CHAPTER 14. Conclusions and Areas of Future Research

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14.1 Project Overview

Although there have been extensive analyses done of the supply chains and environmental impacts of conventional fuels, ethanol-based fuels derived from starch, and ethanol-based fuels derived from cellulose, the economics and emissions from other emerging renewable motor vehicle fuel sources have not been well understood. In this project, life cycle performances of eight biofuel feedstocks were examined. Four of the target fuels are currently in large scale production: gasoline from petroleum, diesel from petroleum, ethanol from corn, and biodiesel from soy. These baseline fuels were chosen because gasoline and diesel are the two dominant types of transportation fuels, and because these four fuels supply the bulk of the US supplies of biofuels, gasoline, and diesel. The emerging biofuel feedstocks analyzed in this work were sugar cane and citrus waste for the production of ethanol, and algae and cottonseed for the production of biodiesel. These emerging renewable sources represent broad categories of emerging fuel types: fuels from land-based energy crops (ethanol from sugar cane), fuels from crop residues (ethanol from citrus waste), fuels from plant oils (biodiesel from cottonseed) and fuels from energy crops grown in aqueous systems (biodiesel from algae). While specific production and processing configurations were selected for these feedstocks, these configurations are not yet optimized and should be viewed as broadly representative of major categories of emerging fuel types.

Performance criteria used in evaluating feedstock production included energy use, water use, greenhouse gas emissions, and land impacts. Net energy is a measure of efficiency that determines the quantity of energy required throughout the life cycle to provide a given energy output when combusted in the engine. Water use, to the extent possible, distinguished between consumption and withdrawals (i.e., that lost to evaporation and that returned to the source in an altered state, respectively). Emissions to air considered in the analyses are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), volatile organic compounds (VOCs), and total oxides of nitrogen (NO_X). For carbon dioxide, methane and nitrous oxide, the sum of emissions weighted by Global Warming Potentials (GWPs) were examined. For air emissions associated with the formation of tropospheric ozone (VOCs and NOx), the potency of emissions was assessed using a regional photochemical model applied to a test region in Central Texas. Finally, land use requirements are described. In assessing all of these performance metrics, the performance is assessed per megajoules of the lower heating value (MJ LHV) of fuel. The assessments performed here are attributional and represent practices and/or technologies taken to be representative of the year 2007.

The sections that follow summarize the findings in energy use, greenhouse gas emissions, water use, and land use for the emerging biofuels and baseline fuels. In addition, infrastructure implications are described.

14.2 Land Use, Area Requirements

The amount of land that is required to produce a biofuel feedstock is greater than the area harvested. In some cases this is an actively managed area that is not producing within a given year, such as land used for seed propagation or an area required to bring a perennial crop to maturity. The US Department of Agriculture (USDA) provides annual data that compares the amount of land planted to the amount of land harvested for a specific crop (ERS, 2009). The US 2007 Census of Agriculture (USDA, 2009) lists both total farm area and harvested area for each of the crops considered in this analysis (with the exception of algae). Information provided in state enterprise budgets are sources of additional information regarding land practices. Land use requirements for cultivation of algae in open pond systems are derived from the reports produced by the US Department of Energy's National Renewable Energy Lab (NREL) (formerly Solar Energy Research Institute (SERI) (Sheehan et al, 1996)). Combining these sets of data, the assumptions given in Table 14.1 are used to determine total land occupation for each of the biofuels considered. The amount of land required for crude oil production is assumed to be much smaller in magnitude than that required for the agricultural stage of the life cycle of biofuels and is therefore not included in this analysis.

Table 14.1. Land use fractions for different activities related to agricultural (aquacultural) production of six different feedstocks.

Activity	Corn for grain	Sugarcane for sugar	Citrus for processing	Soy for beans	Seed cotton	Algae, Saline
Harvested	0.80	0.68	0.61	0.76	0.72	0.53
Fallow or unharvested	0.15	0.18	0.04	0.19	0.23	0.09
Propagation	0.05	0.05	0.02	0.05	0.05	0.07
Other	0.00	0.09	0.33	0.00	0.00	0.31

While it is recognized that there are multiple uses for the products harvested, including various types of fuels and food products, only ethanol produced through fermentation or fatty acid methyl ethyl (FAME) biodiesel derived from triacylglycerides (also triglycerides or TAG) are considered in this analysis. Expected yields of both the agricultural product and the fuel are given in Table 14.2.

It should be noted that in order for any of the proposed fuels to have a noticeable impact on the portfolio of US transportation fuels (including their environmental footprint), the volume needed to be produced would create such an over production of any by-product (including those that are currently the primary product, such as cotton lint or citrus juice) that significant new and as yet undefined markets would have to be created in order for these by-products not to be considered as a waste stream. Therefore, although it is common practice to allocate resources among various by-products in conducting a life cycle assessment, allocation is not done in this exercise.

