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A Review of Life-Cycle Based Tools Used to Assess the Environmental Sustainability of Biofuels in the United States

Mary Ann Curran, Ph.D.

Life Cycle Assessment Research Center
U.S. Environmental Protection Agency
Cincinnati, Ohio, 45268

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Systems Analysis Branch
Sustainable Technology Division
National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Cincinnati, Ohio, 45268

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) within the Office of Research and Development (ORD) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

This publication has been produced as part of ORD’s strategic research plan. It is published and made available to assist the user community and to link researchers with their clients. The production, distribution, and use of biofuels have been analyzed in the literature using several different life cycle assessment methodologies, leading to variant assessments. These literature reports attempted to capture benefits and environmental impacts, sometimes even considering sustainability considerations. The differences in the methodologies raised the question of gaps that need to be filled for conducting useful life cycle analysis (LCA)-based assessment of biofuels. This publication is such a gap analysis that points to development needs for satisfying sustainability and regulatory concerns with respect to various different biofuels development and their production, distribution and use. A peer-reviewed journal article derived from the data and information in this report was published in the open literature (Curran MA (2012) “Assessing Environmental Impacts of Biofuels Using Lifecycle-Based Approaches,” *Management of Environmental Quality: An International Journal,* Vol 24(1); 34 – 52). This report is being made available to the user community by EPA’s Office of Research and Development as supplemental material.

Cynthia Sonich-Mullin, Director
Sally Gutierrez, Director 2004-2011
National Risk Management Research Laboratory

Abstract

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

The issue of environmental sustainability related to bio-based materials is a complicated one. Achieving sustainability requires a re-thinking of our systems of production, consumption and waste management and an increased awareness of the need to avoid the shifting of problems, which often occurs with isolated measures. The environmental advantages should outnumber or outweigh the disadvantages to the environment and human health. The benefits of bioenergy have come under increasing scrutiny as researchers look closer at the global environmental impact of their production. For example, increased demand for corn could result in diverting corn supplies from making food and feed to making bioethanol, which could in turn affect the production of competing crops such as soybean, or the conversion of lands to use for corn production. The overall impacts of these types of shifts are not well understood. If used properly, bioenergy can help the United States meet its needs while maintaining ample supplies of food, animal feed, and clean water. 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.

Life Cycle Assessment (LCA) is a developing tool that can assist decision-makers in evaluating the comparative potential cradle-to-grave, multi-media environmental impacts of their actions in order to prevent unintended consequences. Some studies are called "life cycle analysis," but focus on a particular issue or pollutant of concern such as greenhouse gas emissions or 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 report explores how a systems thinking approach, such as LCA, can help decision-makers view the potential "cradle-to-grave" environmental impacts of various types of biofuels and, thereby, choose the most favorable options that will keep us on the path toward sustainability. Ten tools that incorporate a life cycle perspective to evaluate biofuels were studied and compared: Carbon Management, Ecological Footprint, Exergy Analysis, Fuel Cycle Analysis, Greenhouse Gas Life Cycle Analysis, Life Cycle Assessment, Life Cycle Risk Assessment, Material Flow Analysis, Net Energy Balance, and Sustainability Indicators. Discussion on data and information needs is also provided.

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Acronyms and Abbreviations

AFOLU	Agriculture, Forestry and Other Land Uses
Btu	British Thermal Unit
CEA	Comprehensive Environmental Assessment
CED	Cumulated non-renewable Energy Demand
CH_4	Methane
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DDGS	Distillers' Dried Grains with Solubles
DOE	U.S. Department of Energy
E85	Automotive fuel that is 85% ethanol and 15% gasoline
EBAMM	ERG Biofuel Analysis Meta-Model
EC	European Commission
EIA	Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EPA	U.S. Environmental Protection Agency
ETOX	Ecotoxicity
EU	European Union
GHG	Greenhouse Gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
J	Joule
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCRA	Life Cycle Risk Assessment
LLNL	Lawrence Livermore National Laboratory
LUC	Land Use Change
MAIA	Material Intensity Assessment
MIPS	Material Intensity Per Service unit
MFA	Material Flow Analysis, or Material Flow Accounting
MOVES	Motor Vehicle Emission Simulator
MTBE	Methyl *Tertiary*-Butyl Ether
N_2O	Nitrous Oxide
NAS	National Academy of Sciences
NEB	Net Energy Balance
NEV	Net Energy Value
NRMRL	National Risk Management Research Laboratory
NO_x	Nitrogen oxides
RFS	Renewable Fuel Standard
SO_2	Sulfur Dioxide
TMR	Total Material Requirement
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	U.S. Department of Agriculture
WBCSD	World Business Council for Sustainable Development
WRI	World Resources Institute
WWF	World Wide Fund for Nature (formerly the World Wildlife Fund)

1.0 Introduction

Energy supplies in the world are dominated by fossil fuels (80%) with biomass resources providing 10-15% of global energy demand (approximately 500 quadrillion Btu) over the next several years (U.S. Department of Energy 2009). In order to increase the use of bio-based energy, policy drivers are being promoted by governments in the United States, the European Union (EU), 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 United States, 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 were originally formed on the notion that fuels are either renewable or non-renewable; that is, they are viewed as either good or bad (EISA later included greenhouse gas emission threshold requirements and the EU added sustainability and greenhouse gas criteria.)

The word "biofuel" covers a variety of products with many different characteristics and a wide range of potential GHG savings as well as other environmental impacts. Accordingly, each biofuel must be assessed on its own merits. Of course, the specific advantages and disadvantages vary depending on whether one is considering biofuels from a cultivated feedstock (e.g., corn), from a waste material (e.g., corn stover), from a lower maintenance source (e.g., perennial grasses), or from other next generation feedstocks (e.g., algae).

Careful analysis shows that different biofuels rely on different non-renewables to varying extents. Furthermore, issues of sustainability and environmental concerns have been raised in response to the wide-scale production and use of conventional biofuels. For example, corn grain and soybean production practices are associated with high rates of fertilizer and pesticide use, extensive water consumption in some regions, and many deleterious environmental effects such as soil erosion, surface water pollution, air pollution, and biodiversity losses (Williams, Inman et al. 2009). The issue of environmental impacts related to bio-based materials, including biofuels, is a complicated one. There is a need to have appropriate metrics for renewable-based technologies in order to better assess their overall sustainability.

The environmental and socioeconomic pros and cons of biofuels are readily available in the open literature (i.e., published 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. These impacts can occur throughout the life cycle, from the acquisition and processing of feedstocks, to transport constraints, and air, water, and land quality issues. The overall merits of biofuels are being openly debated, especially regarding the issue of whether biofuels have a positive energy balance. The pros and cons held by the general public regarding the advantages and disadvantages of biofuels are identified in Table 1.

Table 1. Commonly Perceived Environmental and Socioeconomic Pros and Cons of Biofuel Production and Use Compared to Conventional Gasoline as Observed by the Author

PROS	CONS
• Use of renewable feedstocks	• Energy intensive production
• Net energy gain	• Land conversion effects
• Reduced greenhouse gas emissions	• Food for fuel tradeoff
• Reduction of imported crude oil	• Increased soil erosion
• Increased National security	• Runoff of agrochemicals to water
• Rural development	• Use of limited water supplies
• Use of waste materials	• Threatened and endangered species
• Corn is a known commodity	• Lower energy content
	• Introduction of invasive species

2.0 The Environmental Impacts of Biofuels

Public awareness has increased as consumers have become more knowledgeable of the fact that it is not only the end product, but also the manufacture of biofuels that needs to be investigated. The following subsections contain brief descriptions of the various global and regional considerations (from Table 1) that have been drawing attention to discussions about increasing the production and use of biofuels.

2.1 Fossil Fuel Use and Depletion

The world consumes over 85 million barrels of liquid fuels per day, with the United States alone consuming over 18 million barrels per day (EIA 2010). Over half of the world's proved oil reserves are located in the Middle East. How much recoverable crude oil is available is never precisely known; current estimates range from 1,184 to 1,342 billion barrels (EIA 2010). The debate continues over whether proven world oil reserves can meet increasing demand.

A reduction in the level of end-use consumption of petroleum 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 this goal (alternate energy sources, such as solar cells, and reduced energy demand are other ways).

2.2 Net Energy Balance

Much attention has been given to determining if the manufacture and use of biofuels is a net gain or a net loss when compared to gasoline. The Net Energy Balance (NEB) of a fuel is calculated by taking the amount of energy contained in the fuel (a gallon of ethanol contains roughly 76,000 Btu) and subtracting the amount of energy that goes into its production. Critics have argued that the net energy gain of the resulting ethanol 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, other researchers have concluded that ethanol has a positive net gain (Patzek 2004). While the calculation of NEB depends on many factors, such as how co-product energy credits are taken into account, the majority of reports in the open literature indicate that corn-based ethanol provides more energy than is required to make it, albeit to varying degrees (von Blottnitz and Curran 2007).

Corn farmers using state-of-the-art, energy efficient farming techniques and ethanol plants integrating state-of-the-art production processes can double the amount of energy contained in a gallon of ethanol and the by-products compared to the energy needed to grow and convert the corn into ethanol. Further, as the ethanol industry expands, it may increasingly rely on more abundant and potentially lower-cost cellulosic crops (i.e., fast growing trees, grasses, etc.). When that occurs, the net energy of producing ethanol will become even more attractive (Lorenz and Morris 1995). NEB, however, continues to be one of the most controversial issues related to bioethanol.

2.3 Global Warming

Focusing on the greenhouse gas (GHG) carbon dioxide, using fossil fuels releases carbon that has been stored underground for millions of years and results in a net addition of CO_2 to the atmosphere. Meanwhile, the argument has been made that biofeedstocks do not add CO_2 to the atmosphere; their use simply recycles what was already there. The Intergovernmental Panel on Climate Change (IPCC) guidelines instruct that CO_2 emissions from biomass (called biogenic CO_2) that are used for energy and fuels be excluded from the total CO_2 emissions figure, that is, they are, in effect, reported as zero, as long as the biomass is grown sustainably. However, net CO_2 emissions are covered in the AFOLU (Agriculture, Forestry and Other Land Uses) Sector, which considers land use changes (IPCC 2006). Furthermore, because it takes fossil fuels, such as natural gas and coal, to make biofuels, they are not quite "carbon neutral."

Production is only part of the story. Engines running on either biofuels or gasoline emit CO_2 in the use phase. 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 GHGs (such as nitrous oxide, N_2O, methane, CH_4, and sulphur hexafluoride, SF_6) from the atmosphere (USDA 2007), others have concluded that the global warming potential (GWP) of biofuels varies widely from being worse than gasoline to being about the same (Fargione J, Hill J et al. 2008). This can be attributed to the formation of non-CO_2 global warming compounds. For example, researchers calculated that if new reactive nitrogen enters the terrestrial biosphere, as when nitrogenous fertilizer is applied to a biofuel (or any other) crop, then on average 3-5% of that nitrogen will appear in the atmosphere as N_2O. They theorize that this contribution explains the observed increase in the global atmospheric concentration of N_2O that has accompanied large-scale fertilizer nitrogen use since the beginning of the 20th century (Crutzen, Mosier et al. 2007).

2.4 Air Quality Concerns from Combustion in Vehicles

The distinct dissimilarities in chemical and physical characteristics between the various biofuels and conventional fossil fuels result in vehicle exhaust emissions that are significantly different. Because biofuels are relatively new, many of the emission factors that are typically used to estimate emissions from the combustion of fossil fuels should be re-analyzed for biofuels. For example, formaldehyde and acetaldehyde emissions are suspected to be higher from vehicles running on bioethanol (Poulopoulos, Samaras et al. 2001; Biello 2007). Although formaldehyde and acetaldehyde are naturally occurring and found frequently throughout the environment, additional emissions may be important due to their role in smog formation and direct effects on human health. One researcher went so far as to say that if every vehicle in the United States ran on fuel made primarily from ethanol instead of pure gasoline, the number of respiratory-related deaths and hospitalizations would likely increase (Jacobson 2007). Numerous studies on ethanol-oxygenated fuel emissions have been conducted, including EPA's testing of oxygenated fuels for section 211(b) of the Clean Air Act (EPA October 15, 2007), the 1999 report to the California Environmental Policy Council on the health and environmental assessment of the use of ethanol as a fuel oxygenate (LLNL 1999), and the Auto/Oil Air Quality Improvement Research Program in the 1990s (Burns, Benson et al. 1991). However, not all possible mixtures of ethanol and gasoline have been evaluated.

It remains unclear whether the atmospheric concentrations that might result from a major shift in urban fuel toward ethanol would be enough to cause significant health impacts. More research is required on this topic (The Royal Society 2008).

2.5 Land Use Impacts from Biofeedstock Supply

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 expanding bioethanol production. The use of corn for ethanol has accelerated over recent years. In the four-year period beginning in the fall of 2005, ethanol increased its share of total U.S. corn use including exports from 14.2% to 30.5% (Wisner 2009). One impact is likely to be an increase in land area for feedstocks, either from the reallocation of land from other crops[1], the use of set-aside land taken (within Europe), or from the cultivation of new land in many developing countries, particularly South and Latin America. Harmful deforestation is already occurring worldwide to fill the need to expand agricultural lands. Certain land types, such as peat lands, tropical rain forests, savannas, and grasslands, represent large carbon sinks. Their conversion to cropland for biofuels will result in greater emissions of soil carbon (Eide 2008). Therefore, not only should direct impacts to land where biofuel feedstocks are grown be considered, but also these types of indirect impacts should be considered. Such direct and indirect impacts are equally important. It is apparent how biofuel development can have major consequences on land use.

