Assessing the Global Potential and Regional Implications of Promoting Bioenergy

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Abstract
There is no simple answer to the question "are materials from bio-based feedstocks environmentally, and socially, preferable?" Bioenergy as an alternative energy source might be effective in reducing fossil fuel use, slowing global warming effects, and providing increased revenue for the farming community, but its production may contribute to other aspects, such as degraded soil and water quality and land use changes. This brings into question how we define and measure 'sustainability.'

The benefits of bioenergy have come under increasing scrutiny as researchers look closer at the global environmental impact of production. For example, diverting corn to make bioethanol could result in shifting production to competing crops, such as soybean, or the conversion of lands to corn production. The overall impacts of these types of shifts are not well understood. If used properly, bioenergy can help us meet our needs while maintaining ample supplies of food, animal feed, and clean water supplies. To make this happen, well thought out national bioenergy policies that support the best options are needed for both the short and long-term future.

Some studies are called 'life cycle analysis' but only focus on a particular issue or pollutant of concern, such as greenhouse gas emissions, while others focus on the net energy gain or loss question. These focused studies fall short of a complete life cycle approach that helps us recognize how our choices influence each point of the life cycle so that we can balance potential trade-offs and avoid shifting problems from one medium to another and/or from one life cycle stage to another.

This paper explores how systems thinking, such as life cycle assessment, can help decision-makers view the potential 'cradle-to-grave' impacts of various types of biofuels and, thereby, choose the most favorable options that will keep us on the path toward sustainability.

Introduction

Current energy supplies in the world are dominated by fossil fuels (80%) with biomass resources providing 10-15% of global energy demand (over 400 exajoules per year). In order to increase the use of bio-based energy, policy drivers are being promoted by governments in the US, Europe, and around the globe. The 2003 EU directive on 'biofuel and other renewable fuels' states that 2% of the fuels for transportation should be biofuels by the end of 2005, and 5.75% by the end of 2010. In the US, President Bush signed into law the Energy Independence and Security Act of 2007 (EISA) which requires biofuel production to increase ninefold by 2022 in order to meet the renewable fuel standard for gasoline. However, these types of policies presume a black-and-white situation in which fuels are either renewable or non-renewable, that is, they are viewed as either good or bad. Careful analysis shows that different biofuels rely on different non-renewables to varying extents. The issue of environmental impacts related to bio-based materials, including biofuels, is a complicated one. There is a need to have appropriate sustainability metrics for renewable-based technologies.

The environmental and socioeconomic pluses and minuses of biofuels are readily available in the open literature, in reports and on the internet. At the national, regional and global levels three main drivers for the development of bioenergy and biofuels seem to emerge: climate change, energy security and rural development. The full picture, however, is much more complex as biofuels differ widely in environmental, social and economic impacts. An expanding range of obstacles can be seen from the acquisition and processing of feedstocks, to transport constraints, and air and water quality issues. Table 1 lists some examples of the advantages and disadvantages related to biofuels.

Table 1. Example environmental and socioeconomic advantages and disadvantages of biofuel production and use

Advantages of biofuels:	**Disadvantages of biofuels:**
• Reduction of imported crude oil	• Energy intensive production
• Renewability	• Runoff of agrochemicals to water
• Rural development	• Uses of limited water supplies
• Use of waste material	• Threatened and endangered species
• Reduction in greenhouse gas emissions	• Increased soil erosion
	• Land conversion effects
	• Introduction of invasive species

The word 'biofuel' covers a wide variety of products with many different characteristics and a wide range of potential savings in terms of greenhouse gas emissions. Each biofuel must be assessed on its own merits. Of course the specific advantages and disadvantages vary depending on whether we are considering biofuels from a cultivated feedstock, such as corn, from a waste material, such as corn stover, or from a lower maintenance source, such as perennial grasses.

Evaluating the Environmental Impacts of Biofuels

The following subsections contain brief descriptions of the various global and regional considerations that have been drawing attention to discussions about increasing the production and use of biofuels.

Fossil Fuel Use and Depletion

The world consumes over 85 million barrels of oil a day (EIA, 2008). A reduction in this level of consumption is the overarching goal of biofuel promotion. At the national level, countries are striving to reduce their dependence on oil from foreign sources. Substituting fossil-based feedstocks with domestic (home-grown) bio-based feedstocks to produce fuels is one way to accomplish these goals. The alternatives include alternate energy sources (solar, fuel cells) or a reduction in energy demand. However, the selection of a fossil fuel alternative requires knowledge of the net energy balance.

Net Energy Balance

The net energy balance of ethanol is calculated by taking the amount of energy contained in a gallon of ethanol (roughly 76,000 Btu) and subtracting the amount of energy that goes into producing a gallon of ethanol. Critics have argued that the net energy gain of the resulting fuel is modest because large amounts of energy are required to grow corn and convert it to ethanol (Pimentel, 2003). Some have even calculated that it has a negative net energy value, meaning that ethanol requires more energy to make than it actually produces. However, numerous studies have shown that ethanol has a positive net gain (e.g. USDA, 2002).