Table 14.3 considers the case where all existing agricultural production is used for fuel rather than its existing function (food or textiles). From this it can be seen that if all current corn grain were used to produce ethanol, it would result in a displacement of 22 x 10^9 gallons of gasoline or 16% of the 2008 US use (EIA, 2009). Similarly, biodiesel from soybean oil has the potential to substitute for 3.7 x 10^9 gallons of petroleum diesel (8.0% of 2008 US consumption). None of the other agricultural products are currently grown in volumes that would have a significant impact on fuel supply even if 100% of it were sourced for that purpose.

Table 14.2. Agricultural product and expected fuel yield per area of harvested land and per area of occupied land; where the fuel considered is only that produced by fermentation to ethanol (etOH) or transesterification of triglycerides (TAG) derived from the agricultural product itself (or a portion thereof).

Agricultural Product	Harvest Yields	Harvested Area / Total Area	Adjusted Yields	Expected Fuel Yields	Fuel Yields					
					Fuel wt% of Harvest	Harvested Land		Occupied Land		
	Mg/ha-yr		Mg/ha-yr			Mg/ha-yr	liter/ha-yr	Mg/ha-yr	liter/ha-yr	gal/ha-yr
Corn for grain [1]	9.46	0.80	7.57	2.7 gal etOH/bushel corn	31.6%	2.99	3,787	2.39	3,030	800
Sugarcane for sugar [2]	76.7	0.68	52.16	85 L etOH/Mg cane	6.70%	5.14	6,510	3.49	4,427	1,169
Citrus waste [3]	16.0	0.61	9.76	13 gal etoh/ton wet waste	4.28%	0.68	868	0.42	529	140
Soy for beans [4]	2.80	0.76	2.13	19 kg TAG/100 kg seed	19.0%	0.53	599	0.40	455	120
Cottonseed [5]	1.41	0.72	1.02	16 kg TAG/100 kg seed	16.0%	0.23	254	0.16	183	48
Algae [6, 7]	61	0.53	32	12.6 kg TAG /100 kg algae	12.6%	7.71	8,685	4.09	4,603	1,216

[1] 2007 Corn harvest yields, NASS, 2009; fuel yields, estimated from ERS, 2002-2010a, EIA, 2009, and EPA 2009

[2] 2007 Sugarcane harvest yield (wet), ERS, 2009; fuel yields, Macedo et al., 2004

[3] Citrus waste yields (wet), chapter 4 this report; fuel yields, Zhou, 2007

[4] 2007 Soy harvest yields, NASS, 2009; fuel yields, estimated from ERS, 2002-2010b

[5] 2007 Cotton harvest yields, NASS, 2009; fuel yields, estimated from ERS, 2002-2010b

[6] Algae harvest yields assume 24g/m2-day, 300 days/yr, 85% harvest efficiency, chapter 6 this report

[7] Algae fuel yields assume 35% lipids, 40% TAG, 90% extraction efficiency; chapter 6 this report

Table 14.3. Current production potential with no land use change.

Feedstock	2007 Area Harvested (10^6 ha)	2007 production etOH or FAME	Potential New Production w/ No Landuse Change *			Impact on Food Supply
			etOH or FAME	Petroleum Fuel Equivalent	% US Gasoline or Motor Distillate Use *	
		10^9 Liters/yr	10^9 Liters/yr	10^9 gallons/yr		
Corn, grain	35.0	4.9	127.7	22.19	15.92%	Significant
Sugarcane	0.3	0.0	2.2	0.38	0.27%	Low
Citrus waste	0.6	0.0	0.5	0.09	0.07%	Approximately Zero
Soybeans	26.0	0.4	15.1	3.72	7.99%	Significant
Cottonseed	10.5	0.0	2.7	0.66	1.41%	Low
Algae	0.0	0.0	0.0	0.00	0.0%	n/a

* Assumes all existing production is used for fuel rather than current use

With the exception of corn and soy, any substantial contribution to the US fuel supply would thus require land use change, and even in the case of soy or corn, land use change would be required in order to avoid a significant impact on the current food supply. Table 14.4 estimates the total area that would be required for each of the feedstocks in order to displace an equivalent volume of petroleum-based fuel at the 10% and 100% level; the 100% level considers the case where all current use of the feedstock is discontinued in favor of fuel production as well as the scenario where there is no reduction in the supply of existing agricultural products for current uses (primarily food or fiber). The feedstock with the smallest amount of land use change is algae. A 10% substitution of petroleum diesel fuel with algae-based biodiesel would require land use change for 4.1 x 10^6 hectares. The amount land required to support enough algae biodiesel to replace all motor distillate is estimated to be 41.1 x 10^6 hectares. While this is feasible, this amount of land is nearly 20% more than the amount of land currently harvested for corn in the US (Table 14.3).