2.6 Food-for-Fuel

Biofuels are produced from the products of conventional food crops such as the starch, sugar, and oil feedstocks from crops, including wheat, corn, sugar cane, palm oil and rapeseed oil. Any major switch to biofuels from such crops would create competition with their use as food and animal feed. In some parts of the world, the economic consequences of such competition can already be seen as large amounts of productive land are being converted from food production to biofuel crops, leading to large implications for food availability and prices. In order to help avoid such competition, 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, forestry products and by-products, the co-products from food production, and domestic vegetable waste (The Royal Society 2008).

2.7 Soil Quality

Forms of soil degradation include soil erosion, soil compaction, low organic matter, loss of soil structure, poor internal drainage, salinization, 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 left on the ground, such as corn stover, are consumed by microorganisms and degraded to produce

[1] The increase in corn supplies in the U.S. was obtained by a large increase in the amount of land dedicated to corn; this shift in land to corn came out of land that previously was used for other crops, most notably soybeans.

valuable nutrients for future crops. When cellulosic ethanol is produced from feedstocks like stover, 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. The widespread human use of biomass, which would normally compost the field, could threaten these organisms and natural habitats (ETC 2008).

There are also issues related to changes in farming practices that may occur in order to meet changing market demands. Double cropping, such as harvesting wheat crop by early summer then planting corn or soybeans on that acreage for harvest in the fall, and switching to planting continuous corn instead of rotating with soybean could result in needing to apply more pesticides and fertilizers, which may have longer term impacts.

2.8 Water Quality Impacts

A study from the World Resources Institute (WRI) indicates that the development of a corn-based ethanol market would only exacerbate problems already associated with large-scale corn production. Such problems include soil erosion, which can reduce downstream water quality, algae blooms, and the formation of "dead zones" in waterways inundated with pesticide and fertilizer runoff (World Resources Institute 2006). For example, it is well-known that agricultural nutrient releases 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.

2.9 Water Availability

Globally, pressures on water supply and quality are increasing from a growing population, per capita usage and the impacts of climate change (UNESCO-WWAP 2006). In some locations, the availability of water can be an important consideration in biofuel production. While most often thought of in feedstock production (i.e., crop irrigation), water is required throughout the entire biofuel supply chain with the distribution of water resources varying greatly according to location and time. 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 and result in a negative impact on water supplies (The Royal Society 2008).

2.10 Loss of Biodiversity

Biodiversity, also called biological diversity, plays an important role in ecosystem functioning, particularly its ability to contribute to essential services such as providing food, livelihood, and recreation. 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). Converting land to grow a single crop in a large area, or monoculture, increases yield but reduces biodiversity. Most experts recognize two aspects that must be considered as indicators of biodiversity: the number of different species in a given area (species richness) and how common or rare a species is relative to other species in a defined location or community (relative species abundance). However, there are many outstanding issues that are yet to be resolved, such as the definitions of species and the identification of a suitable area in which to measure biodiversity. Researchers continue to seek out more effective measures of biodiversity to move toward more sustainable practices (Suneetha 2010).

2.11 Introduction of 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 an 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 U.S. 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, Anderson et al. 2006).

2.12 Socio-Economic Aspects

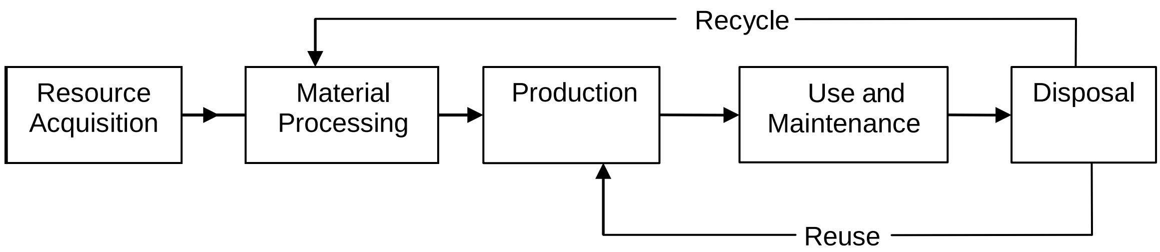
Of course, the rate of production and use of agricultural feedstocks, like corn, soybean and sugar, is affected by global economic markets. At the regional level, Midwest-U.S. corn growers will likely benefit financially from the increased demand for their product. In developing countries, areas of high biomass productivity are often areas of low wealth and earnings. In these areas, the socio-economic benefits of production 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. Also, some feedstocks are also used for food and their use for fuel production may result in price increases. Other feedstocks, such as waste biomass, will not have that impact. Since different feedstocks result in different impacts, attention is being focused on diversifying the energy matrix in many countries. As such, many countries are looking to increase the number and variety of crops that can be cultivated and collected for bioenergy. Programs are needed to ensure that rural and regional economies benefit from the domestic production, use, and export of feedstocks (The Royal Society 2008).

3.0 Life-Cycle Based Analytical Approaches and Tools Selected for Study

As pointed out previously, the use of renewable resources is not synonymous with sustainability. A myriad of factors relating to fuel and feedstock production and use must also be considered. Therefore, we need to use tools to measure the complete process and value chain before we can evaluate the sustainability of a process or the 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 (see Figure 1). It is common to find studies that are called "life cycle," but focus on a particular issue or pollutant of concern. For example, one study may perform a life cycle accounting of GHG emissions and another may focus on the net energy gain or loss question.

Figure 1. Generic Stages of a Product Life Cycle (arrows represent transportation)



These types of narrowly defined studies fall short of a complete, multi-media life cycle approach, which would enable the United States and others to recognize how our choices influence each point of the life cycle. Such a perspective would afford the ability 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 may affect the reusability of materials for subsequent product life cycles).

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 (RD&D) (The Royal Society 2008). An effective life cycle approach can identify where potential tradeoffs may occur across different media and across the life cycle stages (Fava, Denison et al. 1990).

Table 2 lists and briefly describes the following ten analytical approaches and tools that are commonly used to assess the environmental impacts of biofuels on a life cycle basis:

- Carbon Management/Carbon Footprint
- Ecological Footprint
- Exergy Analysis

- Fuel Cycle Analysis
- Greenhouse Gas Life Cycle Analysis
- Life Cycle Assessment
- Life Cycle Risk Assessment
- Material Flow Analysis
- Net Energy Balance
- Sustainability Indicators

Two themes emerge from reviewing these tools: (1) there seems to be no clear definition of these terms and (2) there is still variability regarding what each tool measures and what units are to be used. Accordingly, this paper is intended to discuss general approaches, and not specific tools, such as EPA's MOVES[2] or DOE's GREET[3]. The ten approaches and tools listed in Table 2 are discussed in more detail in the following sections.

Table 2. Life-Cycle Based Approaches and Tools Used to Evaluate Biofuels

Common Name	Description	Measure	Units
Carbon Management or 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.	Amount of carbon dioxide released	Total kilograms of CO_2
Ecological Footprint	Calculates the 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.	Biocapacity and demand	Giga hectare (gha)

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

Table 2. Continued

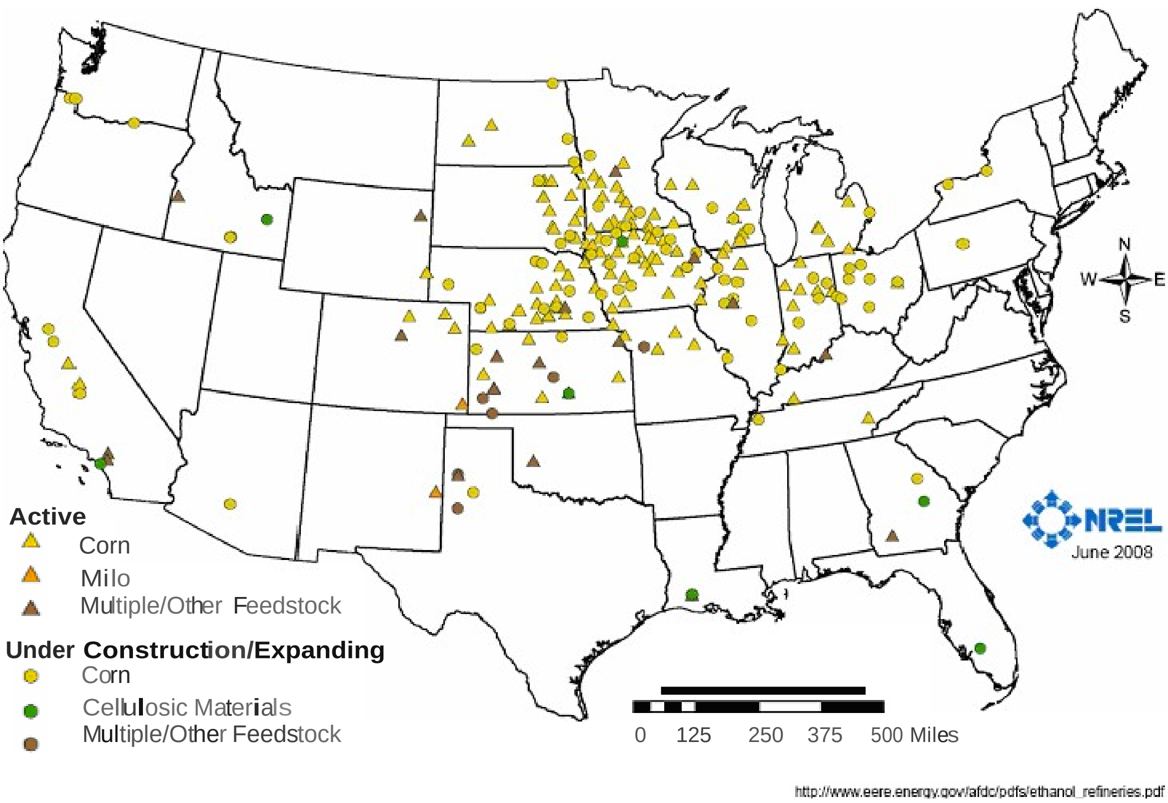
Exergy Analysis	Based on the second law of thermodynamics, to provide a mathematical calculation of the loss of available work across a system.	Exergy	Joules (J)
Fuel Cycle Analysis	Tracks the number of interdependent processes to account for energy inputs and associated releases to air and water.	Energy efficiency, air emissions criteria pollutants, toxics, water impacts	Multiple
Greenhouse Gas Life Cycle Analysis	Quantifies the total amount of carbon dioxide (CO_2) and other GHGs that are emitted over the full life cycle of a product, process, or service.	Greenhouse gases (GHGs) including CO_2	CO_2-equivalents (CO_2-eq).
Life Cycle Assessment (LCA)	Evaluates multi-media, cradle-to-grave burdens of an industrial system by quantifying energy and materials used and waste released to the environment and assessing multiple potential impacts.	Multiple, to include global warming, ozone depletion, human health, ecological health, eutrophication, acidification, smog formation, resource use, land use, and water use.	Multiple
Life Cycle Risk Assessment (LCRA)	Considers primary and secondary contaminants, multiple environmental media, fate and transport processes, cumulative and aggregate exposure, and ecological and human health (cancer and noncancer) risks across the product life cycle.	Human health and ecological impact	Not applicable (usually a probability)
Material Flow Analysis (MFA)	Quantifies and analyzes the flows of a material (or a substance in a "substance flow analysis") in a well-defined system usually at the regional or national level.	Material flows	Kilograms (kg)

Table 2. Continued

Net Energy Balance	Determines the net energy value (NEV) by subtracting the energy needed to produce a fuel (input energy) from the useful energy in the fuel (output energy). Net Energy Ratio (a ratio of less than one indicates a net energy loss.)	Energy flows	Btu
Sustainability Indicators	A select 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.	Multiple	Multiple

Where possible, applications to biofuels, especially corn ethanol, are included if available. Corn ethanol is a commonly studied biofuel and an important feedstock in biofuels production in the United States. As of July 15, 2010, the Renewable Fuels Association reported 200 operating ethanol biorefineries and another 13 under construction or expanding (http://www.ethanolrfa.org/bio-refinery-locations/). Figure 2 shows that the majority of corn production occurs along the central corridor of the United States, known as the Corn Belt States.

Figure 2. The Locations of Ethanol Biorefineries in the United States as of June 2008



Data Source: Renewable Fuels Association and Ethanol Producer Magazine, June 2008

3.1 Carbon Management

With the recent urgency associated with global climate change, many methods and tools have been developed to calculate and account for carbon emissions. The open-access journal *Carbon Balance and Management* is dedicated to providing research results aimed at a comprehensive, policy relevant understanding of the global carbon cycle. According to the journal's website (http://www.cbmjournal.com/info/about/), the global carbon cycle involves important interactions between climate, atmospheric carbon dioxide (CO_2) and the terrestrial and oceanic biospheres. The carbon management methodology accounts for dissolved organic carbon, biomass carbon and produced CO_2 and identifies potential atmospheric CO_2 sources and sinks.