The net energy can be increased if fuel production is based on the use of low-maintenance crops, such as switchgrass. Algae is another possible, lower-energy alternative. Although, the production of biofuels based on switchgrass or algae will require significant policy changes because the technologies to produce such fuels are not fully developed.

Global Warming

Some argue that because plants and trees are the raw material for biofuels and need carbon dioxide to grow, the use of biofuels does not add carbon dioxide (CO_2) to the atmosphere, it just recycles what was already there. On the other hand, the use of fossil fuels, , releases carbon that has been stored underground for millions of years, resulting in a net addition of CO_2 to the atmosphere. Similarly, engines running on biofuels emit CO_2 (the primary source of greenhouse gas emissions) just like those running on gasoline. Furthermore, because it takes fossil fuels – such as natural gas and coal – to make biofuels, they are not quite "carbon neutral." A number of recent studies have attempted to assess the total carbon footprint of biofuels. While research by the USDA has shown that biofuels have the potential to remove CO_2 and other greenhouse gases from the atmosphere (USDA, 2007), others have concluded that the global warming potential of biofuels varies widely from being worse than gasoline to being about the same (Fargione et al, 2008). This can be attributed to the formation of non-CO_2 global warming compounds. For example, researchers have calculated that growing some of the most commonly used biofuel crops releases around twice the amount of the potent greenhouse gas nitrous oxide (N_2O) than previously thought, hence, wiping out any benefits from not using fossil fuels and, worse, contributing to global warming (Crutzen et al, 2007).

Air Quality

Variations in chemical and physical characteristics of the various biofuels lead to large differences in the species of pollutants in exhaust emissions. Uncertainty arises from the use of regulated drive cycles versus actual data from real-world tests. Because biofuels are relatively new to the modern vehicle, many of the emission factors that are taken for granted with fossil-fuel powered vehicles should be re-analyzed for biofuels. For example, formaldehyde and acetaldehyde emissions are suspected to be higher from vehicles running on bioethanol. Although formaldehyde and acetaldehyde are naturally occurring and are frequently found in the wider environment, additional emissions may be important due to their role in smog formation and direct effects on health. It remains unclear whether the atmospheric concentrations that might result from a major shift in urban fuel use towards ethanol would be sufficient to cause health worries. More research is required on this topic.

Land Use

There are many competing demands on land: to grow food, for conservation, urban development and recreation. Increasing demand for agricultural products as feedstocks for bioenergy and biofuels constitutes a significant change for the commodity markets. This is illustrated in the unprecedented demand for corn arising from the expanding bioethanol production. One impact is likely to be an increase in land area for feedstocks, either from reallocation of land from other crops, use of set-aside land taken (within Europe), or from cultivation of new land in many developing countries, particularly South and Latin America. Harmful deforestation is already occurring to fill the need to expand agricultural lands. Certain land types, such as peat lands and tropical forests, represent large carbon sinks. Their conversion to cropland for biofuels will result in greater emissions of soil carbon. Therefore, biofuel development can have major consequences on land use.

Food-for-Fuel

Biofuels are currently produced from the products of conventional food crops such as the starch, sugar, and oil feedstocks from crops that include wheat, corn, sugar cane, palm oil and oilseed rape. Any major switch to biofuels from such crops would create a direct competition with their use for food and animal feed. In some parts of the world we are already seeing the economic consequences of such competition. The larger the amount of productive land diverted away from food production to grow biofuel crops, the larger the implications for food availability and prices. Future biofuels are likely to be produced from a much broader range of feedstocks including the lignocellulose in dedicated energy crops, such as perennial grasses, from forestry, the co-products from food production and domestic vegetable waste (The Royal Society, 2008).

Soil Quality

Soil erosion is one form of soil degradation along with soil compaction, low organic matter, loss of soil structure, poor internal drainage, salinisation, and soil acidity problems. Typical tillage and cropping practices lower soil organic matter levels, cause poor soil structure, and result in compaction which increases soil erodibility. Carbon compounds in waste biomass that is left on the ground are consumed by microorganisms and broken down to produce valuable nutrients that are necessary for future crops. When cellulosic ethanol is produced from feedstock (like switchgrass and sawgrass) the nutrients that are required to grow the lignocellulose are removed and cannot be processed by microorganisms to replenish the soil nutrients. The soil is then of poorer quality. On a larger scale, plant biomass waste provides small wildlife habitat, which in turn ripples up through the food chain. The widespread human use of biomass which would normally compost the field could threaten these organisms and natural habitats.