Table 14.4. Land use change required for 10% and 100% displacement of petroleum equivalent fuels with biofuels.

Feedstock	Occupied Land Requirement 10^6 ha-yr		10% displacement of petroleum fuel	100% displacement of petroleum fuel	100% displacement of petroleum fuel with no impact on current use
	per 10^9 L *	per 10^9 gal *	Total Land Use Change (10^6 hectares)		
Corn, grain	0.5	1.9	0.0	222.7	264.9
Sugarcane	0.3	1.3	17.6	180.8	181.3
Citrus waste	2.9	10.9	150.6	1515.5	1516.5
Soybeans	2.4	8.9	8.3	382.6	415.8
Cottonseed	5.9	22.2	88.9	1020.5	1035.1
Algae	0.2	0.9	4.1	41.1	41.1
* petroleum fuel equivalent					

14.3 Water Use

The means for determining water use for emerging biofuels during life cycle stage 1 (agriculture or aquaculture) is described in Chapters 3 through 6 of this report. The 2008 Farm and Ranch Irrigation Survey (USDA, 2010) was used to estimate water use for corn and soy, using the same methodology as for cotton (Chapter 5). Water used in producing crude oil is taken from Wu and others (2009). Figure 14.1 illustrates the amount of freshwater withdrawn (both surface and ground) as well as that consumed. It is assumed that algae are grown in a saline medium using water from naturally occurring saline aquifers. Freshwater in the cultivation of algae is needed to adjust the water chemistry and is dependent primarily on the difference between evaporation rates and rainfall. Because algae ponds are assumed to consist of large open expanses of water area, the former always exceeds the latter and therefore the amount consumed equals the amount withdrawn. Any tendency to develop algae systems in hot dry areas or to use increasingly saline water would result in increased freshwater use. Total water withdrawals (fresh plus saline) are two orders of magnitude higher (an estimated 167 x 10^6 liters of water per hectare-year). This is also the total minimum water that would be required for a freshwater rather than a saline algae system. All conventional crops rely in part on rainfall to supply water, thus consumption always exceeds withdrawals. Regions of the country that are exhibiting increased areas planted in each of the five crops tend to be characterized by less rainfall and a heavier reliance on irrigation; thus any increase in production is expected to result in both an increase in consumption (due to increased evaporation) and increased water withdrawals.

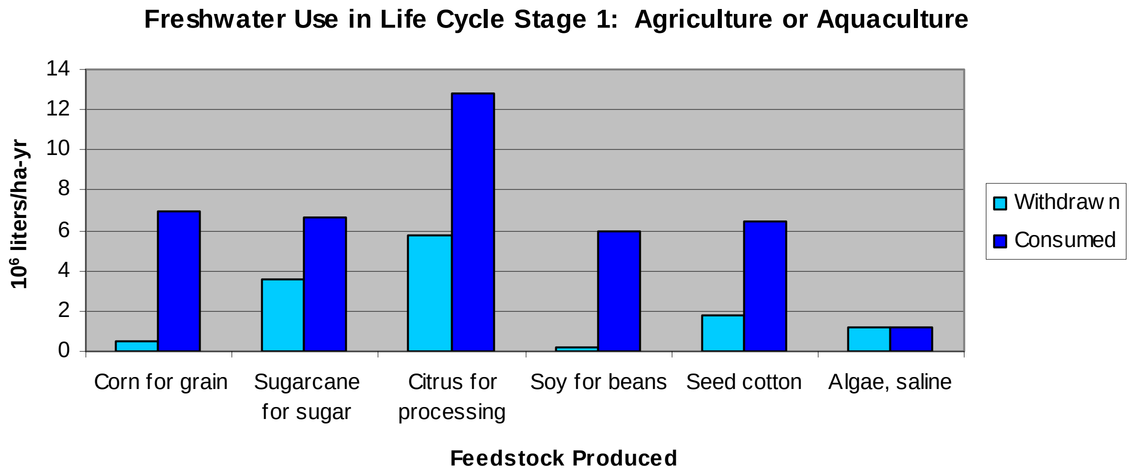

Figure 14.1. Traditional crops make use of rainwater; thus the amount consumed can be significantly higher than the amount of freshwater withdrawn from surface and groundwater. Algae cultivation requires additions of freshwater to control water chemistry in saline systems; the amount consumed is assumed to be equal to the amount withdrawn.

