Sustainability impacts of first-generation biofuels

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Implications

- First-generation biofuels can have several environmental and socioeconomic impacts.
- Major impacts include greenhouse gas emissions, atmospheric pollution, water overconsumption and pollution, deforestation, biodiversity loss, rural development, food security, energy security, public health, and social conflicts.
- The nature and the magnitude of biofuel impacts depend on the feedstock, the mode of feedstock production, the agricultural practices adopted during feedstock production, the environmental and socioeconomic context of biofuel production, the stage of the biofuel's life-cycle, and the policies in place during biofuel production, use, and trade.
- Trade-offs are inevitable, but at least some of biofuels' negative impact can be mitigated through careful planning.

Key words: biodiesel, bioethanol, biofuels, impacts, sustainability

Introduction

Biofuels are fuels derived from solid biomass through different chemical and biological processes. Common biofuel types include bioethanol, biodiesel, syngas, and biogas. Biofuels have been used mainly for the displacement of conventional transport fuel (e.g., gasoline, diesel) in the U.S., Brazil, EU, China, and India. Bioethanol and biodiesel can be blended with conventional transport fuels in different proportions. For example, a mix of 5% bioethanol and 95% gasoline is denoted as "E5." Similarly, "B5" denotes a mix of 5% biodiesel and 95% conventional diesel. Depending on the raw material (feedstock) and conversion technology used, biofuels can be distinguished as first-, second-, and third-generation biofuels (Lee and Lavoie, 2013). Liquid biofuels such as bioethanol and biodiesel (termed henceforth simply as biofuels) are by far the most widely adopted types of biofuels for transport purposes.

Bioethanol is the most widely produced biofuel globally with the U.S. (from corn), Brazil (from sugarcane), the EU (from sugar beet, wheat), China (from corn), and India (from sugarcane molasses) being the largest producers (IEA, 2010; Figure 1). Less popular bioethanol feedstocks include cassava (in Southeast Asia, China), sweet sorghum (in China), and sweet potato (in China). Numerous other developing nations, particularly in Sub-Saharan Africa and Latin America, are promoting sugarcane ethanol production (Gasparatos et al., 2012a). On the other hand, the main biodiesel producers are the EU (mainly from rapeseed) and the U.S. (mainly from soybean). Emerging producers include Brazil and Argentina (from soybeans) and Malaysia and Indonesia (from palm oil; Figure 1). India, China, and several Sub-Saharan and Southeast Asia countries promote jatropha biodiesel (Gasparatos et al., 2012a). Beef tallow and used cooking oil can also be used as feedstocks for first-generation biodiesel. In some cases, pure plant oil from oil-bearing crops such as jatropha has been used directly as a fuel for lighting, rural electrification, and power generation (Gasparatos et al., 2012a).

Despite large feedstock potential globally (Field et al., 2008), there is currently no commercial production of second-generation biofuels anywhere in the world (IEA, 2010). While there are significant research efforts in developed countries, (mainly in the U.S. and the EU), with the exception of Brazil and China, plans to produce second-generation biofuels in other developing countries are almost nonexistent (IEA, 2010).

Global biofuel production has increased more than fivefold in the past decade (OECD-FAO, 2010) but the drivers of biofuel expansion and the adopted feedstocks vary considerably across different regions of the world (Gasparatos et al., 2011; Gasparatos and Stromberg, 2012). Due to increasing global demand, biofuel production is expected to increase

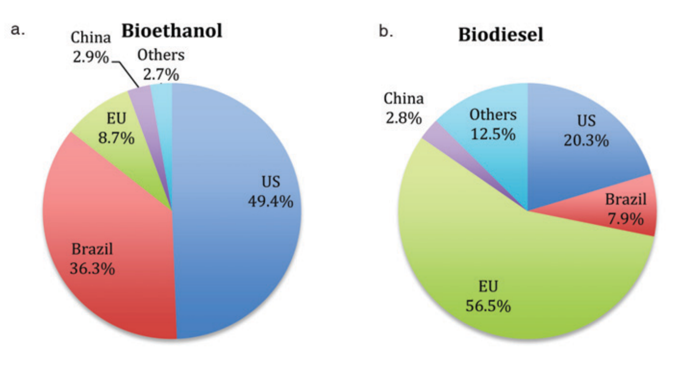

Figure 1. Bioethanol and biodiesel production in 2008 by major producers. Source: IEA, 2011.

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significantly, mainly due to the expansion of first-generation biofuels in developing nations such as Brazil, China, and India (OECD-FAO, 2010). Compared with 2009 levels, biofuel consumption might increase as much as 500% in OECD countries and 678.0% in non-OECD countries by 2035 (IEA, 2010).

However, biofuel production and use can have numerous socioeconomic and environmental impacts (Howarth and Bringezu, 2009; Gasparatos et al., 2011). Perhaps the most emblematic of all is the impact of biofuels on food prices and food security that has sparked the food vs. fuel debate. Other impacts include effects on greenhouse gases (**GHG**) emissions, atmospheric pollution, water consumption/pollution, deforestation, biodiversity loss, rural development, energy security, health and social conflicts, among several others (Gasparatos and Stromberg, 2012).

As a result of the above, biofuel sustainability has emerged as an important policy topic. For example, the EU-Renewable Energy Directive (**EU-RED**) has specified a set of sustainability criteria such as GHG emissions, biodiversity loss, and food security, that must be met before certain biofuel practices can be widely adopted within the EU (EC, 2009). However, with a few exceptions, such policies lack wider environmental and social provisions (Gasparatos and Stromberg, 2012). Voluntary standards are a second type of policy instruments that aim to boost biofuel sustainability. They are promoted by multi-stakeholder alliances and can either target biofuels (e.g., the Roundtable on Sustainable Biofuels [RSB, 2010]) or specific feedstocks [e.g., the Roundtable on Sustainable Palm Oil (RSPO, 2007)]. Usually, such standards are comprehensive in the sense that they encompass a wide range of economic, environmental, and social criteria that have to be met if a biofuel–feedstock practice is to be considered sustainable.

Table 1 includes a list of main sustainability issues associated with biofuel production and use, as identified by the Roundtable for Sustainable Biofuels (**RSB**) and the Global Bioenergy Partnership (**GBEP**).

However, different biofuels can have radically different impacts, both by type and by magnitude depending on several factors such as:

- the feedstock
- the mode of feedstock production
- the agricultural practices adopted during feedstock production
- the locality of biofuel production and use (i.e., environmental and socioeconomic context)
- the stage of the biofuel's life-cycle
- the policies in place during biofuel production, use, and trade

Considering the above, this paper provides a short introduction of the modes of production and impacts of first-generation biofuels.