"Carbon Footprint" is a term that has become widely used in relation to carbon management and the threat of global climate change (for example, http://www.carbonfootprint.com/). Despite its ubiquitous appearance, there seems to be no clear definition of this term. There is still much confusion as to what it actually means, what it measures, and what unit is to be used. While commonly understood to refer to certain gaseous emissions that are relevant to climate change and associated with human production or consumption activities, there is no agreement on how to measure or quantify a carbon footprint. Questions remain regarding whether the carbon components should be weighted and normalized based on their potential effect in the atmosphere. Other questions that need to be answered include the following:

- Should the carbon footprint include just carbon dioxide (CO_2) emissions or other GHG emissions as well, e.g., methane?
- Should it be restricted to carbon-based gases or can it include substances that do not have a carbon atom in their molecule, e.g., N_2O, which is another powerful GHG?
- Should the carbon footprint be restricted to substances with a global warming potential at all since there are gaseous emissions that are carbon-based and relevant to the environment and health, such as carbon monoxide (CO), which can convert into CO_2 through chemical processes in the atmosphere?
- Should the measure include all sources of emissions, including those that do not stem from fossil fuels, e.g., CO_2 emissions from soils? (Wiedmann and Minx 2007)

Sometimes the carbon footprint is expressed in kilograms of carbon rather than in kilograms of CO_2. CO_2 can be converted to carbon by multiplying by a factor of 0.27 (1,000 kg CO_2 equals 270 kg carbon[4]). But more commonly, carbon footprinting accounts for *all* GHG releases, not only carbon dioxide. Other GHGs that might be emitted, such as methane and N_2O, are also counted in the calculation of a carbon footprint. They are converted into the amount of CO_2 that would cause the same effects on global warming (this is called CO_2-equivalents). This was the approach that was taken in an assessment by the U.S. Environmental Protection Agency for a life cycle greenhouse gas analysis they conducted in support of the national Renewable Fuel Standard (RFS) program (EPA 2010).

[4] CO_2 has an atomic weight of 44 (a carbon atom weighs 12; an oxygen atom weighs 16), therefore, the carbon content of 1,000 kg CO_2 = 1,000 x 12/44 ≈ 270.

The assessment of GHG emissions is covered in more detail in a later section (see 3.5 Greenhouse Gas Life Cycle Analysis).

In a calculation for ethanol, most of the carbon footprint falls into one of several categories in roughly ascending order (depending on the source and process): the fuel used to produce it, the fuel used to grow or transport the feedstock, the carbon content of the fuel itself, and the lost carbon not sequestered in the vegetation that would have been on the land used to grow the feedstock. The main difference across carbon footprint calculations appears to largely depend on how land use is modeled. Determining where a crop is grown can have a more significant impact on the outcome than what type of crop is grown (Johnson and Heinen 2008). For example, land use for ethanol feedstock that is already in production will have a carbon footprint at the low end of the range since there is little net reduction in the carbon sink. Conversely, converting forests to cropland, or the use of marginal lands that produce low yields, will have a carbon footprint at the high end of the range (Dikeman 2008).

An Example of a Carbon Management (CO_2) Study

Dias de Oliviera et al. (Dias de Oliveira, Vaughan et al. 2005) calculated the CO_2 balance for corn ethanol production, distribution, and combustion in the United States and found a total CO_2 release of 5,030 kg/ha (see below). They accounted for the generation of CO_2 from the harvesting and processing of one hectare of corn to produce 3.04 m^3 of ethanol. After gasoline is added to form the mixture, the total fuel volume of 3.58 m^3 of E85 will allow the reference vehicle to run for approximately 24,400 km. They assumed that the production and distribution of gasoline results in 375 kg of CO_2 emitted per m^3 of gasoline produced. Consequently, 203 kg of CO_2 are emitted from the production and distribution of the 0.54 m^3 of gasoline added to 3.04 m^3 of ethanol to form the E85 mixture. Combustion of this volume of gasoline emits 1.267 Mg of CO_2.

Process	Total CO_2 released (kg/ha)
Agricultural Inputs	1237
Increase in Soil Organic Carbon	-660
Corn Transportation	154
Ethanol Conversion	2721
Ethanol Distribution	108
Gasoline Portion of E85:	
- Production and Distribution	203
- Combustion	1267
Total	5030

Based upon this example and comparing E85 to an equal amount of gasoline, the CO_2 emissions for the gasoline portion can be reapportioned to calculate emissions for 100% gasoline, such that:

$$(203 + 1267) \text{ X } (1.00/0.15) = 9800 \text{ kg } CO_2$$

Adjusting for thermal efficiency: $9800 \text{ X } 0.75 = 7350 \text{ kg } CO_2$

Therefore, according to this data, the comparison of driving a vehicle 24,400 km using the two fuels results in the following CO_2 emissions:

E85 = 1.267 Mg CO_2 Gasoline = 7.350 Mg CO_2

Thus, in this analysis, using corn ethanol instead of gasoline can potentially reduce CO_2 releases by almost one-sixth.

3.2 Ecological Footprint

Ecological Footprint was originally designed to measure the amount of land area a human population requires to produce the resources it consumes and to absorb its waste under a prevailing technology. More recent calculations also include water use.

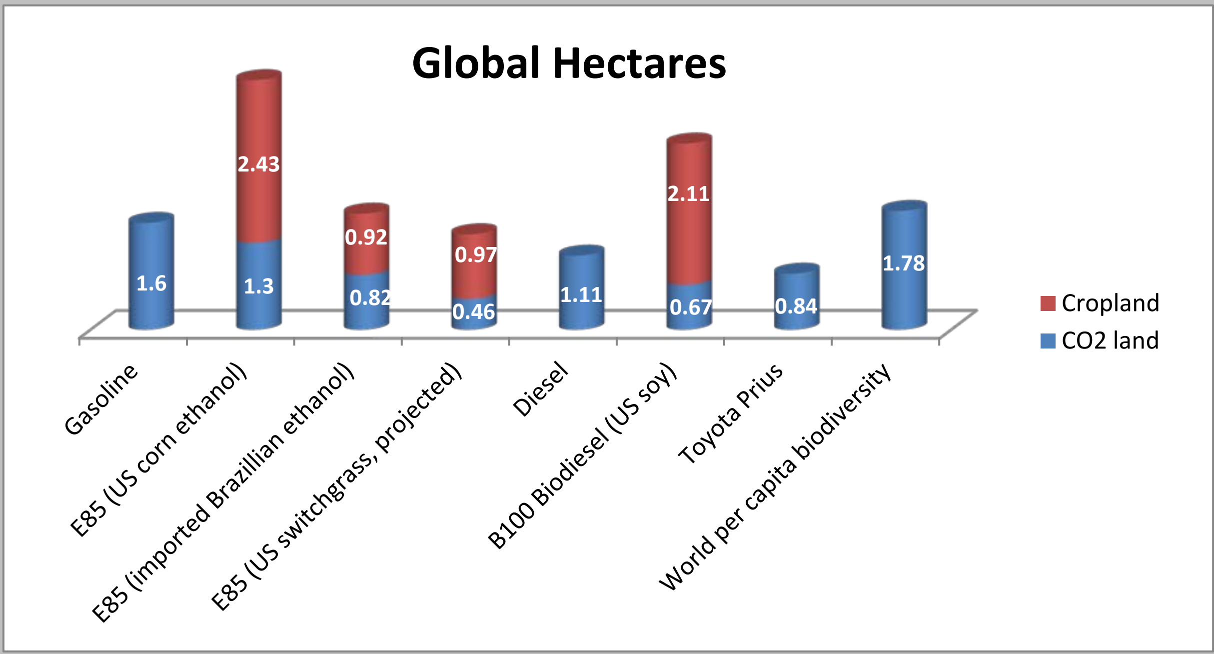
Ecological Footprint measures the amount of cropland, grazing land, forest area, and fishing grounds that are needed to satisfy humanity's need for food, clothing, shelter, and products and services. In addition to that, it measures the amount of land required to sequester our emissions after subtraction of the oceans' absorptive capacity. In modeling land use, Ecological Footprint expresses all the land area the earth has available for generating renewable resources using a single unified metric, the global hectare (or global acre). A global hectare is a mathematical representation of the productivity of real land, established by Wackernagel in his 1994 Ph.D. thesis (Wackernagel 1994). It is calculated in a manner that allows a comparison of the productivity of different land types around the globe. It encompasses all products and services derived from raw materials that came from a land area (or out of the earth) as well as resulting emissions that need to be absorbed somewhere.

Humanity's Ecological Footprint has been steadily increasing over the past four decades. According to the Living Planet Report 2006, humanity as a whole uses nearly 25% more resources than the planet can make available annually. In other words, humanity today would need 1 ¼ planets to sustain us. Some people use more while some people use less. If everybody lived like the average American, we would need more than five planets. Italians live on about 2 1/3 planets, while the people of Thailand use only ¾ of a planet (WWF 2006). Over the years, we have been able to increase biocapacity, mainly through increased crop yields and expanding area under cultivation; however, this increase has not been able to keep up with the increase of the world population and increased consumption (Vos 2007).

An Example of Ecological Footprinting

Sustainability Planning Partners (Vos 2007) presented examples of different fuels that can be used in a typical passenger car. The Toyota Prius hybrid vehicle was added for comparison purposes as well as the per capita biocapacity available to each person on the planet (1.78 Global Hectares). Calculations were based on an average annual use of 12,500 miles using the 2006 EPA fuel mileage rating system.

Ecological Footprint of Fueling a Passenger Car for 12,500 miles (Source: Vos 2007)



In other words, Vos calculates that the Ecological Footprint of corn ethanol is 2.3 times larger than the fuel it aims to replace.

The carbon component of the Ecological Footprint goes beyond carbon footprinting in that it describes the physical quantity of carbon being emitted by indicating the amount of nature's limited regenerative capacity required to get this carbon back out of the atmosphere.

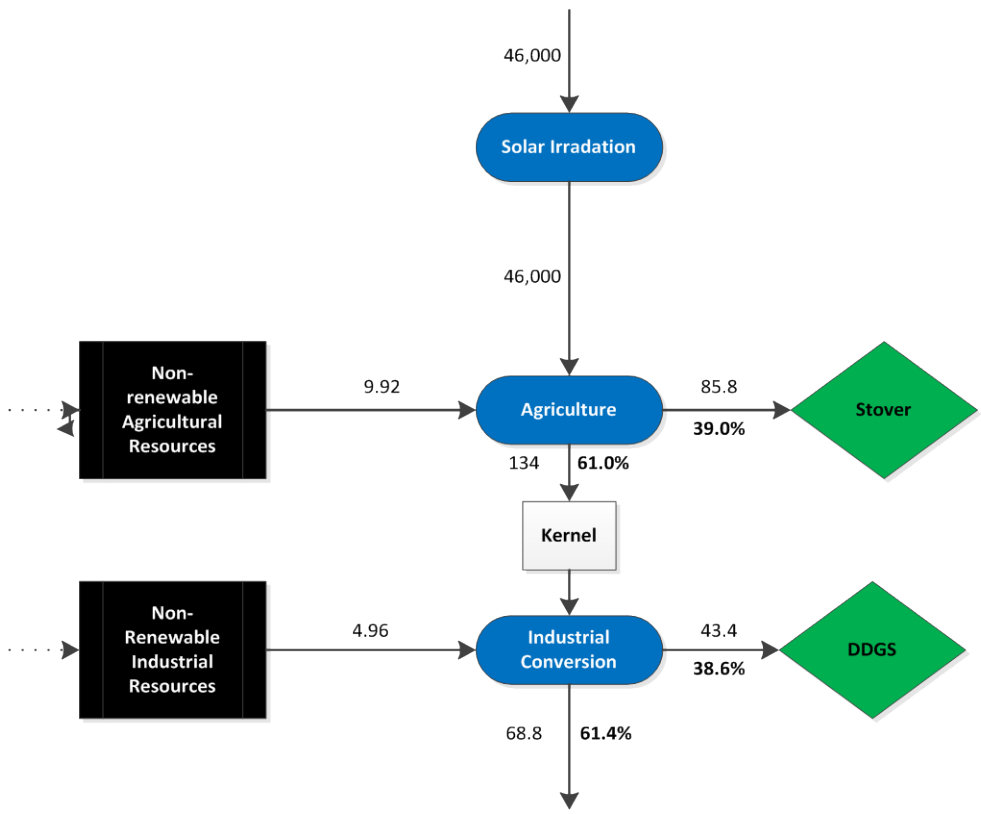
The ecological footprint concept extends the land use per capita indicator both spatially (to cover the globe) and functionally (the land requirements to maintain all types of consumption). Global aggregates imply that land area requirements are greater than the world's available land, suggesting that current consumption patterns are "unsustainable." However, this idea is based upon severely limiting assumptions to include: no substitution of other factors of production for land; low rates of technological change; small countries with large populations are inherently bad; urban residents consume more natural resources than rural residents; gains from trade are negligible and/or undesirable; and price signals have little value (Gordon and Richardson 2008). Such simplifying assumptions can be seen as a weakness in the tool. For example, nuclear power is treated the same as coal power although the two modes of power generation are very different.

3.3 Exergy Analysis

"Exergy" was introduced by Rant in 1956 to describe the maximum amount of work that may be obtained from a thermodynamic system under ideal conditions. Based on the second law of thermodynamics, it reflects the maximum (mechanical) work possible during a process, i.e., available energy that brings the system into equilibrium with the surroundings. Exergy, therefore, is the potential of a system to cause a change as it achieves equilibrium with its environment. Thus, exergy has been applied to ecological evaluation, resource accounting, and environmental impact assessment. The dispersion of pollutants throughout the environment is thought to be essentially a process that converts the exergy of mixing embodied in the initial state (the concentrated pollutant) into entropy of the final state (the dispersed pollutant) (Seager and Theis 2003).