There is a great deal of uncertainty regarding the amount of water used in the production of crude oil; this is discussed in more detail in Chapter 10 of this report. The amount of water per unit area of land is much smaller than that used for biofuels and is not accounted for in this analysis. Wu and others (2009) suggest that total water use relative to barrel of crude oil produced is approximately 8 to 1 on a volumetric basis, while consumption is 3 to 1. These values are taken to be representative in the current analysis. It is assumed at this juncture that water used in crude oil production is freshwater, although there is a significant amount of uncertainty attached to this assumption. The estimated volume of fuel in petroleum equivalent units that can be produced per unit area of land is given in Table 14.5 along with the volumetric ratio of freshwater to fuel (in petroleum equivalents).

Table 14.5. Water use for different feedstocks during life cycle stage one, raw material acquisition.

Feedstock	Freshwater (10^6 L/ha-yr)		Fuel Yield	Fuel Yield (petroleum equivalent)	Volume of Freshwater / Volume of Fuel (petroleum equivalent)	
	Withdrawn	Consumed	L/ha-yr	L/ha-yr	Consumed	Withdrawn
Corn for grain	0.45	7	3,787	2,490	2,811	181
Sugarcane for sugar	3.59	6.7	6,510	4,281	1,565	839
Citrus for processing	5.76	12.8	868	570	22,440	10,098
Soy for beans	0.18	6	599	558	10,759	323
Seed cotton	1.77	6.5	254	236	27,486	7,485
Algae, saline	1.2	1.2	8,685	8,083	148	148
Crude oil					3	8

14.4 Net Energy

The present analysis assumes that the agricultural products under consideration are grown in such large volumes that fuel is by far the dominant product. Under such circumstances, the net energy produced is perhaps the most critical metric. Direct energy inputs to the agricultural enterprise consist of field operations, which in conventional agriculture are performed primarily with diesel-powered tractors pulling various implements for tilling or other operations. Self-powered, diesel-fueled sprayers and harvesting equipment are also common. In the case of algae, the only “field” operation is that used to provide water circulation within the ponds. The total amount of field operation energy required for corn and soy field operations is taken from Nelson et al. (2009), which uses state cost and return (enterprise) budgets to estimate the energy used to grow major crops in the US based on whether conventional, reduced, or no-till systems are used. The use of crop-specific, state-level enterprise budgets is the same approach used for the emerging fuels that are the focus of this report. Indeed, the energy use for cotton determined by Nelson and others is very close to that arrived at independently through the current analysis. The proportion of crops grown using each of the tillage systems is taken from the most recent ARMS data (2005 for corn and 2006 for soy); these values are used to weight energy used based on tillage system to arrive at a weighted US average for corn and soy.

Irrigation and other forms of water management are treated separately because they can be the most significant use of on-site energy. The methods used to determine energy use for sugarcane, citrus waste, cottonseed, and algae are discussed in detail in Chapters 3 through 6 of this report. The amount of energy used to irrigate corn and soy was determined using the same information and methodology as used for cotton (Chapter 5). The proportion of water supplied by diesel, electric, and natural gas pumps is assumed to be spatially uniform throughout the state. Citrus cultivation utilizes both pumped water and wind machines to protect the trees against freezing. Algae cultivation requires pumping of groundwater, presumed to come from saline aquifers. Once at the surface, water, which makes up the bulk of the culture medium, must be repeatedly pumped between inoculum, cultivation, and harvest ponds. The rate at which this pumping occurs depends upon both the type of system employed (batch vs. semi-continuous) and the retention time. The current model assumes a semi-continuous production system with a retention time of two days. All currently demonstrated lipid extraction systems require that algae biomass have at least 10% solids. Given the size of the production targets for this feedstock, solar drying is probably not an option, therefore a natural gas-fueled dewatering step is assumed. However, due to the energy intensity of this process; a significant amount of research is focused on developing harvesting methods that can deliver a dewatered product and/or a lipid extraction methodology that can tolerate large amounts of water. For this reason, the amount of energy required is reported separately with and without natural gas-fueled dewatering. A summary of direct (on-site) energy inputs for each of the potential biofuel crops is presented in table 14.6.

The amount of irrigation energy used in the production of each agricultural product is represented as a weighted US average (estimated for the years 2007/2008). The amount of energy used just for irrigated land is also provided, as the trend in the US is toward increased irrigation, even without additional pressure for increased production in response to demand for biofuels. The data suggest that if all corn were irrigated, for example, that the direct energy usage would nearly double. In contrast, citrus, which is already 100% irrigated, would see no change. It is worth noting, however, that any increase in the production levels of any of the crops evaluated (with the exception of algae) is likely to result in development of crop land that will require increased irrigation and/or pumping from deeper sources. This in turn will result in an increase in related energy consumption, both direct and upstream; the latter is discussed in the following paragraph.

Table 14.6. Direct energy inputs required for cultivation of potential biofuel crops; estimated fuel yields refer only to ethanol and biodiesel from triglycerides.