Biofuel Life-cycle and Modes of Feedstock Production

Biofuel chains encompass several different stages such as feedstock production (agricultural phase), feedstock transport, feedstock processing, biofuel production, and biofuel distribution, storage, dispensing, and combustion (Hess et al., 2009; Figure 2). It has been shown that the magnitude and scale of impacts vary significantly between the different stages of the life cycle of biofuels (Howarth and Bringezu, 2009; Gasparatos and Stromberg, 2012).

Table 1. Sustainability standards of the Roundtable for Sustainable Biofuels (RSB) and sustainability indicators of the Global Bioenergy Partnership (GBEP).

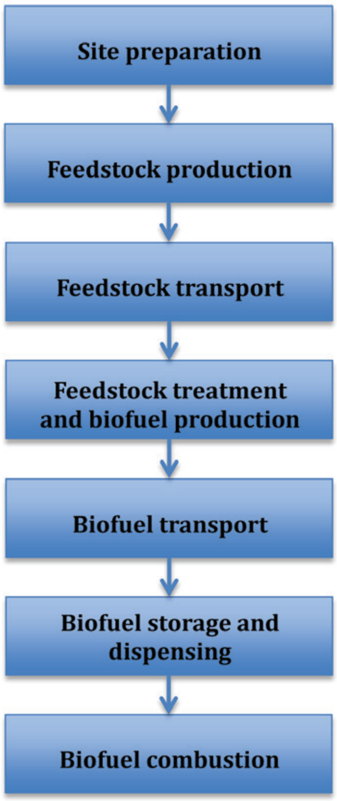
Principles
Principle 1: Legality
Principle 2: Planning, Monitoring, and Continuous Improvement
Principle 3: Greenhouse Gas Emissions
Principle 4: Human and Labor Rights
Principle 5: Rural and Social Development
Principle 6: Local Food Security
Principle 7: Conservation
Principle 8: Soil
Principle 9: Water
Principle 10: Air
Principle 11: Use of Technology, Inputs, and Management of Waste
Principle 12: Land Rights
Indicators
Indicator 1: Lifecycle GHG emissions
Indicator 2: Soil quality
Indicator 3: Harvest levels of wood resources
Indicator 4: Emissions of non-GHG air pollutants, including air toxics
Indicator 5: Water use and efficiency
Indicator 6: Water quality
Indicator 7: Biological diversity in the landscape
Indicator 8: Land use and land-use change related to bioenergy feedstock production
Indicator 9: Allocation and tenure of land for new bioenergy production
Indicator 10: Price and supply of a national food basket
Indicator 11: Change in income
Indicator 12: Jobs in the bioenergy sector
Indicator 13: Change in unpaid time spent by women and children collecting biomass
Indicator 14: Bioenergy used to expand access to modern energy services
Indicator 15: Change in mortality and burden of disease attributable to indoor smoke
Indicator 16: Incidence of occupational injury, illness, and fatalities
Indicator 17: Productivity
Indicator 18: Net-energy balance
Indicator 19: Gross value added
Indicator 20: Change in consumption of fossil fuels and traditional use of biomass
Indicator 21: Training and re-qualification of the workforce
Indicator 22: Energy diversity
Indicator 23: Infrastructure and logistics for distribution of bioenergy
Indicator 24: Capacity and flexibility of use of bioenergy

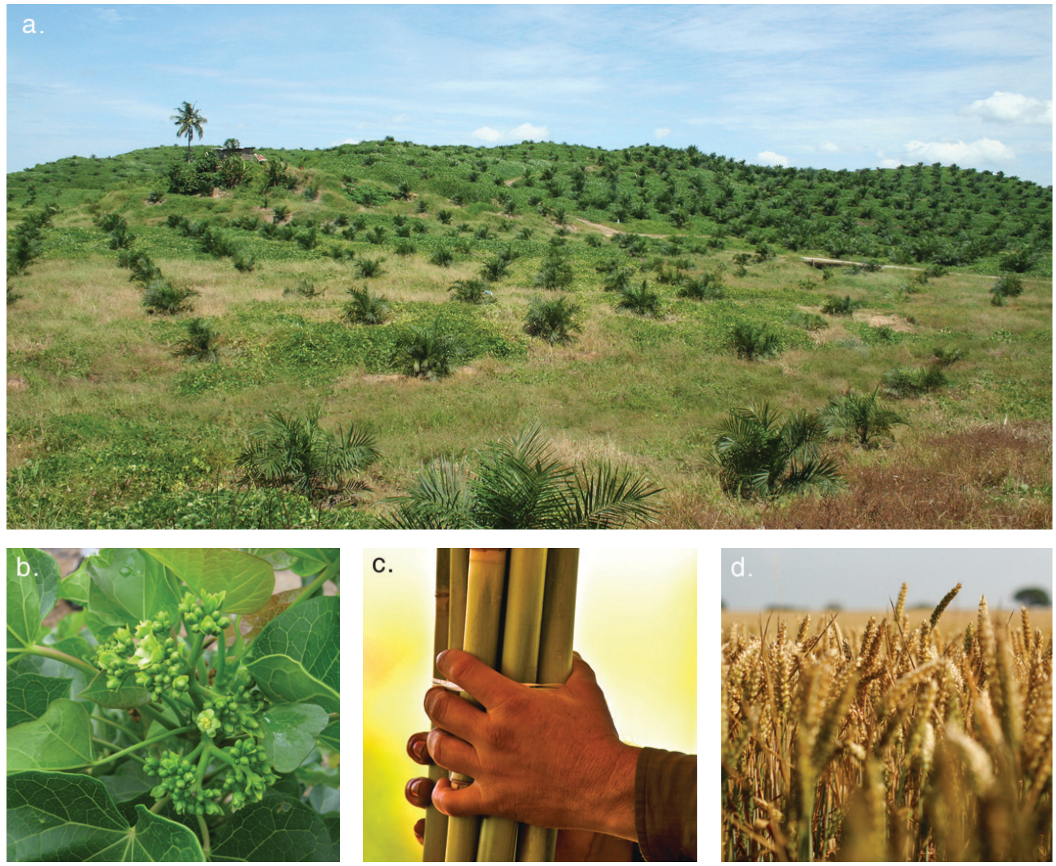
Source: RSB, 2010; GBEP, 2011

Feedstock production is perhaps the most important stage for impacts related to biodiversity loss, water use, water pollution, rural development, food security, and social conflicts, while it contributes significantly to other impacts such as GHG and air pollutant emissions. There are three main modes of feedstock production (von Maltitz et al., 2012; von Maltitz and Setzkorn, 2013):

- large-scale feedstock production for commercial purposes
- smallholder feedstock production for commercial purposes
- small-scale feedstock production for local use.

Figure 2. The seven stages of the biofuel life cycle.





Life-cycle assessment (LCA) studies have shown that biofuels from feedstocks such as palm oil (*a*), wheat (*b*), sugarcane (*c*), and jatropha (*d*) have the potential to be significant net-energy providers. Photo credit: Angela Sevin (*a*); flickr.com/jnlsnet (*b*); Sweeter Alternative (*c*); and Ton Rulkens (*d*).