Although exergy analysis is a most useful method as a way to evaluate the thermodynamic efficiencies of biomass conversion processes, researchers have attempted to apply exergy calculations to industrial systems to assess environmental impacts. Increased energy efficiency benefits the environment by avoiding energy use and the corresponding resource consumption and pollution generation. Exergy and energy analyses are best carried out together to most effectively find ways to improve industrial systems (Kanoglu, Dincer et al. 2009). Exergy analysis of both utilities and feedstocks as inputs, and products, waste streams and generated irreversibilities as outputs, shows how efficiently resources are employed toward products. An exergetic life cycle analysis adopts a life cycle perspective by quantifying exergy on a cradle-to-grave basis. Figure 3 presents the exergy values along the life cycle stages of corn ethanol.

Figure 3. Flows of Exergy Associated with the Annual Production of Bioethanol from One Hectare of Corn (GJ $ha^{-1} \cdot yr^{-1}$)



(Source: Dewulf, Langenhove et al. 2005)

Researchers sometimes consider the exergy of the current formation of natural resources from a small number of exergy inputs (usually solar radiation, tidal forces, and crustal/geothermal heat). This application not only requires assumptions about reference states, but it also requires assumptions about the real environments of the past that might have been close to those reference states.

Because the exergy that is embodied in resources, products, and waste materials has the potential to cause change in both the industrial environment as well as the natural ecosystem, exergy and entropy have been proposed not only as a measure for economic losses and dematerialisation, but also for waste accounting and ecotoxicity. While Dewulf et al. are supporters of the use of exergy analysis as a tool in environmental impact analysis, claiming it as possibly the most mature field of application, particularly with respect to resource and efficiency accounting, they are also quick to point out the tool's deficiencies (Dewulf, Langenhove et al. 2008). Emissions, for example, have an exergy value because they are not in thermodynamic equilibrium with the surroundings. However, their exergy value does not represent their environmental impact. Exergy analysis is much more oriented toward resource and product, and, hence, efficiency. Nevertheless, efforts to assess environmental impact not only through resource intake but also through emission generation have been developed based an exergy analysis.

When compared to other resource accounting methods, exergy has the major advantage that it is able to weigh different masses in a scientifically sound way that brings mass and energy into a single scale. Different kinds of resources, including renewable resources (biomass, solar, wind, hydropower), fossil fuels, nuclear fuels, metal ores, minerals, water resources, and atmospheric resources, can be quantified on a single scale. The resource category "land use" is still omitted in most exergy calculations.

Exergy analysis continues to be developed and promoted within the field of thermodynamics as a way to design and develop more sustainable industrial processes. It is supported by individuals who believe that exergy is a good method to provide insights into energy systems to identify potential reductions in thermodynamic losses and efficiency improvements (Rosen and Bulucea 2009). However, a defensible link between exergy calculations and environmental impact has yet to be fully demonstrated (Rosen and Dincer 2001; Rosen 2009).

3.4 Fuel Cycle Analysis

Joshi et al. (Joshi, Lave et al. 2000) provide a good description of the general approach for fuel cycle analysis (more commonly referred to as a "Well-to-Wheel" study by individuals in the transportation sector). Basically, a fuel cycle analysis attempts to track the number of interdependent processes to account for energy inputs and associated air and water emissions, which may include criteria pollutants and toxic compounds. Significant interdependencies are accounted for where other fuels, such as residual oil, coal and electricity, are used as intermediate energy inputs. The production processes also result in a number of co-products to which energy and environmental impacts must be allocated. While modeling practices vary across studies, the basic structure is similar and involves the following features:

- For fossil fuels, the fuel cycle is divided into four stages: feedstock extraction; feedstock transportation and storage; fuel production; and fuel transportation, storage and distribution.

- For biofuels, the biomass farming stage constitutes the feedstock extraction phase. The major inputs to farming include fertilizers and agricultural chemicals in addition to energy.

- For each of these stages, the energy requirement and fuel mix are estimated.

- Depending on the equipment in which the fuel is combusted (boilers, vehicles, ocean tankers, compressors, etc.), appropriate combustion emission factors are used to estimate combustion-related emissions.

- Non-combustion emissions such as process emissions, venting/flaring and fugitive emissions are also estimated for each stage.

- For biofuels, life cycle energy use and emissions for fertilizers and other inputs are accounted.

- The emissions associated with co-products are allocated using selected criteria. Relative processing energy intensity is most commonly used as the basis of allocation for fossil fuels. A common basis for biofuel co-product allocation is less obvious.

- These individual stage energy use and emissions are aggregated to estimate full fuel cycle emissions.

Joshi et al. (Joshi et al. 2000) point out that unavoidable variations occur in modeling large, complex fuel systems. Accordingly, final estimates of energy use and emissions per GJ of fuel delivered to a vehicle can vary significantly across studies for gasoline and bioethanol. Reconciliation of differences is difficult since estimates, calculations and assumptions are seldom available in published reports.

An Example of a Fuel Cycle Analysis

Argonne National Lab (Wang, Saricks et al. 1999) conducted a comparative analysis of fuel-cycle petroleum use, GHG emissions, and fossil energy use of fuel ethanol relative to conventional gasoline. The fuel-cycle analysis included all production, combustion, and transportation stages — from feedstock recovery to vehicular fuel combustion — for both ethanol and gasoline. The study modeled emissions of three major GHGs: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), as well as emissions of five criteria pollutants: volatile organic compounds [VOCs], carbon monoxide [CO], nitrogen oxides [NOx], particulate matter with a diameter of less than 10 microns [PM_{10}], and sulfur oxides [SOx].

Reductions in Energy Use and Emissions per Vehicle-Mile for Corn-Based Ethanol (1999) Compared to Gasoline

	E10	E85	E95	E10	E85	E95
	Dry Milling			Wet Milling		
Petroleum	6.4%	74.9%	87.7%	6.1%	72.5%	85.0%
GHG Emissions	1.3%	18.8%	24.9%	0.8%	13.7%	19.1%
Fossil Energy	2.7%	35.0%	44.3%	2.7%	34.4%	42.3%

Reductions in Energy Use and Emissions per Gallon for Corn-Based Ethanol (1999) Compared to Gasoline

	E10	E85	E95	E10	E85	E95
	Dry Milling			Wet Milling		
Petroleum	93.3%	94.9%	94.7%	90.2%	91.9%	91.8%
GHG Emissions	19.2%	23.8%	26.9%	12.4%	17.3%	20.7%
Fossil Energy	40.3%	44.4%	46.5%	39.5%	43.6%	45.7%

The results showed that using a gallon of ethanol, regardless of the blend mix, can achieve large emissions and energy use benefits, although the benefits are enhanced slightly for the more efficient vehicle/fuel technologies using E85 and E95. The differences among the per-gallon-of-ethanol results for ethanol in each of the three blends are caused primarily by the fuel economy differences of the vehicles fueled by E10, E85, and E95.

3.5 Greenhouse Gas Life Cycle Analysis

Many studies over the past several years have attempted to answer the question of whether or not biofuel production and use will result in a net reduction of GHG emissions when compared to gasoline. The Greenhouse Gas Protocol (GHG Protocol) is a joint initiative of the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). The protocol is intended mainly for corporate or company-level reporting, but the principles of the protocol can also be applied to a single product. The protocol categorizes GHG emissions into "direct" and "indirect" emissions. GHG emissions from the production and use of biofuels are calculated as:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{ccs} - e_{ccr} - e_{ee},$$

where:

E = total emissions from the use of the fuel;
e_{ec}= emissions from the extraction or cultivation of raw materials;
e_l= annualized emissions from carbon stock changes caused by land use change;
e_p= emissions from processing;
e_{td}= emissions from transport and distribution;
e_u= emissions from the fuel in use;
e_{ccs}= emission savings from carbon capture and sequestration;
e_{ccr}= emission savings from carbon capture and replacement; and
e_{ee}= emission savings from excess electricity from cogeneration.

Emissions from the manufacture of machinery and equipment are not taken into account (European Commission 2008).

The Green Car Congress (Green Car Congress 2009) reports that Emanuela Menichetti and Martina Otto (2009) reviewed and assessed 30 LCA studies, particularly those relating to the energy balance and greenhouse gas (GHG) emissions of biofuels produced from a range of crops and other biomass feedstocks using various conversion technologies (Menichetti and Otto 2009). Among their general observations was that while the number of full LCA studies continues to increase, it is still relatively small, and that most studies focus on traditional first generation feedstocks such as corn, sugarcane, rapeseed and wheat. Other reported observations included:

- Most studies only include energy consumption (sometimes only non-renewable energy, sometimes total energy) and CO_2 emissions. A few studies also include other relevant impact indicators such as acidification potential, eutrophication potential, ozone depletion potential and various toxicity potentials. However, very few studies include water use impacts.
- Methodologies to develop biodiversity quality indicators are still under discussion. No study in the review presents results in terms of biodiversity.

- Very few studies take into account land use impacts driven by biofuel crop production. More specifically, only one third of the studies defines an alternative land use reference system and calculates the carbon stock. Potential impacts in terms of indirect land use change driven by increased bioenergy demand are not considered in the sample analyzed.
- The transparency level of reports is quite heterogeneous with respect to hypothesis and assumptions, yields, heating values, emission factors, and other background methodological choices. Very few studies include a data quality review according to the requirements of the ISO standards for LCA.
- Heterogeneity was observed in terms of the treatment of co-products and allocation methods that were followed.
- Social issues are very often overlooked in the studies. This is not surprising, given the purely environmental focus of LCA technique.
- Many databases and LCA software programs are used to model data. In particular, some of the life cycle inventory databases used in the studies appear relatively old. This affects the quality of results, regardless of the quality of the primary data collected.

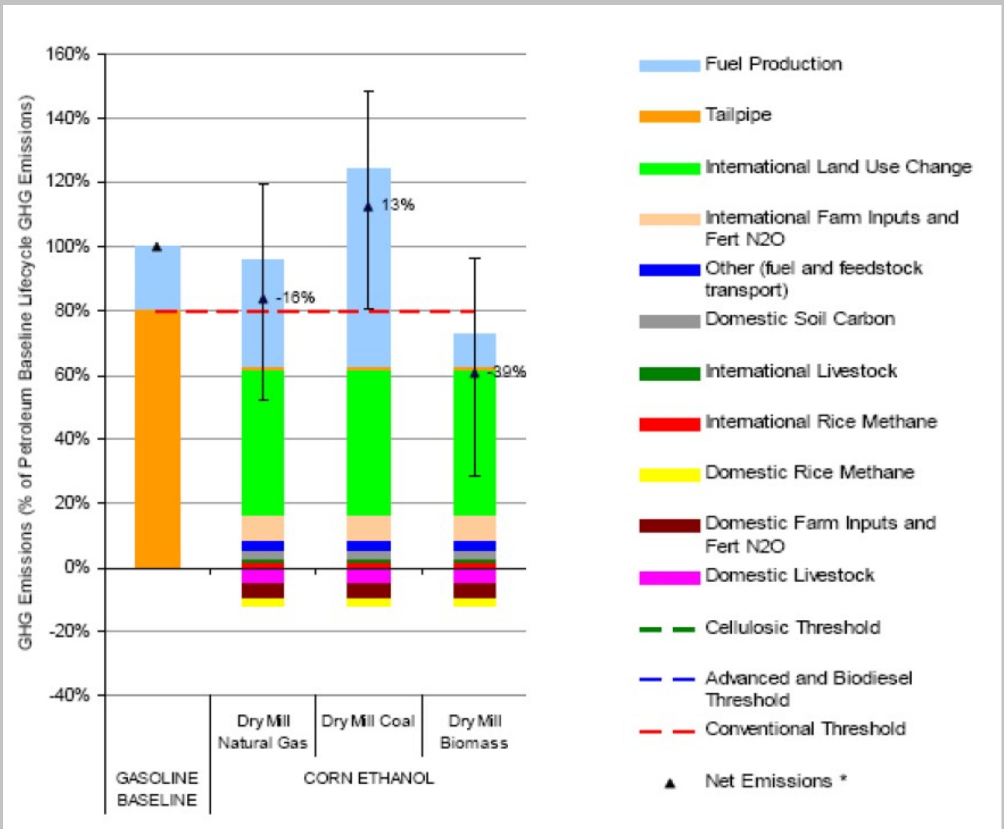
More analysis and research is needed in order to improve the incorporation of land use change into estimates of GHG emissions from biofuels. The calculation of GHG emissions associated with biofuels is complicated by the addition of factors associated with both direct and indirect land use changes. In addition, only recently has the potential for soil to act as a net sink for carbon begun to be included in studies. Improvements can be made to existing methods by being more precise in defining system boundaries. In its assessments to inform regulatory determinations, the U.S. EPA recognizes that as the state of scientific knowledge continues to evolve in this area, the life cycle GHG assessments for a variety of fuel pathways will continue to be enhanced. The U.S. EPA is seeking expert advice from the National Academy of Sciences as well as other experts (EPA 2010).