Agricultural Product	Fuel Yield	Fuel Yield	Water and Wind Management (including Irrigation) [1]		Field Operations [2]	Total Direct Energy
			Wtd US average	Irrigated Land		
	L/ha-yr	GJ/ha-yr	GJ/ha-yr			
Corn for grain [1, 2]	3,787	80.57	0.79	3.67	3.28	4.07
Sugarcane for sugar	6,510	138.50	1.87	3.40	11.71	13.58
Citrus for processing	868	18.46	15.37	15.37	9.90	25.28
Soy for beans [1, 2]	497	16.55	0.23	3.99	2.35	2.58
Cottonseed	286	9.52	2.87	9.63	6.63	9.51
Algae w/o natural gas dewatering	8,685	289.39	1,670.08	1,670.08	334.55	2,004.63
Algae w/ natural gas dewatering	8,685	289.39	1,670.08	1,670.08	36,330.13	38,000.21

[1] Energy use for irrigation of corn and soy estimated from FRIS 2008 (USDA, 2010)

[2] Direct energy for field operations for corn and soy estimated from Nelson et al, 2009 and ARMS

In addition to direct or on-site energy inputs, energy is required to produce and deliver energy as well as nutrients supplied to the crops. The amount of nutrients and pesticides applied to corn and soy are taken from ARMS data (ERS, 2008). The methodology used to determine the amount of energy required to produce these substances for all six biofeedstocks is described in Chapters 3 through 6 of this report. In the case of algae, energy is utilized in the manufacture of the materials from which the containment system is constructed, such as plastic and/or concrete pond liners. The current model assumes concrete harvest ponds, high density polyethylene (HDPE) plastic lined inoculum cultivation ponds, and unlined evaporations ponds. With the exception of a small portion of the inoculum ponds, none of the ponds are assumed to be covered. All conventional crops incur the greatest amount of upstream energy consumption as the result of mining, production, and transportation of nutrients and soil amendments. For algae, most of the upstream energy consumption is due to production and delivery of energy for onsite use. This is due to the significant amount of onsite energy required, particularly in the case where natural gas dewatering is employed. However, even when dewatering is omitted, the significant energy requirements for managing (pumping) the aqueous culture medium results in a very large upstream energy demand as well (Table 14.7).

Adding together direct energy inputs and upstream energy requirements gives the total energy inputs for a given crop. This value may be subtracted from the energy value of the fuel produced to give net energy production. The energy return on investment (EROI) is derived by dividing the energy output by the total energy input. Finally the percent of the total energy budget (constrained by the final energy value of the produced fuel) that is “consumed” during the first stage of the fuel life cycle is determined by taking the reciprocal of the EROI (Table 14.8).

Table 14.7. Upstream energy inputs associated with cultivation of different agricultural products.

Agricultural Product	Energy	Nutrients and Amendments	Pesticides	Materials	TOTAL
	Production and Transportation Energy (GJ/ha-yr)				
Corn for grain	1.4	11.3	0.6	0.0	13.2
Sugarcane for sugar	3.8	5.2	2.9	0.0	11.9
Citrus for processing	8.2	24.1	5.4	0.0	37.7
Soy for beans	0.6	3.5	0.7	0.0	4.8
Cottonseed	4.6	10.5	3.7	0.0	18.8
Algae w/o natural gas dewatering	5,300.2	4,098.9	0.0	390.4	9,789.6
Algae w/ natural gas dewatering	45,975.2	4,098.9	0.0	390.4	50,464.6

14.8. Net energy production, energy return on investment (EROI), and the percent of the total energy budget consumed during raw material acquisition (life cycle stage one)

Agricultural and Fuel Product	Fuel Yield (Energy Out)	Total Direct Energy	Total Upstream Energy	Energy Inputs	Net Energy (Energy Out – Energy In)	EROI (Energy Out / Energy In)	Percent of Energy Budget Consumed in Life Cycle Stage 1
	GJ/ha-yr	GJ/ha-yr					
Corn grain ethanol	80.57	4.07	13.25	17.31	63.25	4.653	21%
Sugarcane ethanol	138.50	13.58	11.85	25.43	113.07	5.446	18%
Citrus waste ethanol	18.46	25.28	37.69	62.97	-44.51	0.293	341%
Soybean biodiesel	16.55	2.58	4.77	7.35	9.19	2.251	44%
Cottonseed biodiesel	9.52	9.51	18.81	28.32	-18.79	0.336	297%
Algae biodiesel w/o dewatering	289.39	2,004.63	9,399.14	11,403.77	-11,114.38	0.025	3941%
Algae biodiesel w/ dewatering	289.39	38,000.21	50,464.59	88,464.80	-88,175.42	0.003	30570%