Large-scale feedstock production usually takes place in large plantations, which are essentially extensive monocultures. The produced feedstock is sold for biofuel production, usually for transport purposes, in national and international markets. This is the dominant mode of feedstock production in the U.S., EU, and Brazil. In some geographical contexts such as Sub-Saharan Africa, outgrowers are linked to large plantations. In several developing countries such as Brazil, feedstocks plantations are usually parts of large corporations owned by foreign investors and funded through direct foreign investments (Abramovay, 2008). This production model appropriates large areas exclusively for feedstock production and has been identified as a major driver of direct and indirect land use and cover change (**LUCC**).

Smallholder feedstock production for commercial purposes is performed by outgrowers (linked to large plantations) or smallholders (linked to feedstock processing plants; von Maltitz et al., 2012; von Maltitz and Setzkorn, 2013). In this mode of feedstock production, small farms produce the feedstock, which they subsequently sell as a cash crop. Large companies, whether plantations or feedstock processing plants, contract farmers to allocate part of their land to feedstock production, and in exchange provide initial inputs including seeds, fertilizers, and sometimes finance (Gasparatos et al., 2012a). In return, the farmers take care of the crop and harvest the seeds, which they are then contractually obliged to sell to the company.

Small-scale biofuel projects entail the use of locally produced feedstock by the producing communities for rural electrification and power generation. Small-scale projects have been promoted in several developing countries as a rural development and poverty alleviation strategy (Energia, 2009; FAO, 2009; Gasparatos et al., 2012a).

Sustainability Impacts

Energy provision and energy security

A key consideration when assessing biofuel sustainability is the extent to which a biofuel provides a net-energy gain when compared with the conventional fossil fuels it displaces. Two commonly used indicators are the energy return on investment (**EROI**) and the percentage fossil energy improvement. The EROI is the ratio of the total energy supplied by biofuel combustion (Eout) to the total energy used during biofuel production (Ein). Values of EROI greater than 1 imply net-energy gains. The percentage fossil energy improvement provides a measure of the amount of nonrenewable energy used during the life cycle of a biofuel. The EROI and percentage fossil energy improvement are usually quantified through life-cycle assessments (**LCA**).

Studies and meta-analyses of LCA have shown that some first-generation biofuels can be significant net-energy providers. For example, a meta-analysis by Stromberg and Gasparatos (2012) report relatively high EROI for sugarcane bioethanol (3.1 to 9.3), wheat bioethanol (1.6 to 5.8), palm oil biodiesel (2.4 to 2.6), and jatropha biodiesel (1.4 to 4.7). Conversely, corn bioethanol (0.8 to 1.7) and certain soybean biodiesel practices (1.0

to 3.2) demonstrate low EROI, lower than 1.0 in some cases. In another meta-analysis, De Vries et al. (2010) have reported that sugarcane bioethanol, sweet sorghum bioethanol, and palm oil biodiesel provide the highest EROI. Sugar beet bioethanol, cassava bioethanol, rapeseed biodiesel, and soybean biodiesel have the next highest EROI, while corn bioethanol and wheat bioethanol exhibit relatively low EROI. LCA have also shown that the production and use of straight jatropha oil can have significant net-energy gains (Gmunder et al., 2010). Using straight jatropha oil as a fuel without any prior processing is not as energy efficient as using jatropha biodiesel, because it can cause malfunctions to the combustion engine (Gmunder et al., 2010). In some cases, the utilization of biofuel by-products, such as sugarcane bagasse combustion for electricity cogeneration, can further boost EROI, economic viability, and GHG emission reduction (Guo and Hanaki, 2010; Pellegrini and de Oliveira, 2011).

The LCA meta-analysis by Menichetti and Otto (2009) concludes that most current first-generation biofuels provide positive percentage fossil energy improvements. Sugarcane bioethanol provides by far the highest and most consistent percentage fossil energy improvements (in the range of 80 to 90%). Other biofuels, such as corn/sugar beet/wheat bioethanol and rapeseed/soybean/sunflower/palm oil biodiesel, provide mostly positive, but highly variable, percentage fossil energy improvements (Menichetti and Otto, 2009). An LCA study ranked the different biodiesel production chains according to their nonrenewable energy use as follows (in decreasing order of energy consumption): soybean (Argentina), soybean (Brazil), rapeseed (EU), rapeseed (Switzerland), palm oil (Malaysia), and soybean (U.S.; Panichelli et al., 2009).

In policy contexts where energy security is the main driver of biofuel expansion, then all things equal, biofuel practices with high EROI and high positive percentage fossil energy improvements provide the largest energy gains and are to be preferred. Energy security has been the overarching policy driver for biofuel expansion in the U.S. (U.S. House of Representatives, 2007), Brazil (Gasparatos et al., 2012b), the European Union (EC, 2009), China (Zhou and Thomson, 2009), India (Zhou and Thomson, 2009), and parts of Sub-Saharan Africa (Gasparatos et al., 2012a).

So far, Brazil offers the only example of a country that has significantly improved its energy security through biofuel production and use. In 2008, biofuels constituted about 21.0% of all road transport fuel and 11.1% of final energy consumed within the country (Gasparatos et al., 2012b). This has had a positive effect on other macroeconomic factors such as trade balances and foreign exchange reserves.

Biofuels can also improve energy security at the local level. In a number of cases in Africa, Asia, and Latin America, energy security has improved at the local level (usually the village level) through small-scale biofuel projects (Energia, 2009; FAO, 2009; Gasparatos et al., 2012a). Examples include rural electrification in Mali, Mozambique, and Uganda (from straight jatropha oil), water pumping in India (from straight jatropha oil), and biodiesel production in South Africa (from sunflower seeds; Energia, 2009; FAO, 2009). This positive effect of liquid biofuels is particularly significant when the costs associated with transporting imported fossil fuel are high (e.g., in landlocked countries) or when road infrastructure is poorly developed (Gasparatos et al., 2012a).

The above suggest that some first-generation biofuels can provide significant net-energy gains, but to different degrees. As a result, biofuels can be feasible energy options in the short-to-medium term. However, most first-generation biofuels not only have much lower EROI than fossil fuels (15 to 20), but they also over rely on fossil fuel–intensive commodities such as fertilizers and agrochemicals. The above might render biofuels' long-term production unviable, if current production practices are pursued.

GHG emissions

The potential climate change mitigation benefits of first-generation biofuels have been another contentious aspect of the biofuel debate. Several studies have quantified the GHG emissions of different biofuels across their whole life cycle and have reached highly different conclu-

Biofuels produced from perennial crops, like miscanthus pictured below, typically have lower greenhouse gas emissions during their whole life cycle compared with annual crops (photo credit: USDA/Bob Nichols).