An Example of a Greenhouse Gas Life Cycle Analysis

As part of proposed revisions to the National Renewable Fuel Standard program (commonly known as the RFS program), EPA (EPA 2010) analyzed life cycle greenhouse gas (GHG) emissions from increased renewable fuels use in order to determine whether or not renewable fuels produced under varying conditions will meet the greenhouse gas thresholds for the different fuel types for which the Energy Independence and Security Act establishes mandates.

The study accounted for secondary or indirect impacts of expanded biofuels use over a 30-year time horizon with 0% discount rate and a 100-year time horizon with a 2% discount rate (the figure below shows the results for the later scenario, comparing gasoline and corn ethanol). They calculated a net present value of emissions because it provides a common metric for the direct comparison of life cycle emissions from biofuels and petroleum fuels. EPA's analysis suggests that the assessment of life cycle GHG emissions for biofuels is significantly affected by the secondary agricultural sector.

Life Cycle GHG Results for Gasoline and Corn Ethanol, Using 100-Year Net Present Value with 2% Discount Rate



(Source: EPA 2010)

3.6 Life Cycle Assessment

Life cycle assessment (LCA) accounts for all the inputs and outputs across a product system from cradle to grave in order to model the potential environmental impacts of resource use and releases to the environment (International Standards Organization 1997; Environmental Protection Agency 2006). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of a product's environmental aspects. It is also valuable in evaluating the many interdependent processes that are involved in a product system. A change to one part of this system may have unintended consequences elsewhere. LCA identifies the potential transfer of environmental impacts from one medium to another (e.g., eliminating air emissions by creating a wastewater effluent instead) and/or from one life cycle stage to another (e.g., from use and reuse of the product to the raw material acquisition stage). If an LCA were not performed, the transfer might not be recognized and properly included in the analysis because it is outside of the typical scope or focus of product design and selection processes.

Quality LCAs require large amounts of input and output data, called the life cycle inventory (LCI) data. While international activities, such as ecoinvent (ecoinvent Centre 2005) and the European Commission's International Reference Life Cycle Data System, have been initiated to assist users in accessing LCI data more easily, LCA practitioners and researchers often have to develop their own data or modify data from other countries. Having easy access to consistent LCI data is needed in order for effective LCA applications to continue (NREL 2009).

Inventory data are subjected to life cycle impact assessment models, which seek to establish a linkage between a system and the potential, related impacts. The impact models are often derived and simplified versions of more sophisticated models within each of the various impact categories. Although consensus has yet to be reached on which impact categories should be included in an LCA, the following are commonly used:

- Ozone Depletion
- Global Warming
- Human Health
- Ecotoxicity
- Eutrophication
- Acidification
- Smog Formation
- Fossil Fuel Use
- Land Use
- Water Use

These simplified models are suitable for relative comparisons of the potential to cause human or environmental damage, but are not indicators of absolute risk or actual damage to human health or the environment. For example, risk assessments are often very narrowly focused on a single chemical at a very specific location. In the case of a traditional risk assessment, it is possible to conduct very detailed modeling of the predicted impacts of the chemical on the population exposed and even to predict the probability of the population being impacted by the emission. In the case of LCA, hundreds of chemical emissions (and resource stressors) that are occurring at various locations are evaluated for their potential impacts in multiple impact categories. The sheer number of stressors being evaluated, the variety of locations, and the diversity of impact categories makes it impossible to conduct the assessment at the same level of rigor as a traditional risk assessment. Instead, models are based on the accepted models within each of the impact categories using assumptions and default values as necessary. The resulting impact models are suitable for relative comparisons, though insufficient for absolute predictions of risk.

Standardized LCA methodology does not include economic factors, such as monetary costs, or social factors, such as child labor.

Furthermore, LCA results can vary widely depending on how the system boundary is drawn and the assumptions that are applied to calculate the input and output data (LCI), as well as the modeling of the environmental impacts. An important variation relates to how the various co-products from industrial processes are modeled (Curran 2007).

Von Blottnitz and Curran pointed out in 2007 that a full LCA of bioethanol in the United States is needed (von Blottnitz and Curran 2007). While this still holds true today for the United States, comparative studies for Europe have been conducted.

An Example of a Life Cycle Assessment of Biofuels

Zah et al. (2007) conducted LCAs of several biofuels (bioethanol, biomethanol, biodiesel and biogas) in Switzerland using a limited set of impacts: GWP (global warming potential), CED (cumulated non-renewable energy demand), SMOG (summer smog potential), EUTR (eutrophication caused by fertilizer use) and ETOX (ecotoxicity). Calculations were based on the method of ecological scarcity (UBP 06). The emission standard petrol EURO3, set by the European Union in 2000 for gasoline-powered passenger cars, was selected as the reference product, i.e., it was set to equal 100%. Zah et al. list a number of considerations related to this study regarding LCA methodology:

- Although the LCA approach used here is very comprehensive, certain environmental impacts are covered only incompletely or not at all. For example, the effects of water utilization are not covered because they differ greatly depending on local conditions (the quantity of precipitation, ground water level, etc.). Biodiversity losses are also incomplete because the data is lacking on tropical ecosystems.
- The assessment approach calculated only the primary environmental impacts of the process chain, e.g., energy consumption and pollutant emission during the cultivation of energy rapeseed. Secondary effects were not covered. For instance, food was grown beforehand on the energy rapeseed field; afterward food had to be imported, causing additional transports and additional environmental impacts due to the transports.
- No distinction is made with cultivation biomass (e.g., grain or potatoes) between harvest waste and biomass produced specifically for fuel production. Nor does the method differentiate between the use of already cultivated fields and newly cultivated fallow fields. Therefore, the method neglects the environmental impacts associated with these aspects of the fields, such as a reduction in biodiversity in newly cultivated fallow fields.
- On the basis of the data from existing life cycle inventories, most of the results refer to existing process chains, and thus cover Reference Year 2004. Future developments are not judged. However, a glimpse of future developments is provided by the sensitivity analyses and possible optimization potentials.
- Since many allocations have been calculated from sales revenue, and revenue depends on market dynamics, the results of this study are not “chiseled in stone” and may have to be verified later.
- The process chains investigated represent only a subset of all production processes. Many more production paths are conceivable. However, the paths chosen are considered especially relevant for the current situation in Switzerland.
- The data from existing life cycle inventories represent average conditions in the respective production countries (Switzerland, Europe, Brazil, U.S, etc.) and apply as an integral whole as regards to use in Switzerland. Therefore, the results may not be applied without qualification to decision situations in partial regions or individual plants because the environmental impacts in individual cases may differ radically from the average situation.

The study provides no answers to the questions of the future consequences of a shift to renewable fuels (e.g., the environmental consequences of agricultural products were to be grown on such a large scale for energetic utilization that agricultural production as a whole had to be intensified) or of any possible rebound effects (Zah, Böni et al. 2007).

An Example of a Life Cycle Assessment of Biofuels (continued)

The table below notes the overall environmental Life Cycle Assessment of all unblended biofuels studied in comparison to a fossil reference. GWP = greenhouse warming potential, CED = cumulated non-renewable energy demand, SMOG = summer smog potential, EUTR = excessive fertilizer use, ETOX = ecotoxicity. Reference (= 100%) is petrol EURO3 in each case.

	GWP %	CED %	SMOG %	EUTR %	ETOX %
Methane manure, optimized	7	40	52	299	40
Methane manure+cosubstrate, optimized	14	40	57	220	40
100% Recycled plant oil ME FR	26	43	50	65	40
Ethanol whey CH	30	43	70	550	45
100% Recycled plant oil ME CH	30	43	50	165	40
Methanol fixed bed CH	30	48	100	110	65
Methane wood	33	50	90	135	75
Methanol fluidized bed CH	35	52	100	112	70
Ethanol sugar cane BR	36	41	500	265	70
Ethanol grass CH	36	49	75	135	50
Ethanol wood CH	37	48	73	380	45
Ethanol sweet sorghum CN	47	53	130	500	75
Ethanol sugar beets CH	47	53	90	500	70
Methane sewage sludge	50	55	70	60	40
Methane grass biorefinery	52	48	70	500	48
100% Soy ME US	52	49	210	500	51
Methane biowaste	55	42	75	75	50
100% Palm oil ME MY	58	57	380	348	500
100% Rapeseed ME CH	60	57	65	500	51
Methane manure+cosubstrate	65	40	80	390	46
Methane manure	70	40	95	410	46
100% Rapeseed ME RER	77	64	160	500	65
Ethanol corn US	93	79	130	500	105
Ethanol rye RER	96	77	125	500	70
Ethanol potatoes CH	97	79	73	475	48
100% Soy ME BR	105	70	500	500	500
Natural gas, EURO3	80	95	60	67	46
Diesel, low sulphur EURO3	93	92	74	175	80
Petrol, low sulphur EURO3	100	100	100	100	100

(Source: Zah, Böni et al. 2007)

3.7 Life Cycle Risk Assessment

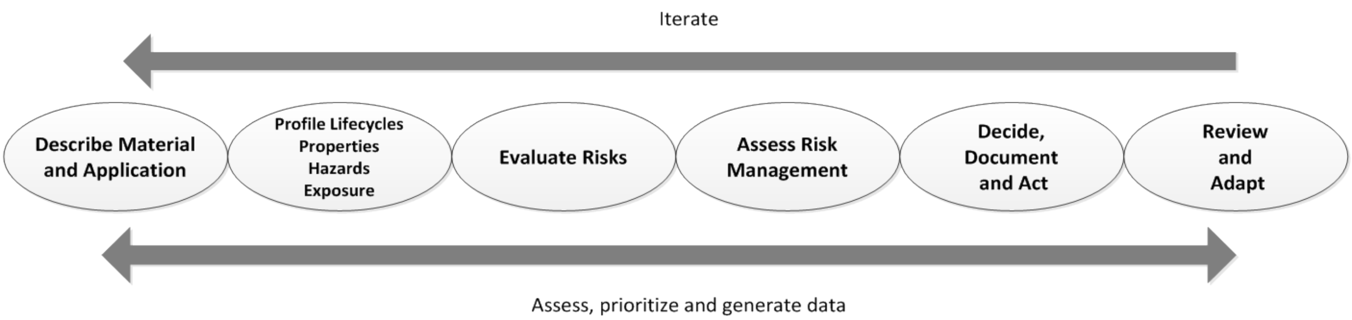
Life Cycle Risk Assessment (LCRA) integrates the traditional risk assessment paradigm with a life cycle perspective. It attempts to examine potential human health and ecological impacts (both positive and negative) in a broad, systematic manner. The life cycle nature of the approach indicates that it encompasses a cradle-to-grave framework while accounting for multi-media environmental fate and transport, exposure, and effects on both ecological receptors and human health. Other dimensions such as economic, political, security, or societal factors are typically excluded.

Two examples of LCRA approaches are 1) the Nano Risk Framework that was developed jointly by Environmental Defense (ED) and DuPont to address concerns related to nanomaterials and their applications and 2) the EPA's Comprehensive Environmental Assessment (CEA).

Nano Risk Framework

In 2005, ED and DuPont entered into a partnership to develop a framework for the responsible development, production, use, and end-of-life disposal or recycling of engineered nanoscale materials. The resulting "Nano Risk Framework" (Figure 4) develops profiles of nanomaterials' properties, inherent hazards, and associated exposures throughout the material's life cycle (ED-DuPont 2007).

Figure 4. ED-DuPont Nano Risk Framework



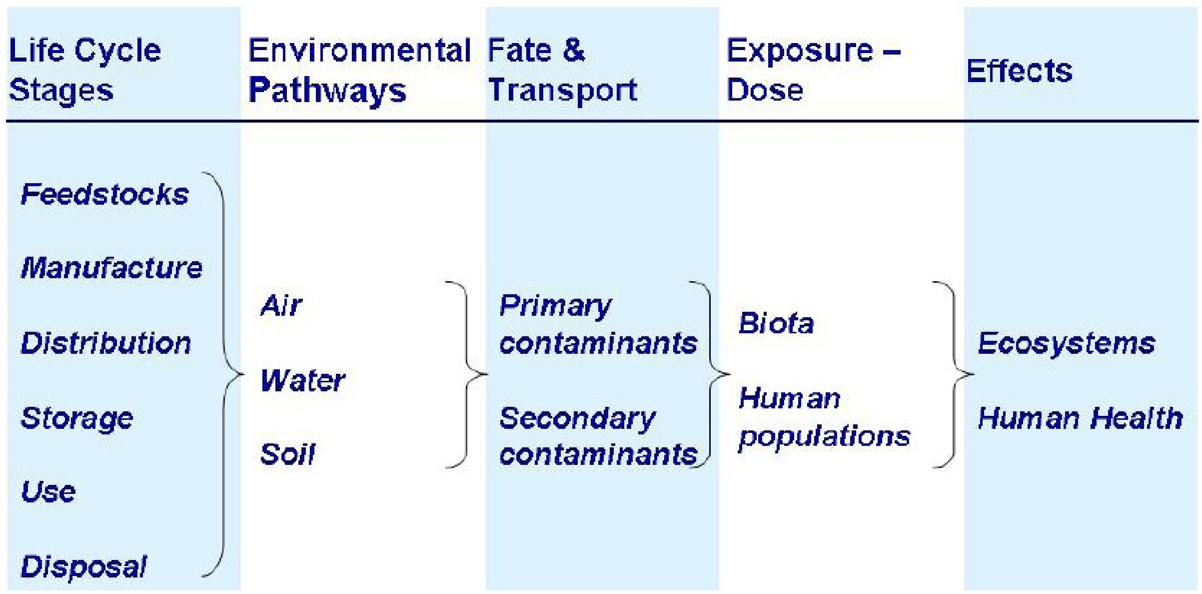
(Source: ED-DuPont 2007)

Comprehensive Environmental Assessment

CEA is a life-cycle based approach that was developed by the EPA's National Center for Environmental Assessment (NCEA) to identify and assess potential risk related to the release of pollutants (Davis and Thomas 2006). As listed in Column 1 of Figure 5, the life cycle of a product is typically comprised of several stages, including feedstock production or extraction, manufacturing processes, distribution, storage, use, and disposal of the product and waste by-products. At any stage across the life cycle, pollutants may enter one or more environmental pathways: air, water, and soil (Column 2). It is important to identify these primary contaminants and, to the extent possible, the transport and transformation processes they undergo. The idea is to characterize the primary as well as secondary or by-product pollutants associated with the entire life cycle for all relevant media (Column 3). The existence of a contaminant in the environment does not necessarily mean that humans or other specific organisms are exposed to it. Thus, CEA is described as going beyond a conventional LCA to apply exposure assessment, a key feature of risk assessment. As indicated in Column 4, exposure and dose, i.e., the amount of substance actually taken into an organism, are relevant to humans and biota generally.