The conventional US biofuels crops (corn ethanol and soy biodiesel) require energy inputs equal to 21% and 44% of the final energy value of the fuel output. Sugarcane ethanol is slightly lower than corn ethanol (18%). All of the other feedstocks consume more energy during the first life cycle stage than they ultimately produce as fuel, by factors of 3 (citrus waste ethanol and cottonseed) to 39 (algae with no dewatering). It still may be possible to justify fuel production from citrus waste and cottonseed as long as they are true byproducts of citrus juice and cotton lint, but this likely restricts their use to that of a minor supplement to some other major stream of biomass. Algae, if it requires energy intensive dewatering, cannot be justified as a fuel source. Even without dewatering, significant changes regarding the assumed process will have to be made in order to make it a viable feedstock. This is true for even the most optimistic biomass yields and utilization of that biomass for fuels. The biggest challenge will be pumping of the aqueous medium, but nutrient inputs are also significant and scale with the biomass yield.

14.5 Emissions to Air

Criteria pollutants and their precursors, as well as greenhouse gas emissions, are released during the onsite operations related to cultivation of the different feedstocks. Additional releases are associated with upstream activities (production of electricity, fuel, nutrients, and materials). The methodologies used to estimate emissions to air, both at the agricultural site and upstream, are presented in Chapters 3 through 6 of this report for the emerging feedstocks (sugarcane, citrus waste, cottonseed, and algae). Emissions related to field equipment operations for corn and soy are estimated by assuming that the equipment technology suite for field operations is similar to that used for cotton, with all field equipment powered by diesel fuel. The amount of nutrients and pesticides applied to corn and soy are taken from ARMS data (ERS, 2008).

14.5.1 Criteria Air Pollutants

Emissions of five criteria air pollutants and their precursors are estimated for the different feedstocks; these are volatile organic compounds (VOC), carbon monoxide (CO), oxides of nitrogen (NO_X), particulate matter (PM), and oxides of sulfur, expressed as sulfur dioxide (SO_2). Direct emissions are relatively low for corn, soybeans, and cottonseed; those for sugarcane and citrus waste emissions are relatively high because of burning practices. The direct emissions that result from algae cultivation are driven largely by diesel powered pumps used to bring saline groundwater to the surface (electric power is assumed for all other activities). Use of natural gas for dewatering more than doubles the total direct emissions (Table 14.9).

Table 14.9. Direct emissions of criteria pollutants and their precursors.

Agricultural Product	Emissions kg/ha				
	VOC	CO	NO_X	PM	SO_2
Corn for grain	0.17	0.65	2.00	0.12	0.08
Sugarcane for sugar	60.78	789.45	33.09	89.63	3.91
Citrus waste	31.34	305.93	172.90	50.29	6.35
Soy for beans	0.11	0.43	1.27	0.08	0.05
Cottonseed	0.42	1.92	4.46	0.28	0.20
Algae w/o dewatering	109.58	293.74	1364.36	96.05	89.65
Algae w/ dewatering	198.03	1620.52	2936.84	213.98	99.48

Upstream emissions for algae are two orders of magnitude greater than that for other crops; this is driven by both nutrient and energy production. Citrus production results in more than double the emissions relative to other conventional crops (Table 14.10) due to the relatively high application rates for nutrients.

Table 14.10. Upstream emissions of criteria pollutants and their precursors.

Agricultural Product	Emissions kg/ha				
	VOC	CO	NO_X	PM	SO_2
Corn for grain	1.0	1.1	1.4	0.6	4.3
Sugarcane for sugar	0.5	0.7	1.7	0.6	3.9
Citrus waste	2.1	2.6	5.5	2.5	5.2
Soy for beans	0.1	0.2	0.6	0.3	1.3
Cottonseed	0.8	1.1	2.6	1.3	3.1
Algae w/o dewatering	125.0	344.7	518.4	8460.2	181.0
Algae w/ dewatering	323.8	618.0	1297.1	8490.1	575.8

With the assumed process, upstream emissions for algae are two orders of magnitude greater than that for other crops; this is driven by both nutrient and energy production. Citrus production results in more than double the emissions relative to other conventional crops (Table 14.11) due to the relatively high application rates for nutrients.

Table 14.11. Total emissions of criteria pollutants and their precursors.

