Climate Environmental Impacts

The environmental impacts of switching from petroleum-based fuels to those from other feedstocks must include the impacts across the complete life cycle of primary energy production, feedstock logistics, conversion to useful fuel, distribution and storage of the fuel, and fuel end use.

Biomass feedstocks include traditional agricultural crops, dedicated energy crops, agricultural residues, forest management residues, and urban wood waste. Dedicated energy crops can result in displacement of other crops, leading to changes in land use, and potentially to more intensive agricultural or forest management practices. These more intensive practices will be more likely to have the types of adverse environmental impacts associated with modern intensive agricultural production, such as increased runoff of fertilizers, herbicides, and pesticides; higher irrigation demand; and potential soil degradation. Additional impacts associated with increased biomass demand can occur in situations in which existing forests or other growth is displaced to meet that demand, whether for fuel or other uses.[1, 2] Additional impacts, such as changes in wildlife habitat, local air quality, and water quality and quantity are also possible.

Use of agricultural residues could impact soil quality if those residues had previously been plowed back into the soil. Use of forest residues could also result in changes to forest soil quality through the removal of material that would otherwise decompose naturally.

Because biomass requires a much greater land area to produce the same energy content as fossil fuels, there will be greater emissions from transportation from biofuel production to plant site (or alternatively, a larger number of plants located closer to the feedstock production), which can have adverse environmental impacts through increased air emissions from transporting feedstocks.

Increased transport of ethanol, either through pipelines or by truck or rail will result in increased potential spills of the fuel. The impacts of such spills include potential major fish kills if spilled into open water bodies, contamination of groundwater, mobilization of inorganic compounds such as iron and manganese, and the potential for generating noxious odors during decomposition.[3] When released into groundwater through fuel tank leaks, the presence of ethanol and gasoline can result in increased benzene concentrations compared to gasoline alone due to the changes in degradation chemistry caused by the ethanol.[3-5]

Increasing levels of ethanol in gasoline also changes the profile of compounds emitted to the air from engine operation. In general, higher ethanol concentrations tend to result in higher emissions of aldehydes, particularly formaldehyde and acetaldehyde.[6] Although emissions of other pollutants, including organic compounds, may decrease due to the higher oxygen content of ethanol-gasoline mixtures, some studies have estimated that wide-scale use of high-ethanol content fuel such as E85 (85% ethanol, 15% gasoline) could result in higher ambient ozone and aldehyde concentrations and therefore higher mortality rates compared to those that would be projected for conventional gasoline or low-ethanol content fuels (E10).[7]

In the conversion step of the supply chain, effluents from cellulosic ethanol plants are likely to include conventional air pollutants as well as waste water and solid residues. Lignin-based residues will likely be one of the more substantial byproducts of cellulosic ethanol production, although it also has value as a feedstock for non-fuel bio-based products or as a fuel for heat and power generation. Another potential solid effluent is gypsum from the use of lime to neutralize sulfuric acid used in the hydrolyzation processes.

Biochemical processes have been developed to use organisms and enzymes that have, in many cases, been developed specifically to enhance ethanol production.[8, 9] There is also considerable interest in feedstocks that have been bred or modified to maximize their energy production potential.[10-12] These biological materials include genetically-modified organisms (GMOs) that are not found naturally in the environment. The impacts of these materials if released into the environment are not understood, and therefore represent a key gap in our ability to evaluate the environmental risks and possible mitigation approaches to such releases.