Table 2. Carbon payback times for different biofuels.

Biofuel type	Region	Original land use	Payback time (years)	Source
Palm oil biodiesel	Southeast Asia	Tropical rainforest	86	(Fargione et al., 2008)
	Southeast Asia	Peat land rainforest	423	(Fargione et al., 2008)
	Malaysia	Lowland tropical rainforest	76	(Achten and Verchot, 2011)
	Indonesia	Mix of lowland tropical primary/secondary rainforest and agricultural land	58	(Achten and Verchot, 2011)
	Indonesia	Mix of tropical peatland forest, swamp and agricultural land.	199	(Achten and Verchot, 2011)
	Indonesia	Lowland tropical primary rainforest with tropical peatland forest, swamp, and agricultural land	84	(Achten and Verchot, 2011)
	Southeast Asia	Tropical rainforest	75 to 93	(Danielsen et al., 2009)
	Southeast Asia	Peat land rainforest	692	(Danielsen et al., 2009)
	Southeast Asia	Grassland	10	(Danielsen et al., 2009)
	Malaysia	Grassland	0 to 11	(RFA, 2008)
	Malaysia	Forest	18 to 38	(RFA, 2008)
	Cameroon	Forest	45 to 53	(Achten et al., 2010)
Soybean biodiesel	Brazil	Tropical rainforest	319	(Fargione et al., 2008)
	Brazil	Cerrado grassland	37	(Fargione et al., 2008)
	Brazil	Cerrado woodland and pasture	41	(Achten and Verchot, 2011)
	Brazil	Degraded pasture	7	(Achten and Verchot, 2011)
	Brazil	Mainly permanent cropland with Amazonian rainforest	16	(Achten and Verchot, 2011)
	U.S.	Grassland	14 to 96	(RFA, 2008)
	U.S.	Forest	179 to 481	(RFA, 2008)
Jatropha biodiesel	Ghana	Mix of open and closed woodland, permanent cropland, and fallow land	71 to 129	(Achten and Verchot, 2011)
	Zambia	Mix of mature miombo woodland, permanent cropland, and fallow land	20 to several centuries	(Achten and Verchot, 2011)
	Mozambique	Mature miombo woodland	187 to 966	(Vang Rasmussen et al., 2012a)
	Africa	Miombo woodland	33	(Romijn, 2011)
	South Africa	Converted savannas	17 to 36	(von Maltitz et al., 2012)
	Zambia	Miombo woodland	32 to 81	(von Maltitz et al., 2012)
	Mexico	Secondary woodland	60 to 101	(Achten and Verchot, 2011)
	Mexico	Mix of secondary forest, fallow land, and permanent cropland	72 to 183	(Achten and Verchot, 2011)
	Mexico	Mainly agricultural land and pasture with secondary forest	7 to 30	(Achten and Verchot, 2011)
	Brazil	Caatinga woodland	10 to 20	(Bailis and McCarthy, 2011)
Sugarcane ethanol	Brazil	Cerrado woodland	17	(Fargione et al., 2008)
	Brazil	Grassland	3 to 10	(RFA, 2008)
	Brazil	Forest	15 to 39	(RFA, 2008)
Cassava ethanol	Mali	Fallow land	37 to 81	(Vang Rasmussen et al., 2012b)
Wheat ethanol	UK	Grassland	20 to 34	(RFA, 2008)
	UK	Forest	80 to 140	(RFA, 2008)
Corn ethanol	U.S.	Grassland	93	(Fargione et al., 2008)
	U.S.	Abandoned cropland	48	(Fargione et al., 2008)
	U.S.	Grassland	2 to 25	(Kim et al., 2009)
	U.S.	Forest	16 to 52	(Kim et al., 2009)
	U.S.	Grassland	40 to 123	(Gelfand et al., 2011)
Prairie biomass ethanol	U.S.	Abandoned cropland	1	(Fargione et al., 2008)
	U.S.	Marginal cropland	No debt	(Fargione et al., 2008)
	U.S.	Grassland	No debt	(Gelfand et al., 2011)

sions. An important caveat when interpreting and comparing the results of such studies is that a wide range of methodologies exists, and that studies are not always comparable (Hoefnagels et al., 2010; Cherubini and Stromman, 2011).

Studies and meta-analyses of LCA have shown that different biofuels have widely different life-cycle GHG emissions that are on several occasions much lower than those of conventional fossil fuels (Zah et al., 2007; Menichetti and Otto, 2009; Acquaye et al., 2012). While in some cases, GHG reductions can be as high as 80 to 90%, several studies have suggested that the choice of feedstock crop has a large impact on the anticipated life-cycle GHG emissions due to the CO_2 fluxes associated with tillage and the N_2O fluxes associated with nitrogen fertilizer use. Biofuels produced from perennial crops (e.g., switchgrass, miscanthus), which are not tilled annually and typically use nitrogen more efficiently, tend to have lower GHG emissions than biofuels from annual crops (e.g., corn).

However, on several occasions LCA have disregarded the effect of LUCC on overall GHG emissions. For example, if LUCC effects are not considered, then jatropha biodiesel in Brazil can emit 55% less GHG than conventional diesel (Bailis and Baka, 2010). However, if LUCC effects are considered, then biodiesel from jatropha emits 59% more GHG than conventional diesel (Bailis and Baka, 2010).

Studies that have considered such LUCC effects have shown that carbon loss from soils can release significant amounts of GHG, creating carbon debts that might take several decades to repay (Fargione et al., 2008; Gibbs et al., 2008). Table 2 highlights carbon payback times due to direct LUCC effects for some of the most common biofuel practices around the world.

Indirect LUCC effects can result in even greater carbon debts (Searchinger et al., 2008; Lapola et al., 2010; Achten and Verchot, 2011). For example, it has been calculated that by 2020, direct LUCC effects due to biofuel expansion in Brazil might create a carbon debt that will take 39 years to repay (4 years for sugarcane, 35 years for soybeans; Lapola et al., 2010). However, the carbon debt due to indirect LUCC effect will be much more substantial, requiring up to 251 years to repay (40 years for sugarcane, 211 years for soybeans; Lapola et al., 2010). In this case, the indirect LUCC effects will be mainly due to the replacement of rangeland to sugarcane and soybean fields, something that might push the rangeland frontier in the Amazon and cause significant deforestation.

Nevertheless, certain first-generation biofuels can result into high GHG savings, even when factoring direct and indirect LUCC effects. A large-scale modeling exercise using the Brazilian Land Use Model (BLUM) predicted little future deforestation due to sugarcane expansion in southeast Brazil (Nassar et al., 2009). Due to these relatively low anticipated carbon debts and high GHG savings, consistently over 50%, the U.S. Environmental Protection Agency (EPA) designated Brazilian bioethanol an "advanced biofuel" (EPA, 2010).