Agricultural Product	Emissions kg/ha				
	VOC	CO	NO_X	PM	SO_2
Corn for grain	1.1	1.7	3.4	0.7	4.4
Sugarcane for sugar	61.3	790.2	34.7	90.3	7.8
Citrus waste	33.4	308.5	178.4	52.8	11.5
Soy for beans	0.2	0.6	1.9	0.4	1.3
Cottonseed	1.2	3.0	7.1	1.6	3.3
Algae w/o dewatering	234.6	638.4	1882.7	8556.2	270.7
Algae w/ dewatering	521.8	2238.5	4233.9	8704.1	675.3

14.5.2 Greenhouse Gases

Three compounds released to the atmosphere contribute directly to the greenhouse gas inventory; these are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (sometimes referred to as dinitrogen oxide (N_2O)). Volatile organic compounds (VOC) and carbon monoxide (CO) also contribute indirectly by providing sources of carbon that can be oxidized to CO_2. Two categories of emissions occur at or nearby the agricultural site, termed direct and indirect emissions. Indirect emissions consist solely of N_2O that is released as the result of nitrogen fertilizer use. Direct emissions are produced through the burning of fossil fuels or biomass, application of fertilizer and soil amendments, biomass residue, and cultivation in areas characterized by organic soils. Total direct and indirect emissions of greenhouse gases are dominated by use of nitrogen fertilizer and limestone (a soil amendment). Emissions of N_2O are high for sugarcane grown on organic soils in the Florida Everglades. Burning of sugarcane prior to harvest releases relatively large amounts of methane. Although there are efforts to eliminate this practice, it is not clear that net emissions would be reduced, as the amount of energy required to operate harvesting equipment when cutting green (unburned) cane increases significantly. The energy demands for algae cultivation as well as natural gas-fuel dewatering of algae contribute greatly to direct emissions of greenhouse gases (Table 14.12).

Upstream emissions for most field crops are relatively uniform (Table 14.13), with soy incurring the lowest and cotton incurring the highest values.

Table 14.14 sums the greenhouse gas emissions and weights the values by the relative global warming potential as given in the IPCC guidelines (2007). The two conventional biofuel feedstocks, corn and soy, have the lowest overall greenhouse gas emissions, measured as CO_2 equivalents. Sugarcane grown in the Florida Everglades has the second highest (after algae). Sugarcane grown elsewhere is comparable to cottonseed.

Table 14.12. Direct and indirect emissions of greenhouse gases.

Agricultural Product	Emissions (kg/ha-yr)		
	CO_2	CH_4	N_2O
Corn for grain	461	0.0	2.103
Sugarcane, US	14,142	23.1	7.141
Sugarcane, non-organic soils	1,309	23.1	2.741
Citrus for processing	2,032	8.8	6.515
Soy for beans	348	0.0	0.356
Cottonseed	824	0.1	5.604
Algae w/o dewatering	53,369	7.2	33.941
Algae w/ dewatering	1,942,311	43.2	67.941

Table 14.13. Upstream emissions of greenhouse gases.

Agricultural Product	Emissions (kg/ha-yr)		
	CO_2	CH_4	N_2O
Corn for grain	856	1.4	0.009
Sugarcane, US	803	2.2	0.010
Sugarcane, non-organic soils	803	2.2	0.010
Citrus for processing	2,573	5.6	4.169
Soy for beans	318	0.7	0.008
Seed cotton	1,339	2.6	1.234
Algae w/o dewatering	556,244	710.5	38.655
Algae w/ dewatering	735,623	7409.6	41.613

Table 14.4. Total greenhouse gas emissions reported as carbon dioxide equivalents (CO2e) for life cycle stage one, raw material acquisition.

	Total Emissions of GHG					Emissions of GHG in CO2e					
	kg/ha-yr					kg/ha-yr					
	CO_2	CH_4	N_2O	CO	VOC	CO_2	CH_4	N_2O	CO	VOC	TOTAL CO_2e
GWP (CO_2e factor)	1	25	298	1.57	3.04						
Corn for grain	1,317	1	2.1	1.7	1.1	1,317	36	629	3	3	1,988
Sugarcane, US	14,946	25	7.2	790.2	61.3	14,946	632	2,131	1,242	186	19,137
Sugarcane, non-organic soils	2,113	25	2.8	790.2	61.3	2,113	632	820	1,242	186	4,993
Citrus waste	4,605	14	10.7	308.5	33.4	4,605	359	3,184	485	102	8,735
Soy for beans	666	1	0.4	0.6	0.2	666	17	108	1	1	793
Cottonseed	2,163	3	6.8	3.0	1.2	2,163	66	2,038	5	4	4,276
Algae w/o dewatering	609,613	718	72.6	638.4	234.6	609,613	17,942	21,634	1,003	714	650,906
Algae w/ dewatering	2,677,934	7,453	109.6	2,238.5	521.8	2,677,934	186,321	32,647	3,518	1,588	2,902,007

14.6 Regional Air Quality Implications

Assessing the environmental impact of fuel use was done through a two-step process. First, regional emission scenarios were incorporated into photochemical air quality modeling simulations to estimate urban air quality impacts of widespread adoption of biofuels. The emission scenarios were intentionally selected to represent an aggressive implementation of biofuels: 30%, 50%, and complete replacement of petroleum-based gasoline and diesel fuel use by 2030. The emission characteristics of the biofuels were assumed to be well represented by data available in the literature. These emission changes resulted in relatively small impacts on ground level ozone and several other photochemical air pollutants, even for 100% replacement of petroleum-based gasoline and diesel fuels with biofuels. The extent of the impacts was put into perspective by comparing the changes to a much smaller extent of electrification of the light duty gasoline fleet of vehicles. Electrification of approximately 20% of the light duty gasoline vehicles produced comparable changes in ozone concentrations to that with 100% adoption of biofuels. Second, engine simulators were used to assess the extent to which emission characteristics of emerging biofuels might differ from current biofuels. Overall, the engine simulations indicated that the emission scenarios considered in the air quality modeling are reasonable, but have significant uncertainties.