Although thermochemical cellulosic ethanol plants can potentially increase emissions of air and water pollutants and solid wastes, these changes are likely to be similar in kind to emissions from other thermochemical processes that have been used commercially for decades. Beyond the question of emissions into water across the biofuel life cycle, biofuels (and particularly ethanol) will also impact water quantity. Recent life-cycle studies suggest significant increases in water consumption of up to 20 times that required for production of petroleum fuels,[13, 14] with one study concluding that corn-based ethanol will require over 1000 gal of water to produce 1 gal of ethanol in the U.S.[14]

A full life cycle assessment of the environmental impacts of biofuels will also need to include issues such as water consumption by feedstock production and conversion to fuel, soil productivity, and other parameters that are impacted by intensive agricultural practices. Finally, there have been considerable advances in the area of conversion of biomass to hydrocarbon fuels.[15] These processes may have different environmental impacts than the biochemically-based fermentation processes that produce alcohols, and both process developers and regulatory agencies need to be aware of such changes and how they may need to be addressed.

Life Cycle Impacts on Greenhouse Gas Emissions

The most immediate impact is through displacement of fossil energy and the consequent reduction in direct tailpipe emissions of fossil-based carbon dioxide (CO_2). However, because of the global impacts of CO_2 and other greenhouse gases (GHGs), emissions over the complete life cycle of biofuels, from feedstock production through end use, must be considered. The first-order impact of biofuels on GHG emissions will largely be determined by the life cycle energy balance for each of the different fuels.

Corn ethanol has been estimated to provide 25-65% more energy at the vehicle than the energy used to produce the fuel, while the energy gain for cellulosic ethanol was estimated at 340-560%. Biodiesel has been estimated to provide a 93% energy gain.[16-18]

Factors other than changes in life cycle CO_2 emissions are crucial to understanding the climate impacts of biofuels, the most important of which is the change in land use to meet the increased demand for fuel feedstocks. Several recent studies have estimated that the expected increases in cultivated land, either directly for fuel feedstocks or to replace cropland converted from food to fuel production, will result in significant increases in CO_2 emissions. One study estimated a net increase of 50-100% in U.S. biofuel-related CO_2 emissions due to this conversion,[2] and a second study estimated even higher releases from conversion of grassland, rain forest, and other uncultivated land outside the U.S. The second study estimated the short term CO_2 increases from land-use change to be 17-420 times the annual benefit from replacing gasoline with ethanol.[1]

Climate impacts must also include life cycle emissions of other GHGs. Of particular concern is N_2O, which is generated by nitrogen fertilizers applied to croplands (whether grain or cellulosic). One study indicates that warming effects due to these N_2O emissions are 1.0-1.7 times larger than the estimated "cooling" effect due to reductions in fossil CO_2 emissions, for both corn ethanol and soy biodiesel.[19] However, a separate study found that croplands were net GHG sinks, even accounting for N_2O.[20]

Finally, there are climate-related impacts beyond direct life cycle emissions of GHGs. Changes in land use have the potential to alter the albedo of the land, in some cases to lower the amount of solar radiation that is reflected back into space and resulting in greater energy capture, and therefore greater warming. The effects are thought to be small in comparison to the albedo effects of clouds, sea ice, and snow. Although additional study is needed to quantify the magnitude (and even the direction) of these changes, large-scale changes in land use due to increased biofuel production does have the potential to change surface albedo such that warming is increased rather than decreased.[21] Soil carbon is also vulnerable to change due to cultivation and climate. It is currently thought that soil carbon content increases as temperature increases, but these changes appear to be temporary.[22] Such changes can be minimized or even reversed by using the appropriate cultivation techniques.[23]

The impacts of large-scale shifts of land to dedicated energy crop production will extend beyond the U.S., reflecting the global markets for food and fuel feedstocks. Not only will the above impacts associated with GHG emissions and albedo be extended, these large areas of energy crop production will also be vulnerable to changes in climate. Production, as it always has, will depend upon temperature, precipitation, and pest and disease damage. Climate and biofuels are closely related in many ways, and it is crucial to clearly understand those relationships if biofuels are to play a beneficial role in addressing climate change.

Conclusions

Biofuels have promise in their ability to displace fossil fuels, but the current biofuel production and conversion processes have considerable environmental problems that cast numerous questions on their sustainability. Further research and development, much of it underway, is needed before biofuels can achieve their full potential.

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