In any case, it should be noted that the calculation of carbon debts and carbon payback time depend on several assumptions and as a result can be highly uncertain (Upham et al., 2009).

Atmospheric pollutant emissions

The main pollutants emitted during biofuel production and use include: particulate matter (**PM**), nitrogen oxides (**NOx**), sulfur dioxide (**SO_2**), ammonia (**NH_3**), carbon monoxide (**CO**), volatile organic compounds (**VOC**), and ozone (**O_3**; Hess et al., 2009). These atmospheric pollutants have been known to be harmful to human health and ecosystems.

Given the complexity of biofuel chains, the wide variety of biofuel practices, the numerous ambient air pollutants emitted, and the very different local meteorological conditions, no general trends can be discerned regarding biofuels' effect on ambient air quality. Studies investigating potential air quality impacts of biofuel production and use have shown that displacing conventional fuels will likely lead to reduced emission for some pollutants (not all) and increases for others (Hess et al., 2009; Wagstrom and Hill, 2012). These varied findings across pollutants and biofuels result partly from the differing experimental setups and modeling approaches employed in the different studies and partly from the differing effects of the fuels themselves as they are deployed in actual use in transportation (Wagstrom and Hill, 2012).

Traffic in São Paulo, Brazil. Sugarcane bioethanol production in Brazil has probably contributed to vehicle modernization throughtout the country, which may have helped reduce air pollutant emissions from the tranport sector (photo credit: Paulo Fehlauer).

Corn ethanol production and use is a significant source of air pollutants in the U.S. (Millet et al., 2012). The bulk of these emissions are concentrated in the Midwestern "Corn Belt" where most of the corn production is located (Tessum et al., 2012). Compared with conventional gasoline, E85 ethanol blends will reduce emissions of CO (by 13%) and NOx (by 14%) but will not affect VOC emissions (Millet et al., 2012). E10 blends will have more modest air quality improvement reducing CO emissions by 6.7 to 7.5% but not affecting NOx and VOC emissions (Millet et al., 2012).

In Brazil, sugarcane bioethanol has probably been a driver of vehicle fleet modernization and as a result might have resulted in lower air pollutant emission from the transport sector (Gasparatos et al., 2012b). Since the early 1980s, neat ethanol and flex fuel vehicles exhibit decreasing emission factors, particularly for CO and NOx (CETESB, 2012). More importantly, the emission factors of these vehicles are much lower than those of pure gasoline cars during the same period (CETESB, 2012). However, for several pollutants, the life-cycle emissions of sugarcane ethanol are greater than those of conventional transport fuel (Tsao et al., 2012). For these pollutants, life-cycle emissions are usually dominated by the agricultural phase, agricultural burning in particular. Pollutants commonly linked to sugarcane burning include PM2.5 and PM10 (Lara et al., 2005; Cancado et al., 2006), polycyclic aromatic hydrocarbons (**PAH**; Martinelli and Filoso, 2008), and NOx (Oppenheimer et al., 2004). The emission of pollutants linked to agricultural burning has been shown to negatively affect public health.

In Southeast Asia, there are several examples of communities adjacent to oil palm plantation reporting decreases in air quality due to activities within the plantations (Obidzinski et al., 2012). Oil palm agriculture, like all other agricultural activities, is an important source of VOC, isoprene in particular. VOC and NOx emissions, which are tropospheric O_3 precursors, are greater in oil palm plantations than from primary rainforest (Hewitt et al., 2009). Land clearing through fire is another practice commonly associated with oil palm agriculture (van der Werf et al., 2008), which is a major source of atmospheric pollution and GHG emissions, negatively affecting public health in the region (Frankenberg et al., 2005).

Water use and pollution

Generally speaking, first-generation biofuels consume much more water throughout their life cycle, when compared with other energy carriers. In fact, biofuels exhibit much greater water footprints (**WF**), sometimes by two or three orders of magnitude, than other energy carriers (Gerbens-Leenes et al., 2009a; Scown et al., 2011). This is mainly a consequence of the high direct water use during feedstock production (agricultural phase; Scown et al., 2011). Nevertheless, different biofuels have radically different water requirements, depending on the feedstock, the region where it is produced, and the production practices adopted (e.g., extensive irrigation vs. rainfed agriculture; Gerbens-Leenes et al., 2009a, 2009b, 2012a; Scown et al., 2011; Chiu and Wu, 2012). For example, jatropha exhibits high WF in regions with extensive irrigation such as India (Gerbens-Leenes et al., 2009b), but in other contexts, such as Africa, it is considered a conservative water user compared with natural vegetation (Gasparatos et al., 2012a).

Biofuel expansion will result in a much greater water appropriation from the transport sector in the following decades (Gerbens-Leenes et al., 2012b). This might result in added pressure on water resources in countries facing increased risk of water scarcity, such as India (Rajagopal, 2008). It has been shown that certain feedstock production practices, such as extensive irrigation, have already resulted in the depletion of vulnerable aquifers in the U.S. in areas that are expected to face water shortages in the future (Chiu et al., 2009).

Fertilizers, agrochemicals, and industrial effluent from biofuel production are a major source of water pollution in regions such as Brazil, U.S., and Southeast Asia. Declining water quality across the state of São Paulo in Brazil has been linked to increased sugarcane production in the state (Gunkel et al., 2007; Martinelli and Filoso, 2008). The palm oil sector has been identified as a major source of water pollution in parts of Southeast Asia, particularly due to fertilizer/pesticide runoff and palm oil mill effluent (Muyibi et al., 2008; Wu et al., 2010; Obidzinski et al., 2012). Several studies have modeled water quality decreases in parts of U.S. due to biofuel expansion, but the magnitude of the effect depends significantly on feedstock type and the production practices adopted (Love and Nejadhashemi, 2011; Love et al., 2011; Wu et al., 2012). If U.S. corn ethanol production meets the 15 to 36 billion gallons of renewable fuel by 2022 without changes in prevailing cultivation practices, then significant added nitrogen loading should be expected along the Mississippi River, subsequently increasing hypoxia in the Gulf of Mexico (Donner and Kucharik, 2008). The above suggest that biofuel-related water pollution can be a potent public health hazard and can contribute to biodiversity loss.

The production of first-generation biofuels can result in high levels of water pollution due in part to the chemicals and industrial effluent involved in the process. In the next nine years, U.S. corn ethanol production is expected to cause significant nitrogen loading along the Mississippi River (pictured above), which can lead to severe ecological impacts further south in the Gulf of Mexico (photo credit: John W. Iwanski).

Forest clearing in Gua Musang, Malaysia. Oil palm expansion in the region has led to the loss of habitat for several species (photo credit: flickr.com/wak1).

Soil erosion

The production of certain feedstocks has been known to cause significant soil erosion. This is because extensive areas of bare soil are left exposed to intense rain and winds during the initial land conversion (removal of native vegetation) and the period between crop harvest and regrowth. Generally speaking, soil erosion tends to be much greater for annual feedstocks than perennial feedstocks.