14.7 Infrastructure Implications

Analyses of historical fuel transitions were performed in order to place barriers to potential biofuel transitions into context. The historical analyses illustrated that fuel transitions are common (for example, leaded to unleaded gasoline; diesel to low-sulfur diesel to ultra-low-sulfur diesel (ULSD); and shifts in oxygenates from methyl-tert-butyl-ether (MTBE) to ethanol) and exhibit variable time scales (the transition to unleaded gasoline took approximately 20 years, whereas the introduction of ULSD required approximately one year). In addition, the ULSD transition occurred during the same time frame as the transition from MTBE to ethanol in motor gasoline, which means the fuel industry successfully managed two major fuel transitions more or less simultaneously in the two largest markets of the US liquid fuels sector. The historical analyses also revealed a variety of infrastructure implications throughout the supply chain that are triggered by fuel transition, and illustrated the importance of properly selecting temporal, spatial, and sectoral boundaries for analysis to avoid unintended consequences.

These historical examples were used to inform forward-looking analysis about the potential transition during which biofuels would displace a substantial fraction of the liquid fuels consumed in the US. A set of six projections, or scenarios, of the liquid fuels sector were analyzed with a Liquid Fuels Transition (LiFTrans) model, which was based on an analysis of historical fuel transitions, and incorporated regulatory renewable fuels standards (RFS) and EIA projections for liquid fuels demand. The model revealed that for the reference case based on meeting the targets in the RFS, E85 consumption is negligible until approximately 2014, when a 10% blend wall is reached. At that point consumption of E85 begins a rapid growth trend that continues through 2022. Prior to the blend wall, most increases in ethanol consumption are from E10. After the blend wall is reached, further increases in ethanol consumption come in the form of E85. This phenomenon is not simply a result of the blend wall, but is also based on the flat demand for total motor gasoline products in this projection. Increasing the blend limit from 10 to 20% (i.e., E20) delays the introduction of E85 by approximately 8 years, and thereby spares significant infrastructure changes (including vehicle stock turnover, retail outlet retrofits, etc.). If total demand were to increase at a rate comparable to total ethanol demand (on an energy basis), then the market could continue to be supplied with E10, forgoing the need for ethanol to be consumed as E85. For diesel markets, with the modest penetration of biofuels and growth in total distillate demand starting in 2010, there is no evidence of issues related to a "blend limit" or "blend wall". Diesel-engine manufacturers place limits on biodiesel use, but the projected volumes of biodiesel fall well below any concerns about reaching a blend wall during the timeframe of this projection, suggesting that infrastructure issues will not be significant in diesel fuel markets.

14.8 Areas of Future Research

14.8.1 Feedstock Production

Most of the feedstocks evaluated are produced under relatively stable conditions. There have been gradual increases in cultivated land area, but no significant land use change. If production of biofuels were to be accelerated, significant land use change is expected to occur. In tandem, there is likely to be intensification of activities on existing cropland, in particular additional irrigation and possibly increased use of nutrients. Mass cultivation of algae in support of fuel production will require significant technical advances and/or shifts from the open pond systems described by the SERI/NREL reports of the 1980's in order to achieve a positive return. Indeed much of this work is currently underway.

14.8.2 Process Definition

Since large scale production of most of the systems discussed is not yet available, it was necessary to postulate what these mature processes would be. The conclusions presented in this report are a result of the processes assumed. Additional research is needed into more processes that are more effective as measured against the criteria of this study. An example of the improvement possible is given in this work. When it was recognized, for example, that there were emerging algae processing technologies that did not require drying, the direct and indirect emissions of CO2 were reduced by more than a factor of 35 (Table 14.12).

14.8.3 Regional Air Quality

The current analysis using emissions factors available in the literature suggests that there are both positive and negative effects on regional air quality as the result of burning biofuels; however, additional work could decrease the amount of uncertainty in emissions factors.

14.8.4 Economic Analysis

The direct economic effects of conversion to biofuels are expected to be related to modification at refineries, to distribution systems, and in motor vehicle compatibility. The indirect economic effects related to land use change, impact of byproduct, and possible climate change mitigation require further investigation.

14.9 References

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