In addition to characterizing exposure and dose, the health and ecological hazards associated with respective contaminants need to be described qualitatively and quantitatively (Column 5). To characterize risk quantitatively, the dose-response characteristics of a toxicant must be considered in relation to exposure potential. Some pollutants may pose low risk because the exposure potential is low or the hazard potential is low, or both. In other cases, risk may be relatively high when exposure potential is low, but hazard potential is high, or vice versa (Davis and Thomas 2006).

Figure 5. Framework for Conducting a Comprehensive Environmental Assessment (Adapted from Davis and Thomas 2006)



CEA can also involve a broad array of technical experts and stakeholders offering their individual analytic judgments in a formal, structured manner that leads to a collective understanding of the trade-offs associated with different fuels (or other technological issues).

An Example of Life Cycle Risk Assessment

The California Energy Policy Council (LLNL 1999) assessed certain potential environmental and health impacts related to methyl tertiary butyl ether (MTBE) and ethanol as fuel oxygenates. The California analysis exemplifies some of the key features of risk assessment in a life cycle framework and considered multi-media impacts of the two oxygenates in a comparative manner. For example, cancer and noncancer risks from selected air pollutants associated with MTBE and ethanol are presented below.

Comparative Life Cycle Model Based on Cumulative Cancer Risks and Noncancer Hazard Indexes (HI) for Selected Air Pollutants in the South Coast Region of California for MTBE and Ethanol Oxygenates in Gasoline (2003 Projections)

Risk Description	Estimate Range	2003 MTBE	2003 2% EtOH, by weight
Cumulative lifetime cancer risk	Upper Lower	1.9×10^{-4} 1.8×10^{-4}	1.8×10^{-4} 1.7×10^{-4}
Cumulative HI for acute eye irritation	Upper Lower	9.6 6.7	9.5 6.6
Cumulative HI for acute respiratory irritation	Upper Lower	3.8 3.7	3.8 3.7
Cumulative HI for chronic respiratory irritation	Upper Lower	5.1 5.1	5.1 5.0

(Source: LLNL 1999)

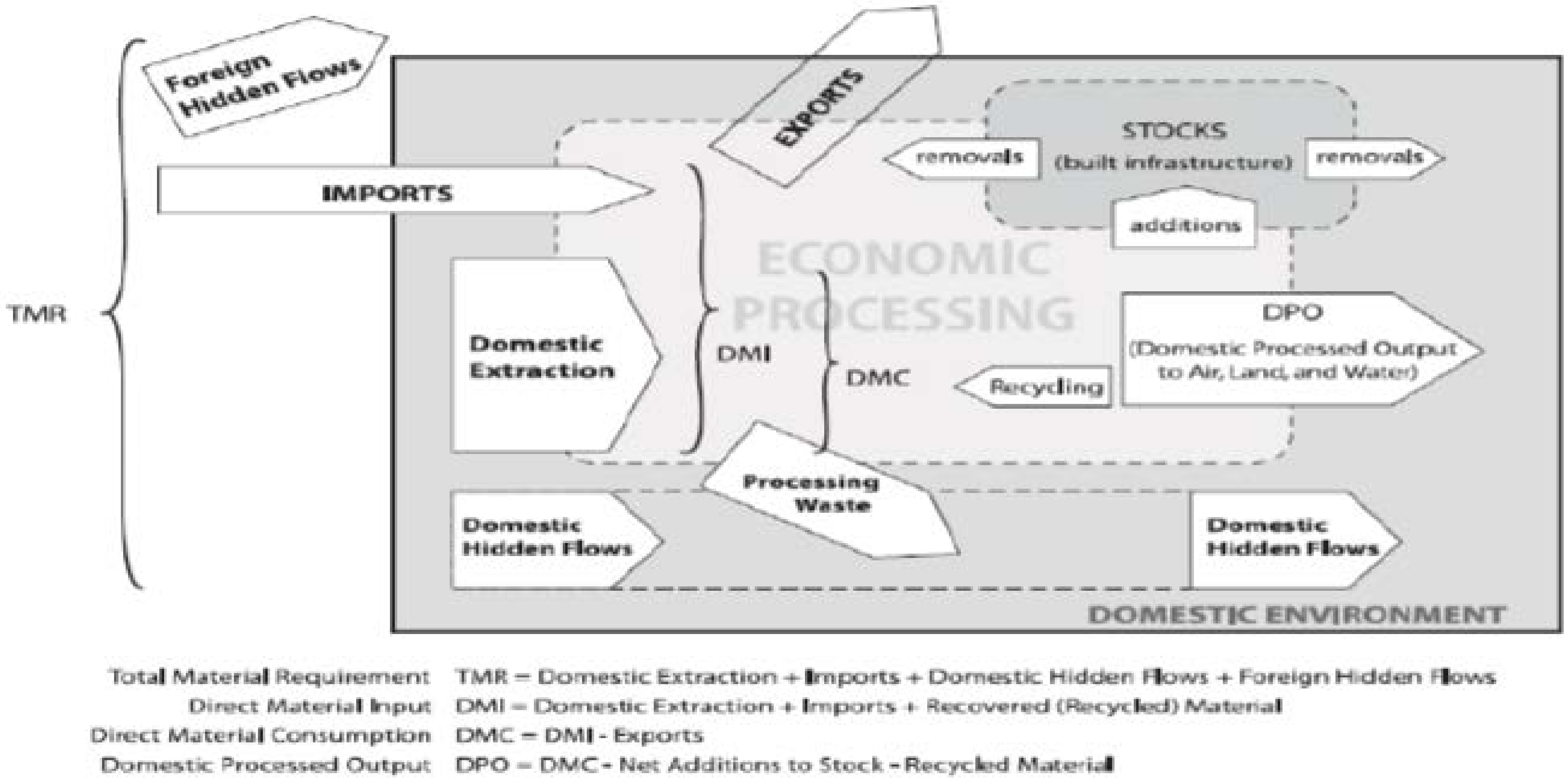
3.8 Material Flow Analysis

Material Flow Analysis or Accounting (MFA) tracks the amounts of materials, ranging from timber and fuel to metals and agricultural products, as they enter and exit the economy through various types of transactions. These materials can accumulate in capital stock such as housing and automobiles or exit to the environment at any phase of their commercial life cycle, from extraction to processing, manufacturing, use, disposal, or recycling (Wernick and Irwin 2005).

On a regional as well as national level, MFA is a useful tool for improving resource management. MFA serves as a system-wide diagnostic procedure related to environmental problems, supports the planning of adequate management measures and provides for monitoring the efficacy of those measures. Furthermore, MFA allows early warning and supports precautionary measures. By quantifying linkages between environmental problems and human activities, the aggregated information from an MFA study can help detect potential problem shifting between regions and sectors and can support decision making.

At present, there is no global consensus on MFA methodology, and the United States still lacks a comprehensive approach for accounting and tracking material flows, but a common goal is understood. That is, the goal is to analyze the flows (in kilograms) of a material in a well-defined system, by space and time, in order to identify and quantify material exchanges between the economy and the natural environment. The term “material” stands for both substances and material goods. The procedure and some elements of studies that have been conducted have common features. The core principle of MFA is the mass balance principle, i.e., the law of conservation of mass where inputs to an economy (extractions + imports) equal outputs from the economy (consumptions + exports + accumulation + waste). Figure 6 depicts the various flows across the economy that are modeled in an MFA. The procedure usually consists of four steps: goal and system definition, process chain analysis, accounting and balancing, and modeling and evaluation. The results of an MFA can be used to minimize the flow of materials while maximizing the human welfare generated by the flow. As such, it is a method for evaluating the efficiency of using material resources. The analysis allows for the monitoring of wastes that are typically unaccounted for in traditional economic analyses (Rogich, Cassara et al. 2008).

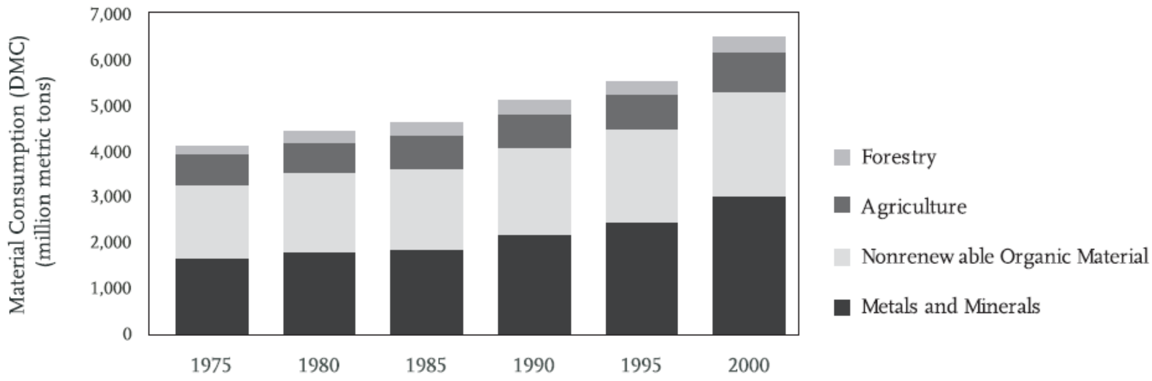
Figure 6. Aggregate Material Flow Accounting (MFA) Indicators



(Rogich, Cassara et al. 2008)
http://pdf.wri.org/material_flows_in_the_united_states.pdf (page 7)

Researchers at the World Resources Institute (WRI) have been engaged in preparing and analyzing material flow accounts since 1995. Among their many MFA studies, they provided a detailed accounting of trends in material flows in four key sectors of the U.S. economy: metal and minerals, non-renewable organic materials (including fossil fuels), agriculture, and forestry. Figure 7 shows how agricultural flows increased 30% between 1975 and 2000. WRI reports that the data show a more than sevenfold increase occurred in the use of grains to produce ethanol for use in automotive fuels (Rogich, Cassara et al. 2008).

Figure 7. Materials Consumption in the United States by Sector of Origin, 1975-2000



(Source: Rogich, Cassara et al. 2008)

3.8.1 Material Intensity per Service-Unit

The concept of Material Intensity per Service-unit (MIPS) was developed by the Wuppertal Institute in Germany to measure the total mass flow of materials caused by the production, consumption (including maintenance) and waste disposal/recycling of a defined service unit or product. The total mass flow for a service unit can consist of overburden, minerals, ores, fossil fuels, water, air and biomass. MIPS employs a life-cycle perspective to include the “hidden” flows of a service unit. MIPS only considers input flows to avoid double counting since input equals output. Also, this approach facilitates accounting since there are fewer inputs than outputs in the industrial economy. The MIPS approach groups inputs into five categories: biotic, abiotic, Earth movements, water and air. Energy demands for the supply of the service unit are also accounted for on a mass basis. To provide additional information, electricity and fuels were added as a sixth category.

The indicator assigns the same relevance to all materials, e.g., 1 kg of gravel and 1 kg of plutonium are equal. In different regions, different fuels and raw materials are used as well as production processes. It is therefore necessary to use the values relevant to each region.

MIPS plays an important role in the promotion of dematerialization. MIPS measures the use of resources during a product’s life cycle. The MIPS indicator is based on the material flow and the number of services or utilizations provided. Reducing the MIPS of a product is equivalent to increasing resource productivity. MIPS quantifies the material intensity of a product or service by adding up the overall material input that humans move or extract to make that product or provide that service. It puts life cycle thinking at the beginning of the product chain. See www.mips-online.info for additional information.

MIPS is measured in kilogram per unit of service. The material input is calculated in five categories: abiotic raw materials, biotic raw materials, water, erosion, and air. The Wuppertal Institute in Germany, which designed material flow analysis, promotes the need to cut material use by 50% and increase the productivity of materials in a much more efficient and more equitably distributed manner (Cleaner Production Action 2008).

Following the concept of MIPS, Materials Intensity Assessment (MAIA) is used to quantify the life-cycle-wide requirement of primary materials for products and services. Analogous to the quantification of the cumulative energy requirements, MAIA provides information on basic environmental pressures associated with the magnitude of resource extraction and the subsequent material flows which end up as waste or emission.