For sugarcane, studies have estimated soil erosion rates that are 5.2 times greater than soil formation rates (de Oliveira et al., 2005). In fact, high erosion rates have been reported in lands consistently used for sugarcane cultivation in São Paulo state (Martinelli and Filoso, 2008). Biofuel-driven expansion of corn and cassava into already degraded upland agricultural systems in Southeast Asia can increase the risk of soil runoff and sediment generation (Valentin et al., 2008). Oil palm has also been shown to cause significant soil erosion, which can lead to a loss of soil fertility and a deterioration of terrestrial and aquatic habitats (Obidzinski et al., 2012). Soybean cultivation in Argentina exhibits greater soil erosion rates than switchgrass, especially when cultivated in degraded grassland rather than abandoned cropland (van Dam et al., 2009).

Conversely, other feedstocks can stabilize soil and reduce soil erosion if grown on degraded lands. For example, jatropha is a tree species and as such does not need to be planted annually. Moreover, because its root system can help bind the soil, jatropha has been proposed as a potential erosion control and soil rehabilitation measure (Karavina et al., 2011). However, no reports could be found verifying or quantifying the soil erosion control benefits of jatropha (Gasparatos et al., 2012a).

Although absolute erosion rates depend significantly on the agro-ecological context, a rough rank of the most common biofuel feedstocks in order of decreasing soil erosion rate is: cassava, soybean, sugarcane, sorghum, corn, sugar beet, winter wheat, oil palm, and winter rapeseed (de Vries et al., 2010).

Biodiversity loss

Large-scale feedstock production in extensive monocultures can be particularly hostile to biodiversity. For example, oil palm plantations host fewer species than rubber plantations, disturbed forests, and primary forests (Fitzherbert et al., 2008; Danielsen et al., 2009; Foster et al., 2011). Extensive sugarcane and corn monocultures are also known to support a relatively limited number of species (Chessman, 2004; Fletcher et al., 2011; Wiens et al., 2011; Gasparatos et al., 2012b). On the other hand, knowledge about species occurrence in emerging biofuel feedstocks such as jatropha is basically nonexistent (Gasparatos et al., 2012a).

Of the six main direct drivers of biodiversity loss identified in the Millennium Ecosystem Assessment (**MA**), four are directly associated with biofuel expansion: habitat destruction, invasive species, pollution, and climate change (Millenium Ecosystem Assessment, 2005). Of these, habitat destruction due to direct and indirect LUCC effects is by far considered as the most important driver of biofuel-driven biodiversity loss. The conversion of natural ecosystems such as grassland and forests is usually associated with greater levels of biodiversity loss when compared with the conversion of cultivated land (Fischer et al., 2009).

Oil palm expansion in Malaysia (55 to 59%) and in Indonesia (at least 56%) has occurred at the expense of primary forest (Koh and Wilcove, 2008). This has potentially resulted in the loss of several species in one of the most biodiverse regions of the planet (Koh et al., 2011). Oil palm expansion in the Brazilian Amazon due to the Brazilian biodiesel mandate can potentially contribute to LUCC effects and biodiversity loss (Lapola et al., 2010). In the southern part of Brazil, it is estimated that 75% of riparian buffer zones in the state of São Paulo protected under the Brazilian Forest Code have already been directly converted to sugarcane and pasture (Koh et al., 2009). Apart from increases in the population of generalist species such as the capybara, it is feared that the degradation of these highly biodiverse riparian ecosystems can further reduce water quality, further threatening biodiversity in the region (Martinelli and Filoso, 2008). However, it is the future combined effect of sugarcane, soybean, and oil palm expansion that can pose an even more significant threat to biodiversity in the country, through direct and indirect LUCC effects in highly biodiverse areas such as the Cerrado (Sparovek et al., 2007; Smeets et al., 2008) and the Amazon (Lapola et al., 2010).

Cropland expansion in Europe for meeting the biofuel mandates set by the 2009 EU-Renewable Energy Directive can have direct and indirect LUCC effects in Europe, Brazil, and Sub-Saharan Africa (Britz and Hertel, 2011). If such LUCC effects result in the degradation of natural habitats, then significant biodiversity impacts are to be expected in Europe and beyond (Hellmann and Verburg, 2010). In the U.S. context, soybean biodiesel and corn/sugarcane ethanol will consistently have the largest direct LUCC effects within the country by 2030 when compared with other energy strategies (McDonald et al., 2009). Significant indirect LUCC effects in other countries are also expected due to corn ethanol expansion in the U.S. (Searchinger et al., 2008). LUCC effects due to sugarcane and jatropha expansion in Africa might pose similar threats to biodiversity across the continent, but there have not been any major studies on this topic (Gasparatos et al., 2012a).

However, even though it is relatively straightforward to estimate the amount of land that must be converted to meet added crop demand due to biofuel mandates, it is very difficult to identify the exact locations where land will be converted for feedstock production. The multifunctional nature of biofuel feedstocks, the lack of a standard definition of deforestation, and the lack of updated data sets with sufficient spatial resolution and global coverage are only some of the reasons why it is extremely difficult to quantify the impact of biofuel expansion on deforestation and biodiversity loss on a global level (Gao et al., 2011).

Finally, some feedstocks can become invasive and as a result threaten biodiversity. Currently, the feedstocks that are mostly associated with invasiveness are jatropha in certain parts of Australia (FAO, 2010) and perennial grasses (Raghu et al., 2006; Pyke et al., 2008; Buddenhagen et al., 2009). Invasiveness of jatropha is still uncertain in the African context as there is sometimes a lag between species introduction and the manifestation of invasive behavior. For this reason, South Africa has chosen to adopt a precautionary stance and ban jatropha cultivation within the country, but several other African countries have chosen to allow jatropha cultivation (Gasparatos et al., 2012a).

Rural development

Rural development has been one of the major drivers of biofuel expansion, particularly in developing countries (Gasparatos and Stromberg, 2012). Biofuel expansion can contribute to rural development through the generation of employment and income opportunities. Biofuels are generally held to be more labor intensive than other renewable energy sources and energy carriers, at least in OECD countries (OECD, 2012). However, such opportunities are unevenly distributed along the biofuel chain and depend a lot on the mode of feedstock production and the geographical, socioeconomic, and political context.

In developing countries, the bulk of biofuel-related jobs are low-skill and low-income and are created during feedstock production. Jobs in feedstock processing and biofuel production usually require greater skills and are better remunerated, but are fewer (Stromberg and Gasparatos, 2012). Employment and income opportunities associated with biofuels' agricultural phase (feedstock production) include the following.