Water Quality

A study from the World Resources Institute indicates that the development of a corn-based ethanol market would only exacerbate problems already associated with large-scale corn production. Such problems include groundwater depletion, soil erosion[1], algae blooms, and

[1] Sediment which reaches streams or watercourses can accelerate ban erosion, clog drainage ditches and stream channels, silt in reservoirs, cover fish spawning grounds and reduce downstream water quality.

the formation of "dead zones" in waterways inundated with pesticide and fertilizer runoff (WRI, 2006). For example, it is well-known that agricultural nutrient losses contribute to hypoxia in the Gulf of Mexico and eutrophication in the Great Lakes of North America. The input of artificial fertilizers to increase yield must be carefully monitored in order to prevent or reduce their migration to surface waters. Improved agronomic practices will undoubtedly play a key role in mitigating negative environmental impacts through the timing and proper application of fertilizers.

Water Availability

In some locations, the availability of water can be a fundamental consideration in the cultivation of crops for biofuel production. Water is required throughout the entire biofuel supply chain, and is best documented for feedstock production. Distribution of water resources varies greatly according to location and time. Globally, pressures on water supply are increasing from a growing population, per capita usage and the impacts of climate change. Consequently, water for all uses is becoming scarce. Developments in the agricultural sector for food and non-food crops will have important implications for water usage and availability. Increased usage of biofuels will raise demand for water, which could, in turn, have a negative impact on water availability for other uses.

Biodiversity

Biodiversity is an important role in ecosystem functioning and its ability to contribute to essential services such as providing food, livelihood, and recreation. However, over the past few centuries human activity has resulted in fundamental and irreversible losses of biodiversity. Globally, habitat conversion for agriculture and forestry has been a major driver of this loss; for example, more land was converted to cropland between 1950 and 1980 than between 1700 and 1850 (The Royal Society, 2008). Most experts recognize two aspects that must be considered as indicators of biodiversity, ‘species richness’ and ‘relative abundance,’ although researchers continue to seek out more effective measures.

Invasive Species

Invasive plants are introduced species that can thrive in areas beyond their natural range of dispersal. Ideal energy crops are also commonly found to be invasive species. For example, several grasses and woody species are being considered for biofuel production, with perennial grasses showing the most economic promise. However, these grasses can be invasive if introduced into some US ecosystems. Not only can they crowd out native species, threatening riparian areas, they can also alter fire cycles. Internationally, there has been little success in eradicating or even controlling invading grasses. (Raghu et al, 2006).

Socio-Economic Aspects

Of course, the rate of production and use of agricultural feedstocks, like corn, soybean and sugar, is affected by global economic markets. In the US, corn growers will likely benefit financially from the increased demand for their product. However, in developing countries, areas of high biomass productivity are often areas of low wealth and earnings. In these areas, socio-economic benefits could be significant. It will be important to facilitate technology transfer to developing countries, particularly for key technologies such as those that increase feedstock yield or processing qualities of biomass. There is already attention focused on the diversifying of the energy matrix in many countries, looking to increase the number and variety of crops that can be cultivated for bioenergy. Programs are needed to ensure that the rural and regional economies benefit from the domestic production and use of feedstocks as well, as their export (The Royal Society, 2008).

Tools for Sustainability

The use of renewable resources is not synonymous with sustainability. Given that the efficiency of many petrochemical processes is often very high, it is possible that processes based on petrochemicals can be 'more sustainable' than similar ones that are based on renewables. Therefore, we need to have measuring tools to look at the complete process, to complete value chain, andto be able to judge the sustainability of a process or a transformation in industry (Dewulf and Langenhove, 2006).

Several tools have been developed in an attempt to capture the view of the complete value chain, or life cycle system. Table 2 lists and briefly describes ten analytical approaches and tools that are commonly used to assess the environmental impacts biofuels. There seems to be no clear definition of these terms and there is still variability regarding what they measure and what units are to be used. Furthermore, this paper is intended to discuss general approaches, and not specific tools, such as EPA's MOVES[2] or DoE's GREET[3].

It is common to find studies that are called 'life cycle' but focus on a particular issue or pollutant of concern, such as a life cycle assessment of greenhouse gas emissions. Other studies focus on the net energy gain or loss question. However, an energy balance addresses the wrong question, since not all BTUs are created equal. An energy balance assumes that one BTU of energy available from one energy carrier is equal to a BTU from any other energy carrier. This assumption is invalid since we do not value energy *per se* but rather we value the service it offers (Dale, 2007).

These types of narrowly-defined studies fall short of a complete, multi-media life cycle approach that enables us to recognize how our choices influence each point of the life cycle in order to balance potential trade-offs and avoid shifting problems from one medium to another (e.g., controlling air emissions which creates wastewater effluents or soil contamination) or from one life cycle stage to another (e.g., the raw material acquisition stage which impacts upon the consequences of reuse of materials for subsequent life cycles of products). The role of LCA is crucial in determining the values of the various metrics and emissions along the entire chain of biofuel production and, as such, must be applied to different processing techniques available now and those that might become available after research, development and demonstration (The Royal Society, 2008).