The input of primary raw materials (including energy carriers) is measured in physical units (kg) and aggregated into five main categories:

- Abiotic Raw Materials (non-regrowing inputs)
- Biotic Raw Materials (regrowing inputs)
- Soil Removal
- Water
- Air (inputs for physico-chemical conversion, usually for combustion, in most cases are also strongly correlated with carbon dioxide emissions)

(Institute of Environmental Sciences (CML) Leiden University 24 April 2009)

3.9 Net Energy Balance

The life cycle balance, or the Net Energy Balance (NEB), of a biofuel should result in a positive Net Energy Value (NEV) when compared to conventional fossil fuel in order for it to be a considered as a viable substitute. However, it is well understood that the conversion of biomass to bioenergy requires additional energy inputs, most often provided in some form of fossil fuel. Depending on the processing choices, the cumulative fossil energy demand to produce biofuels can vary widely. However, the bulk of the studies that have been published report moderate to strong fossil fuel substitution for bioethanol systems (von Blottnitz and Curran 2007).

Bioethanol also has its detractors. Often quoted are the works of Pimentel (Pimentel 2003) and Patzek (Patzek 2004), who have both been critical of bioethanol and other biofuels. Their studies contend that bioethanol, and biofuels in general, are "energy negative," meaning they take more energy to produce than is contained in the final product. Perhaps one of the biggest differences between the conclusions by Pimentel and Patzek and other studies that conclude positive net gains is the approach to counting energy credits from by-products (Pimentel has also been criticized for using older production data). Shapouri, Wang and others maintain that ethanol by-products (such as dried distillers grains, gluten meal, gluten feed, and whey) are themselves useful products whose market or energy value should be brought into the analysis to help offset the energy costs of ethanol production (Shapouri, Duffield et al. 2002).

Biofuel production requires energy to grow crops and convert them into biofuels. Hill et al. (2006) estimated farm energy use for producing corn and soybeans, including both direct and indirect energy uses such as energy to grow the hybrid or varietal seed planted to produce the crop, to produce and then power farm machinery and buildings, to produce fertilizers and pesticides, and to sustain farmers and their households. They also estimated the energy needed to convert crops into biofuels, including energy use in transporting the crops to biofuel production facilities, building and operating biofuel production facilities and sustaining production facility workers and their households. Outputs included the biofuels themselves as well as co-products, such as distillers dried grains with solubles (DDGS), which were assigned energy equivalent values. Despite the use of expansive boundaries, Hill et al. show a positive net energy for corn ethanol. However, the net energy gain for corn ethanol is small, providing approximately 25% more energy than required for its production. Corn grain ethanol has a low net energy gain because of the high energy input required to produce corn and to convert it into ethanol (Hill, Nelson et al. 2006). Almost all the entire net energy gain is attributable to the energy credit given to ethanol for the DDGS co-product, which is used as animal feed.

Although energy balances continue to be calculated and discussed, some do not view NEB as the primary way to address energy security (Dale 2008). Instead, what matters is how feedstocks such as coal and natural gas can effectively be used to convert corn into a premium liquid fuel that replaces imported petroleum. This approach reduces the energy balance issue to looking at the net energy of the liquid fossil fuels used in the production of corn-ethanol.

Examples of Net Energy Value Calculations

Farrell et al. (Farrell, Plevin et al. 2006) compared the NEV of (Iowa) corn grain ethanol production to gasoline using the same system boundaries. Even though ethanol production is a far less efficient process than gasoline production, overall, producing one MJ of ethanol requires less fossil inputs (0.774 MJ) than is required to produce one MJ of gasoline (1.19 MJ) As in some NEB models, this study gives energy credits to co-products that are generated when ethanol is made. Credit is calculated by identifying co-products that displace products such as dried distiller grains with solubles, corn gluten feed, and corn oil, thereby partly offsetting the energy required for ethanol production. This is known as the displacement method (Wang, Saricks et al. 1999).

	Net Fossil Inputs MJ_{fossil} **needed for each** MJ_{fuel}	**Net Fossil Ratio** MJ_{fuel} **produced for each** MJ_{fossil} **input***	**Petroleum Input** $MJ_{petroleum}$ **needed for each** MJ_{fuel}
Gasoline	1.19	0.84	1.10
Ethanol	0.774	1.30	0.04

* Net Fossil Ratio = the inverse of Net Fossil Inputs

The USDA explored how allocation rules and co-product credits can make a difference in calculating NEV and energy ratios (Shapouri, Duffield et al. 2002). The following table summarizes the energy requirements by phase of ethanol production on a Btu-per-gallon basis. It includes energy losses from line loss, venting losses at the ethanol plant, and losses associated with mining, refining, and transporting raw materials. Also presented is the NEV of corn ethanol without co-product credits for wet-milling, dry-milling, and a weighted average of wet and dry milling. The weighted average is based on two-thirds of U.S. ethanol capacity from wet-milling and one-third from dry-milling. The average conversion rate for the two processes is 2.525 gallons per bushel. The energy ratio, i.e., the ratio of energy-out to energy-in, is close to 1 in all three cases. In other words, the Btu in a gallon of ethanol is about equal to the energy required to produce a gallon of ethanol even when energy co-products are not considered.

	Milling process		
Production phase	Dry	Wet	Weighted average
	Btu/gal		
Corn production	21,805	21,430	21,598
Corn transport	2,284	2,246	2,263
Ethanol conversion	48,772	54,329	51,779
Ethanol distribution	1,588	1,588	1,588
Total energy used	74,447	79,503	**77,228**
Net energy value	9,513	4,457	**6,732**
Energy ratio	1.11	1.04	**1.08**

(Source: Shapouri, Duffield et al. 2002)

Examples of Net Energy Value Calculations (continued)

The table below presents the NEV and energy ratio results for corn ethanol when energy credits are included in the calculation. Three conversion processes are considered: wet mill, dry mill, and a weighted average of wet and dry milling (2 to 1, as described above). For comparative purposes, the co-product energy values are shown for four methods: output weight, energy content, market value, and replacement value. With co-products credit, the average energy ratio increases from 1.08 (shown previously) to between 1.34 (using a replacement value approach) and 2.22 (using an output weight basis).

NEV and Energy Ratio Calculations for Corn Ethanol

	Energy allocation					
	Ethanol	Co-products	Energy use without co-product credit	Energy use with co-product credit	NEV with co-products	Energy ratio
	Percent	Percent	Btu/gal	Btu/gal	Btu/gal	Btu/gal
Output weight basis:						
Wet mill	48	52	79,503	39,987	44,974	2.15
Dry mill	49	51	74,447	37,289	46,672	2.25
Weighted average	48	52	**77,228**	37,895	**46,066**	**2.22**
Energy content:						
Wet mill	57	43	79,503	46,000	37,961	1.83
Dry mill	61	39	74,447	46,032	37,929	1.82
Weighted average	58	42	**77,228**	45,459	**38,502**	**1.85**
Market value:						
Wet mill	70	30	79,503	56,129	27,832	1.50
Dry mill	76	24	74,447	56,961	27,000	1.47
Weighted average	72	28	**77,228**	56,049	**37,912**	**1.50**
Replacement value:						
Wet mill	81	19	79,503	64,699	19,262	1.30
Dry mill	82	18	74,447	61,332	22,629	1.37
Weighted average	81	19	**77,228**	62,856	**21,105**	**1.34**

(Source: Shapouri, Duffield et al. 2002)

3.10 Sustainability Indicators

In deciding which metrics are important for achieving sustainability goals, most countries agree on general principles for protecting agricultural lands and ecosystems and for reducing GHG emissions. These metrics are more popularly known as indicators. Two classes of indicators are in development by various groups to indicate the state and performance of a system. Those that indicate the state of a system are known as *content* indicators and those that measure the behavior of a system are known as *performance* indicators (Sikdar 2003). There have been many initiatives to develop indicators of national-level sustainability, resilience and vulnerability, but combining them with indicators from other countries can be problematic. The Socioeconomics Data and Applications Center (SEDAC 2009) sought to make the acquisition, comparison and analysis of sustainability indicators easier by compiling them in a single database, incorporating multiple country codes, and condensing the indicator descriptions into short methodological summaries in an accompanying metadata database. As a result, the compendium includes 426 indicators from the following six collections:

- 2006 Environmental Performance Index (EPI) (Esty D.C., Levy M.A. et al. 2006)
- 2005 Environmental Sustainability Index (ESI) (Esty D.C., Levy M.A. et al. 2005)
- 2004 Environmental Vulnerability Index (EVI) (Kaly U.L., Pratt C.R. et al. 2004)
- Rio to Johannesburg Dashboard of Sustainability (O'Connor J. and Jesinghaus J. 2002)
- The Wellbeing of Nations (Prescott-Allen R. 2001)
- 2006 National Footprint Accounts (Ecological Footprint and Biocapacity) (Global Footprint Network 2006)

While the United States is leading on many sustainability issues, it has not yet compiled an official list of best practices or defined a set of sustainability principles, criteria, or indicators. However, research to develop a satisfactory list of indicators is on-going; for example, Green Communities work is being conducted by the EPA (EPA 2009). The following two sections present examples that are developing sustainability indicators that are specific to biofuels: the National Roundtable on Sustainable Biofuels and the Sustainability Interagency Working Group of the National Biomass R&D Board.

3.10.1 Roundtable on Sustainable Biofuels

On August 13, 2008, the Roundtable on Sustainable Biofuels (Board of the Roundtable on Sustainable Biofuels 2008) announced a new draft of sustainability standards for sustainable biofuels, developed through global stakeholder discussion around requirements for sustainable biofuels. The standard includes *principles* (general tenets of sustainable production) and *criteria* (conditions to be met to achieve the principles). The following principles are proposed by the Roundtable for Sustainable Biofuels:

1. Legality
2. Consultation, Planning, and Monitoring
3. Greenhouse Gas Emissions
4. Human and Labor Rights
5. Rural and Social Development
6. Food Security
7. Conservation
8. Soil

9. Water
10. Air
11. Economic Efficiency, Technology, and Continuous Improvement
12. Land Rights

The group is working on developing indicators to evaluate a farm, producer, or company in meeting the principles and criteria.

3.10.2 Sustainability Interagency Working Group

In 2008, the National Biomass R&D Board formed the Sustainability Interagency Working Group, an interagency group led by the U.S. Department of Energy, Department of Agriculture and the Environmental Protection Agency (Biomass R&D Board 2008; Hecht 2009). Table 3 lists the set of sustainability criteria that has been drafted by the group for discussion along the headings of Environmental, Economic, Social, and Energy Diversification and Security (Hecht 2009).

Table 3. Draft Sustainability Criteria Developed by the National Biomass R&D Board for U.S. Biofuels

Bin	**Criterion**	**Description**
Environmental	Reduce greenhouse gas emissions	Life cycle assessment for specific feedstocks and fuels, processes, and transportation.
	Conserve or improve land productivity and soil quality	Long-term soil quality and productivity of working lands; conservation and stewardship practices, soil quality, yield improvement, management of nutrient and chemical inputs and retention (plant stock, fertilizers, pesticides, water) and appropriate pest and disease management.
	Increase water use efficiency and maintain or improve water quality	Water quality and water use efficiency, water reuse and treatment.
	Reduce airborne pollutants to improve air quality: the production of biofuels	Emissions of relevant criteria air pollutants and toxics including those that are associated with acute or chronic health risks.
	Conserve or improve biological diversity	Conservation of terrestrial and aquatic biodiversity and ecosystem services in compliance with applicable laws, regulations,
	Minimize negative land use change impacts	Direct and indirect land used for and resulting from the production of biofuels.

(Adapted from Hecht 2009)

Table 3. Continued

Economic	Enhance resource use and conversion efficiency and productivity	Reduce waste
	Improve cost competitiveness	Reduce production costs
	Enhance economic development and rural prosperity	Increase GDP
Social	Maintain adequate supply of food, feed, and fiber products to meet demand	Impacts of biofuels production and use on the availability of affordable and secure food, water, feed, and fiber for domestic consumption and foreign export.
	Ensure public health and safety	Protection of public safety and health, including incidental pollutant exposure, in all aspects of the biofuels supply, distribution, and use chain.
	Comply with relevant legal and institutional frameworks	Compliance with applicable environmental, land, and labor laws, regulations, treaties, agreements, and executive orders pertaining to the biofuels supply and use chain.
	Increase workforce capacity	Workforce capacity as needed to meet current and future needs for the biofuels supply chain.
Energy Diversification and Security	Reduce imported oil and increase displacement of imported oil-based products:	Biofuels as one means to diversifying energy supply by reducing reliance on imported oil and ultimately the displacement of oil-based products.
	Ensure positive net energy balance	Net energy balance resulting from life cycle analysis of biofuels, accounting for the entire supply chain as compared to fossil fuels.
	Increase access to affordable energy	Long-term availability of biofuels to the public as compared to fossil fuels

Sustainability Indicators provide broad-based tools that cover a variety of issues, including biodiversity and social impacts. However, effective metrics that can be used to measure progress are still needed. Furthermore, the check-list type approach offered by Sustainability Indicators does not appear to offer a straightforward way to avoid potential trade-offs or unintended consequences.