- employment and income through salaried work in feedstock plantations (direct mechanism)
- contracted supply of feedstock to companies by smallholders who grow feedstock as a cash-crop (direct mechanism)
- training and up-skilling activities (direct mechanism)
- creation of higher-paid manufacturing and service jobs through small-scale biofuel projects (e.g., rural electrification; indirect mechanism)

In Brazil, approximately 1 million people are involved in the sugarcane ethanol industry as a whole. Most of these jobs are low-skill (e.g., cane cutting), but technological innovation has boosted high-skill job creation in many regions (Gasparatos et al., 2012b). Increased mechanization

Harvesting sugarcane for ethanol production. Sugarcane ethanol production is responsible for approximately 1 million jobs in Brazil alone, most of which are low-skill positions. Increased mechanization in the region is expected to eliminate over 400,000 of those jobs by 2014 (photo credit: Sweeter Alternative).

is expected to generate 171,000 high-skill jobs by 2014, but is also set to eliminate 420,000 low-skill jobs in the state of São Paulo alone. Income from salaried work in the sugarcane sector has increased in absolute terms, but although the salaries in sugarcane plantations in São Paulo are on average higher than those paid in other agricultural sectors, they are not usually high enough to allow workers to escape poverty (Smeets et al., 2008). Due to the economies of scale achieved through large-scale sugarcane production, smallholder sugarcane producers have practically disappeared in São Paulo state. On the other hand, social inclusion and "pro-poor" rural development has been a major objective of the Brazilian biodiesel program. Nevertheless, the involvement of family farmers is much lower than initially expected, with the overall participation of family farmers being largely limited to soybean farmers (Gasparatos et al., 2012b). Ambitious biodiesel production targets that fail to address the structural problems faced by family farms may cause the Brazilian biodiesel experience to be similar to that of the ethanol program, which ended up promoting only large-scale agriculture.

In parts of Africa, plantation jobs are also generally better paid than other comparable agricultural activities but tend to be seasonal rather than permanent (Gasparatos et al., 2012a). Furthermore, the relatively low number of jobs generated per hectare implies a modest employment generation potential from large-scale feedstock production. Additionally, several large-scale jatropha projects across the continent have closed or encountered financial difficulties, further reducing employment opportunities from the biofuel sector. On the other hand, sugarcane outgrower programs in Tanzania, South Africa, and Kenya have contributed to the development of a relatively prosperous smallholder sector, significantly reducing the number of people gaining less than the minimum wage (Gasparatos et al., 2012a). In fact, economy-wide studies suggest that biofuel programs in Sub-Sahara Africa depending on smallholders and outgrowers are more likely to induce "pro-poor" growth than large-scale biofuel production (Arndt et al., 2010, 2012).

Small-scale biofuel projects (e.g., for rural electrification) can create new employment opportunities, increase labor productivity, and increase income in rural communities (FAO, 2009). The benefits from small-scale biofuel projects mainly materialize through the local production and consumption of a renewable energy carrier, which boosts local energy security and has a ripple effect on local economic activity (FAO, 2009; Stromberg and Gasparatos, 2012). Such projects have been used as means of alleviating rural poverty in developing countries, but their success has been highly variable across the world (Gasparatos et al., 2012a).

In some cases, the "high" incomes obtained from salaried employment in plantations or smallholder feedstock agriculture have influenced rural households to abandon other on- and off-farm activities, such as subsistence agriculture. It should be stressed that in most cases, biofuel-related income and employment generation can be precarious, given the agro-ecological and market uncertainties and risks associated with feedstock production and trade (Stromberg and Gasparatos, 2012). Such risks are particularly high for untested feedstocks such as jatropha. There are examples of increased food insecurity and social conflicts manifesting when smallholders switch their entire cash crop/food production into biofuel feedstock production (Stromberg and Gasparatos, 2012).

Food security

Biofuel expansion has contributed to the food price increases witnessed in the past decade (Fischer et al., 2009). However, the extent of this contribution is highly contested, possibly ranging between 3 and 30%, as various studies have reached very different conclusions (Mitchell, 2008; Fischer et al., 2009; Ajanovic, 2011; Mueller et al., 2011). Global biofuel expansion might further increase the price of agricultural commodities by 8 to 34% (cereals), 9 to 27% (other crops), and 1 to 6% (livestock) by 2020, putting an additional 131 million people at risk of hunger (Fischer et al., 2009).

However, it is very difficult to unravel the effect of biofuel expansion on food security. Food and biofuel production can compete directly and indirectly, with the impacts of this competition manifesting at different spatial scales: household, local, and national. Direct competition occurs when a food crop (e.g., corn) is diverted into biofuel production. Several developing countries, such as China and India, have prohibited the use of food crops for biofuel production to avoid such direct competition (Zhou and Thomson, 2009). Corn (a major food crop) was initially an important bioethanol feedstock in China. To avoid food–fuel competition, the corn used for bioethanol production in China was required to be of inferior quality and unsuitable for human consumption (Zhou and Thomson, 2009), usually coming from the reserve stockpiles after a two to three year period (Koizumi and Ohga, 2007). Still, there have been instances of the inferior corn stocks running low during high ethanol demand and normal corn being used for ethanol production (Zhou and Thomson, 2009). The requirement to avoid food–biofuel competition eventully dampened the momentum of corn bioethanol in China (Yang and Chen, 2012). Indirect competition manifests when feedstock production is competing with food production for inputs such as land, labor, water, and fertilizers. In some cases, this indirect competition poses a much more important threat to food security (Gasparatos and Stromberg, 2012; Gasparatos et al., 2012a).

Like any other biofuel impact, biofuels' effect on food security, particularly at the household and the local level, depends on the socioeconomic context of biofuel production and the policies in place during biofuel production and trade. There have been several occasions when smallholders have diverted their entire food production into biofuel. In some instances, unexpectedly low yields have resulted in low income generation and increases in food insecurity, particularly when subsistence agricultural activities have been eliminated in favor of feedstock production (Gasparatos et al., 2012a). On the other hand, there are examples of food security potentially improving due to higher salaries offered in plantations or the high income opportunities associated with feedstock production (Smeets et al., 2008; Gasparatos et al., 2012a).

The above suggest that when aiming to understand biofuel impacts on food security, it is key to consider how the welfare effects of higher food and feedstock prices are distributed among the net-producers and net-consumers of crops used for biofuel production and across different regions of the world (Stromberg and Gasparatos, 2012). In general, developing countries' subsistence farmers, landless people, and urban poor face much greater risks of biofuel-driven food insecurity (Fischer et al., 2009).