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[2] MOtor Vehicle Emission Simulator (MOVES)
[3] Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model

Table 2. Analytical approaches and tools that are used to evaluate biofuels

Carbon Balance - also called carbon footprint, measures the total amount of carbon dioxide (CO_2) emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product, process, or activity.
Ecological Footprint – calculates human demand on nature by measuring the land and sea area required to provide all the natural (biological) resources and services to maintain a given consumption pattern, including the resources it consumes and the ability to absorb the waste generated by fossil and nuclear fuel consumption. This can then be compared to available bio-capacity, also expressed in land and sea areas, measured in 'global hectares' (gha).
Exergy Analysis - based on the second law of thermodynamics, exergy is a mathematical calculation of the loss of available work across a system. Exergy, like energy, is measured in joules.
Fuel Cycle Analysis – quantifies air emissions and assesses their health impacts as they correspond to each step in the life cycle of a fuel. Emissions from facility and vehicle manufacturing are not included.
Life Cycle Assessment (LCA) – evaluates the multi-media, cradle-to-grave burdens associated with an industrial system by quantifying energy and materials used and wastes released to the environment and assessing potential impact such as such as global warming, human health, eco-toxicity, eutrophication, acidification, smog formation, ozone depletion, resource use, etc.
Life Cycle Greenhouse Gas Analysis – quantifies the total amount of carbon dioxide (CO_2) and other greenhouse gases emitted over the full life cycle of a product, process, or service. Usually expressed as grams of CO_2-equivalents, a GhG analysis accounts for the different global warming effects of different greenhouse gases.
Material Flow Analysis (MFA) - quantifies and analyzes the flows (kg) of a material (or a substance in a 'substance flow analysis') in a well-defined system under study.
Net Energy Balance – a unitless ratio that is derived by dividing the useful energy contained in a product (such as a fuel's energy released in burning) by the total energy inputs to a system. A ratio of less than one indicates a net energy loss.
Material Intensity per Service Unit (MIPS) - quantifies the material intensity of a product or service by adding up the overall material input which humans move or extract to make that product or provide that service. It puts life cycle thinking at the beginning of the product chain. MIPS is measured in kilogram per unit of service.
Sustainable Development Indicators – a selected group of categories for which information and data on the economy, society and the environment are needed to determine if actions are heading toward a satisfactory outcome. Indicators for environmental sustainability include the state of the environment as well as future environmental conditions.

Avoiding a Fragmented Approach to Sustainability

The definition of sustainability often includes the three conditions of economic, social and environmental "endowments" and "liabilities" that we embrace and pass on to future generations. In addition to the above environmental assessment tools, there is a need to incorporate social and economic assessments of biofuels to ensure that overall sustainability can be addressed. Instead of a fragmented approach toward sustainable development one should examine the linkages between environmental indicators and socio-economic factors that influence and interact with the indicators. Future research efforts should be directed to further define these linkages and provide guidance for decision makers to integrate all three facets of sustainability into the decision-making process.

Conclusions

The benefits, as well as the drawbacks, of biofuels have come under increasing scrutiny as researchers and policy makers look closer at the global environmental impact of their production. Unintended consequences may reduce or override the expected benefits. The widespread deployment of biofuels will have major implications for land use, with associated environmental impacts that must, in turn, be assessed. For example, diverting corn to make biofuels could result in shifting production to competing crops, such as soybean, or the conversion of lands to corn production. The overall impacts of these types of shifts are not well understood. In order to achieve sustainability, biofuels need to be approached at the international level in order to capture both global and local issues. If used properly, biofuels can help us meet our energy needs while maintaining ample supplies of food, animal feed, and clean water supplies. To make this happen, well thought out national biofuels policies that support the best options are needed for both the short and long-term future.

In addition, biofuels must be assessed by integrating the environmental information with the economic and social aspects of the full life cycle, from growth of the biomass, transport to the refinery, refining, distribution to consumers, and ultimately, end use. Since it is likely that international trade in these commodities is likely to expand in coming years, it is essential that we use the appropriate assessment tools and establish a commonly-accepted set of sustainability criteria, by which to assess the different biofuels and bio-feedstocks, including food and non-food, and their production systems. A coherent biofuels policy must address and balance all these factors if biofuels are to make a sustainable contribution to reducing climate change and improving energy security.

The application of a life cycle view will be an essential requirement if we are to achieve the potential that is offered by the newly emerging bio-economy. Members of the scientific community need to actively communicate and work together to develop a consensus on what the science needs are to support our policy-makers in delivering sustainable energy systems.

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