4.0 Results

Table 4 categorizes the ten analytical tools and approaches that were investigated in this study by the information that each develops and the environmental concerns they measure or address. A tool may generate data or information that is relevant to a particular environmental impact, but not necessarily report on that impact. For example, a GHG Life Cycle Analysis identifies and quantifies GHG emissions without going to the next step of modeling the potential contribution to global warming. Life Cycle Assessment, on the other hand, includes such models and reports global warming potential. As can be seen in the table, no single tool addresses all environmental concerns.

Table 4. The Information or Data Typically Generated by Life-cycle Based Assessment Approaches Mapped Against Commonly Reported Environmental Concerns Related to Bio-based Products.

	Resource Use	Energy Use	Global Climate Change	Air Quality	Water Quality	Soil Quality	Land Use	Water Use	Food-for-Fuel	Bio-diversity	Invasive Species	*Socio-Economic Impacts*
Carbon/GHG Management												
Ecological Footprint												
Energy Assessments												
Fuel Cycle Analysis												
Life Cycle Assessment												
Life Cycle Risk Assessment												
Material Flow Analysis (MIPS)												
Sustainability Indicators												//////////// ////////////

* MIPS: Material Input per Service
Environmental concerns that are currently modeled are represented by dark grey; emerging or quasi applications are indicated by light grey.
Sustainability Indicators is the only approach to address socio-economic impacts as well as various environmental impacts.

5.0 Discussion

In reviewing the literature, it quickly becomes clear that the early concern in switching from gasoline (petrofuels) to biofuels was the net energy issue. Numerous researchers calculated, debated, and debated again whether fuels from biofeedstocks result in an overall gain or a loss of energy. While the debate continues, the prevailing consensus is that corn-based ethanol, to varying degrees, has an advantage over gasoline when it comes to energy inputs.

The energy ratio allows for some comparisons to be made between fuel types, however, the true value of fuels is not reflected in an energy analysis because one kJ of ethanol is more useful as a fuel for vehicles than one kJ of natural gas or coal. Bruce Dale argues that the net energy argument is irrelevant and misleading since it assumes all energy carriers are equally valuable, but they are not (Dale 2008).

Recent awareness of Global Climate Change has driven researchers to study, on a system-wide basis, CO_2 emissions, which comprise the flip side of the energy coin since much of our energy is produced from petroleum resources. Because the interest in CO_2 releases has been driven by concerns of increased global warming effects, the list of air emissions was expanded to include other GHGs. This expansion had the effect of making approaches such as Carbon Management, which began as a carbon accounting approach, very similar to Fuel Cycle Analysis and GHG Analysis.

Exergy analysis continues to be developed and promoted as a way to identify potential reductions in thermodynamic losses and efficiency improvements, and to address sustainability issues in a quantitative fashion. For example, researchers at Ohio State University are developing an ecologically-based life cycle analysis (Eco-LCA™) tool which emphasizes the essential role of ecosystem goods and services. Eco-LCA™ is both an economic analysis and an exergy-based calculation of the ecological resource efficiencies of supply chains (Zhang, Baral et al. 2010). The use of exergy calculations should be further investigated and developed in order for it to achieve broader acceptance as an environmental assessment tool.

Ecological Footprinting is widely used around the globe as an indicator of environmental sustainability. Its appeal is the simplicity of the results that are presented in a single measurement. However, simplicity is also the weakness of the tool. For example, the ecological footprint model treats nuclear power the same as it treats coal power, even though the actual effects of the two modes of power generation are radically different. In addition, some questions remain regarding the validity of the model and the underlying assumptions.

Life Cycle Assessment attempts to model the entire range of environmental impacts across the product system (cradle to grave) of biofuels, including global climate change, air quality, water quality, soil quality, and resource use as well as the potential reduction of fossil fuel use and GHG emissions. Land use changes and water use impacts can be captured by LCA only if all the necessary life cycle inventory data are collected.

Material Flow Analysis was originally developed as a way to account for the extraction and use of materials as they flow through the economy. As such, it can generate useful information for understanding the potential impacts on our use of natural resources; its main goal is dematerialization. Later generations of MFA, including MIPS and MAIA, have expanded its usefulness to include information on air quality, soil quality and water use.

The use of Sustainability Indicators is the only approach of the ones studied here that takes biodiversity and social impacts into consideration. However, the implementation of indicators toward sustainability, especially the application of metrics by which progress can be measured, has yet to be developed. Furthermore, the check-list type approach offered by Sustainability Indicators does not appear to offer a straightforward way to avoid potential trade-offs or unintended consequences. For example, choosing to use more biofuel in order to reduce greenhouse gas emissions will potentially have resultant impacts to water and soil quality, as was mentioned earlier. How a checklist allows the user to achieve one goal without sacrificing another is not clear.

5.1 Data and Information Needs

Effective environmental decision making and public policies need to be based on a broad range of data and information and not only on single issues, such as fossil fuel dependency, which can lead to an "all biofuels are good" perspective. In order to capture the entire spectrum of impacts that are outlined at the outset of this report, a wide array of data is needed. In addition, the descriptions of the slate of tools and approaches provided herein make it clear that more and better data are needed for their full implementation. A summary of the data and information needed to accurately assess biofuels (not only corn-based ethanol, but all bio-based fuels) is provided below.

5.2 Environmental Data

5.2.1 Production Data

Biofuel production techniques and farming practices are changing quickly, and becoming more efficient. Thus, published studies may rely on old data that need to be updated in order to account for increased efficiencies. Ethanol plants can have distinctly different energy and GHG emission effects on a full fuel-cycle basis. In particular, GHG emission impacts can vary significantly—from a 3% increase if coal is the process fuel to a 52% reduction if wood chips are used (Wang, Wu et al. 2007). Therefore, not only are accurate input and emissions data for different biofeedstocks needed, data to reflect the types of plants used to produce corn ethanol are needed as well.

5.2.2 Water Use and Availability

Water Use in Corn Ethanol Production (Biorefining)

Water usage is a significant, yet not fully recorded, issue in the United States for the ethanol industry. It is estimated that 3-4 gallons of water are used per gallon of ethanol produced using the dry milling production process (which is prevalent in 80 percent of U.S. ethanol production facilities) while 2 to 2.5 gallons of water are used per gallon of gasoline produced (Aden 2007). However, the amount of water used in the biorefining process is modest compared to the water used to grow bioenergy crops.

Water Use in Crop Irrigation

Each biofuel feedstock presents unique implications for water resources. Water use varies a great deal depending on whether the biofuel is grown on irrigated land or not, and whether there is an increase in overall agricultural production. In the United States, the vast majority of biofuels are currently grown on non-irrigated land (as much as 96% of field corn used for ethanol production is not irrigated). For corn that is irrigated, water consumption estimates are not widely available. For the field corn used for ethanol production that is irrigated, water use has been reported to be approximately 785 gallons on average for each gallon of ethanol produced (Aden 2007).

5.2.3 Water Quality

Among the various potential biofuel crops, corn requires the greatest amount of nitrogen and phosphorous fertilizer per unit of net energy captured in the biofuel. Nitrogen that washes off farmers' fields into bodies of water causes water quality problems; excess nitrogen washing into the Mississippi River is known to cause an oxygen-starved "dead zone" in the Gulf of Mexico (Costello, Griffin et al. 2009). However, the data that represent the amount of agrochemicals that are applied to the land but run off into adjacent waterways are not readily available. Simulation models are available for such estimations, but their application is region-specific and the calculations have not been performed for all the United States.

5.2.4 Land Use Changes

Land Use Change (LUC) issues may be very important but have not been fully explored. It is projected that the rush to produce corn-based ethanol could see an increase of 10 to 12 million corn acres nationwide, depending if it assumed that per acre crop yield will continue to increase as it has in the last few decades (from 79 bushels per acre in 1970 to 150 bushels per acre in 2005). Globally, the conversion of forested, pasture or savannah-type land to (annual) bioenergy crop cultivation could cause higher GHG emissions from released soil carbon and cleared biomass than is fixed by the cultivation of energy crops. This leads to a change in carbon stocks which needs to be considered in the overall GHG balance.

Along with bringing new land into production, changes in crop rotations and tillage practices from increased corn production lead to increases in soil erosion and nutrient loading, particularly in the U.S. Corn Belt and Northern Plains (USDA 2007).

5.2.5 Soil Erosion and Sedimentation

Sedimentation occurs when soil erodes from land and washes down into surface water bodies. Sediments impair water quality and also carry agricultural and other pollutants. The amount of sediment eroding from agricultural areas is directly related to land use – the more intensive the land use the greater the erosion.

Producing biofuels from perennial crops that hold soil and nutrients in place and require less fertilizers and pesticides, like switchgrass or poplars, is an option to reduce the effects of sedimentation. There are, however, large uncertainties surrounding the production of cellulosic ethanol from such crops. Such crops have very little history of use in large-scale cultivation, so even basic information on water, nitrogen or herbicide use, or impact on soil erosion or even overall yields is preliminary (The National Academies of Science 2008).

5.2.6 Human Health Effects

Ethanol use in vehicle fuel is increasing worldwide. However, the potential cancer risk and ozone-related health consequences of a large-scale conversion from gasoline to ethanol have not been thoroughly examined. Several concerns have been raised regarding the possibility of emissions from higher ethanol fuels worsening health risks from air pollution (Naidenko 2009). In addition, Jacobsen (2007) concluded the following:

- E85 (85% ethanol fuel, 15% gasoline) may increase ozone-related mortality, hospitalization, and asthma by about 9% in Los Angeles and 4% in the United States as a whole relative to 100% gasoline usage.
- Ozone increases in Los Angeles and the Northeast United States are partially offset by decreases in the Southeast United States
- E85 also increased peroxyacetyl nitrate (PAN) in the United States, but was estimated to cause little change in cancer risk.
- Due to its ozone effects, future E85 may be a greater overall public health risk than gasoline.
- Unburned ethanol emissions from E85 may result in a global-scale source of acetaldehyde larger than that of direct emissions (Jacobson 2007).

The cultivation of bioenergy crops can cause not only land use conflicts, but also direct impacts on human health depending on the type of crop and harvesting procedures. Pesticides are the primary cause of health risks for agricultural workers. Air pollutants caused by field burning can lead to adverse health effects, especially as a result of the cultivation of sugar cane and palm oil. Furthermore, it is not certain how well workers are educated about the health risks of using pesticides. The use of spraying aircraft can cause pesticides to drift outside of the target area, damage other farmers' crops and harm their animals (Bickel/Dros 2003). Harvesting is dangerous work carried out using sharp tools. Cutting and planting green cane causes skin irritations. Burned cane can also cause skin irritation. Smoky and polluted environments are a danger to health, as are the residues of toxins used in weed control. Medical care is often not available on the plantations. Furthermore, exposure to the sun, insects and snakes and uncomfortable positions during work all impact on human health (Zamora et al. 2004).

5.2.7 Biodiversity

The replacement of lands to grow corn can have a large impact on the diversity of species. It is suspected that higher corn prices, caused by increased ethanol demand, will motivate some U.S. landowners to convert pastures to row crop production. The impact of land conversion is not well known, however, it is likely that the destruction of rainforests and other ecosystems to make new farmland would threaten the continued existence of countless animal and plant species (Doornbusch and Steenblik 2007).

5.2.8 Invasive Species

Some plants that are being considered as feedstock for biofuel crops are known to be very invasive. For example, *Sorghum Halepense* (Johnson grass) is an introduced forage grass that became an invasive weed in 16 of the 48 contiguous states in which it occurs. The African oil palm, recommended for biodiesel, has already become invasive in parts of Brazil, turning areas of threatened forest from a rich mix of trees and plant life into a homogenous layer of palm leaves. Our understanding of potential impacts of biofeedstock production on wildlife habitat and the spread of invasive species is in its infancy. The risks of growing these crops widely need to be evaluated before these crops are planted (Graham 2007).

5.2.9 Socio-Economic Impacts

The definition of sustainability 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. For instance, the cascading effects of large changes in markets are often not addressed. Potential trade-offs, such as food-for-fuel, should be thoroughly examined (the surging biofuel industry will use 27% of this year's American corn crop, challenging farmers' ability to meet food demands). In Mexico, soaring corn prices, sparked by demand from ethanol plants, doubled the price of tortillas, a staple food (Tillman and Hill 2007).

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 (environment, economy, and society) into the decision-making process.

6.0 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 move toward 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.

Various tools and approaches are being applied to closely examine the production and use of biofuels in order to better understand their potential environmental impact. Ten such tools that are based on the cradle-to-grave, life cycle concept study were examined in this report in order to see how the information that they generate relates to the major environmental and social-economic concerns that are the center of attention in the media and published literature. Growing concerns over global climate change have led to the promotion of assessment tools that focus on greenhouse gases, such as Carbon Footprint and Greenhouse Gas Life Cycle Analysis. Fuel Cycle Analyses have traditionally modeled air emissions and are also useful for addressing global climate change, as well as other human health-related air impacts and energy use. Other tools fill very specific niches, such as Ecological Footprint, which accounts for human demand on nature as measured in land area, and Material Flow Analysis (MFA), which models the use of natural resources and identifies potential losses as goods and materials move through the economy. Since no single tool encompasses all possible environmental impacts, an effective method is needed to integrate these tools into a framework that supports the decision-making process as we further develop biofuels.

Looking beyond even an integrated, holistic assessment of environmental impacts, it is also important to consider the economic and social aspects of the full life cycle of biofuels, 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 biofeedstocks, 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 to holistically assess biofuels 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 science is needed to support our policy-makers in delivering sustainable energy systems.

7.0 References

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