Public health

Atmospheric emissions associated with biofuel production and combustion can have negative effects on public health. The health related costs due to the emissions of PM2.5 from corn ethanol in the U.S. are comparable, and in most cases greater, than similar costs from conventional gasoline (Hill et al., 2009). According to Jacobson (2007), the substitution of conventional gasoline to E85 will increase tropospheric O_3–related mortality and other health effects by 9% in Los Angeles and by

4% in the rest of the U.S. by 2020. In São Paulo state, hospital admissions due to respiratory problems (particularly in children) increase two to three times during the sugarcane harvest season in those parts of the state where sugarcane burning is still prevalent (Cancado et al., 2006; Uriarte et al., 2009). Finally, PM and mites released during soybean production and treatment in Argentina can also have negative public health effects (Tomei and Upham, 2009).

Numerous acute and chronic health symptoms have been linked to short- and long- term exposure to agrochemicals used in sugarcane cultivation. Bad application practices have in some cases resulted in water/soil contamination, poisoning, and death (Smeets et al., 2008; Lehtonen, 2009). Agrochemical use in soybean production in the vicinity of rural communities in Argentina has been linked to cancer, respiratory illnesses, and fetal abnormalities (Tomei and Upham, 2009).

The toxicity of seeds, oil, and other co-products of jatropha (e.g., seedcake) can be potentially threatening to human health (Gasparatos et al., 2012a). Caution has been advised during the production and use of such products particularly in enclosed spaces (Achten et al., 2008).

On the other hand, some biofuel practices can provide positive health benefits at the household level through the decrease of indoor air pollution. For example, a major health hazard in Africa is indoor air pollution from cooking in conventional biomass stoves that use charcoal, wood, and dung. Switching to ethanol stoves can reduce the emission of hazardous indoor pollutants such as PM and CO and have significant benefits to human health. Ethanol stoves have already been deployed in Ethiopia, Tanzania, and Mozambique (Takama et al., 2011).

Burning sugarcane fields in Brazil before harvesting gets rid of dried leaves and straw, also known as "trash." While this makes the harvesting process easier, it can also lead to human respiratory problems, especially in children (photo credit: Joe Kelly).

Social conflicts

Biofuel expansion has been an agent of social conflict, particularly in parts of the developing world where biofuel expansion happened without having in place strong institutions to regulate it.

Biofuel-related social conflicts are usually related to land tenure issues. Some examples include the displacement of poor families in Mozambique and Tanzania, the concentration of land to powerful actors in Brazil, Indonesia, and Papua New Guinea, the loss of land rights through coercion and lack of information in Indonesia, and even aggressive land seizures in Colombia (Cotula et al., 2008). There have been allegations that communities in Tanzania, Mozambique, Ghana, Kenya, and Zambia lost access to their communal land after large-scale jatropha production was initiated (FoE, 2011). Aggressive jatropha expansion promoted by the Indian government and the biofuel industry may displace millions of poor rural farmers from areas they use for their food, fuel wood, fodder, and timber (Agoramoorthy et al., 2009).

The Brazilian sugarcane sector has also been historically marked by disputes between landowners and workers over the access of workers to land (Abramovay, 2008). Eventually, land ownership was restricted to a few large landowners (Lehtonen, 2012). As a result, the apparent lack of land tenure conflicts during the recent sugarcane ethanol expansion in São Paulo state can be attributed to this prior consolidation of land into the hands of a few large landowners (Smeets et al., 2008).

Biofuel-related conflicts can go beyond land tenure issues. For example, food price increases during the 2007 to 2008 food crisis, which were partly attributed to biofuel expansion (see above), resulted in food riots in Egypt, Mexico, Indonesia, and several Sub-Saharan African countries (Stromberg and Gasparatos, 2012). Furthermore, some feedstock production practices such as large-scale sugarcane and oil palm agriculture have been associated with harsh and degrading working conditions. In other cases, the structure of the payment scheme in sugarcane plantations, combined with the loss of purchasing power in 2008, resulted in several canecutter strikes across São Paulo state that was met with strong responses by the industry (Gasparatos et al., 2012b). Ariza-Montobbio and Lele (2010) have shown that conflicts related to jatropha projects, failed jatropha projects in particular, can manifest across several levels:

- within households over the responsibility over, and the response after, the failure of jatropha cultivation
- between jatropha-growing communities and outsiders (e.g., companies and NGOs promoting jatropha)
- between farmers (including promoters) and private companies, when the companies did not meet their initial promises of assisting farmers during the production phase and buying the jatropha seeds at remunerative prices

Finally, as with any other agricultural activity, there could be gender-related angles to issues of land tenure and social conflicts associated with feedstock production. It has been suggested that the potential negative impacts of first-generation biofuels in Brazil, India, and Sub-Saharan Africa might be gender differentiated, with women being more likely to face the negative impacts (Rossi and Lambrou, 2008). Women might also fail to benefit to the same extent as men from feedstock production. For example, longstanding gender inequality in many parts of Africa, as men usually own the land, may interfere with efforts to leverage jatropha markets and improve women's livelihoods and income (Gasparatos et al., 2012a). There have been cases of women either not being allowed to plant jatropha or losing parts of their profits to men, once women turned jatropha to a cash-generating activity (van Eijck et al., 2010).

Conclusions

This paper provided a brief overview of the main impacts of first-generation biofuels in different parts of the world. On several occasions, the discussion about biofuel sustainability is dominated by a relatively small number of impacts, most notably food security, energy security, and GHG emissions. In this paper, we discussed a much wider array of impacts. We also acknowledged that the great variety of first-generation biofuel practices can have radically different impacts on the environment and on human wellbeing. In fact, the term biofuels is essentially an "umbrella" term that includes an array of different production/use practices that are performed in different ecosystems, for different purposes, and which can complement but also compete with other human activities and natural processes.

For example, the drivers and the environmental and socioeconomic impacts of large-scale sugarcane bioethanol production in Brazil are certainly different from those of small-scale jatropha biodiesel production for rural electrification in rural Sub-Saharan Africa. Furthermore, the drivers, impacts, and potential of the same biofuel practice might vary significantly across different world regions.

With this in mind, it would be reckless to group biofuels under the same banner when discussing their impacts (and their sustainability) as it is very important to understand the environmental and socioeconomic contexts within which current biofuel expansion is taking place. Such understanding can provide a better starting point when aiming to assess biofuel trade-offs and the factors that shape the acceptability of biofuels by different stakeholder groups. It should be noted that a major challenge for obtaining a comprehensive picture of biofuel tradeoffs is the fact that the biofuel literature is multidisciplinary and rapidly expanding (Gasparatos et al., 2012c). To make matters more complicated, there is no consistent way to report the findings about the environmental and socioeconomic impacts of biofuels.

In our view, all the impacts discussed in this paper, and their interrelationships, need to be considered when aiming for sustainable biofuel production and use. Some of these trade-offs are inevitable, but in many cases, at least part of the negative impact can be mitigated through careful planning. Assessing only a subset of biofuels' impacts is probably worse than not addressing any of them at all. We strongly believe that the piecemeal assessment of biofuel impacts can result in inappropriate resource use decisions and can be easily misunderstood, manipulated, and used to support narrow economic interests.

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