Title: Assessing the environmental sustainability of biofuels.

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Key Words

Biofuels, sustainability, life cycle analysis, evidence-based policy

Highlights

1. Liquid biofuels can be produced from a range of biomass feedstocks, but not all approaches will provide sustainable alternatives to fossil fuels.
2. True sustainability requires a holistic consideration of the environment, economy and the wider society.
3. Life Cycle Assessment (LCA) is a quantitative approach that can be used for objective estimation of the environmental sustainability of biofuels.
4. Plant science research can contribute to biofuel LCAs by establishing robust data for energy crop productivity, and improving models of land use.

Abstract

Biofuels vary in their potential to reduce greenhouse gas emissions when displacing fossil fuels. Savings depend primarily on the crop used for biofuel production and on the effect that expanding its cultivation has on land use. Evidence-based policies should be used to ensure that maximal sustainability benefits result from the development of biofuels.

Main text

I. Not all biofuels are created equal

In the search for renewable energy sources to decarbonize global economies, biofuels offer the potential of both decreased greenhouse gas (GHG) emissions and energy security. Whilst the second is essentially a political consideration, the first can be objectively assessed provided a standardized quantitative method is used to discriminate between biofuel products. Familiarity with the principles of measuring GHG emissions will allow plant scientists to contribute actively to this growing practice.

The debate over what differentiates the so-called good biofuels from the bad has raged for a number of years, particularly as concerns over probable effects of biofuels on food prices were raised in 2008 [1]. Time has shown that there are further interconnected social, environmental and economic facets to consider [2]. In the following article we will discuss the quantifiable aspects of the environmental sustainability of biofuels, focussing on GHG emissions. However, it is important to note that, to be considered truly sustainable, biofuels would also need to meet other non-quantifiable standards, summarised in Figure 1 for the interested reader.

1. Creating biofuels

Fuels produced from harvested biomass (biofuels) can be either solid, gas or liquid. Biosolids, such as woodpellets or forestry waste, and biogas, produced by anaerobic digestion of biomass, are used primarily for electricity generation and heating, whereas liquid biofuels provide drop-in fuels that can be used directly in the transport sector, without change in infrastructure. In theory it is possible to convert any biomass feedstock into a liquid or gas fuel using appropriate chemical engineering techniques, but the efficiency of conversion, cost and scale of demand/supply have led to preferred practices. Interestingly, within the EU, the current laws controlling the production and use of liquid biofuels are more stringent than for solid biomass and biogas. Liquid biofuels are regulated both by the EU Fuel Quality Directive and the EU Renewable Energy Directive (Table 1). Whilst the sustainability issues of all biofuels are similar, for concision, here we focus on liquid transport biofuels only.

There are two main types of liquid biofuels: biodiesel and bioethanol, which can substitute or be blended with diesel or petrol (gasoline), respectively. Bioethanol is more corrosive than gasoline, so complete substitution is not compatible with most current engine models. Engine manufacturers' warrantees, and individual national legislation control the fuel blends available for purchase. At present most liquid biofuels are produced from food crops: bioethanol by microbial fermentation of sugars from starch crops such as sugar cane, maize or sugar beet, and biodiesel by trans-esterification of extracted neutral lipids, mainly from palm, soy and oilseed rape (canola).

It is possible to produce liquid biofuels from non-food parts of plants, for example ethanol from the lignocellulosic material in plant cell walls, either from agricultural or other waste, or from energy crops such as *Miscanthus* sp. and short rotation willow, which can be grown on marginal or non-arable land. However, lignocellulose requires pre-treatment to release the fermentable sugars, and technological advances in understanding how to deconstruct this material are needed to make this process more efficient and cheaper [3]. An alternative biodiesel feedstock is microalgae, many of which can accumulate high levels of neutral lipids, and which again do not need arable land for cultivation, and can even be grown in wastewater [4]. Another important feedstock for biodiesel in the EU is waste cooking oil, constituting more than 50% of the biodiesel on the market in the UK in 2011 [5].

However, from an environmental perspective, comparing biofuels based on the feedstock used to derive them is not sufficient to infer a sustainability benefit. Instead, a quantitative assessment, known as environmental life cycle assessment (LCA) can be used. LCA queries the net impact of a commodity on the environment by considering all stages associated with the presence of the product on the planet, i.e. from “cradle to grave”. As a consequence, it also provides an assessment of the technologies used at each stage, which can thus inform future strategies to optimize the process.

2. Comparing biofuels

It is important that LCA is carried out using a defined methodological framework, because conclusions are highly sensitive to several factors, including the boundary conditions set, the assumptions made about each stage in the process (including scale), as well as the databases used to provide the final quantifications. LCAs can be used to quantify the environmental footprint of a product on a range of assets, for example stocks of freshwater or the net radiative forcing of the atmosphere. For biofuels, the effect on the latter is termed Global Warming Potential (GWP) and is measured in units of kilograms of CO_2 equivalents per tonne of biodiesel produced ($kgCO_2eq/te$). GWP is more informative than considering CO_2 alone, because many emissions, such as NOx, SOx and methane, are in fact more potent at trapping heat in the atmosphere. Alongside this, GWP is assigned to fossil fuels that the biofuels aim to replace; for example the GWP of fossil derived diesel is calculated to be ~3707 kgCO_2 eq/te [5]. Estimates of GWP are carried out following International Standards ISO 14040:2006 and ISO 14044:2006, which provide methods of calculation and conventions: for example, it is conventional to report the effects of biofuels on the environment over a time horizon of 100 years.

In establishing an LCA, first it is necessary to define the process steps or flowsheet. If these processes are spatially separated, then transport between facilities and place of end-use must be taken into account. The different steps for producing biofuel are typically grouped into the following stages: cultivation of chosen crop, harvesting, processing and extraction of fuel substrate, conversion into biofuel, and end use, which is usually taken as burning in an internal combustion engine. Finally, the total estimated burden is allocated between the fuel produced and any by-products. Figure 2 shows a summary schematic for a production pipeline and associated GWP estimates for biodiesel produced from oilseed rape grown and processed in the UK. Transport becomes a significant consideration when feedstocks for biofuels are produced in a country of origin different to consumption.

Early LCA findings highlighted the differences in GWP of biofuels produced from various crops. Fertiliser use, biomass yields, proportion of extractable fuel substrate and harvesting techniques, which are specific to individual to crop species, will contribute towards GWP to differing extents. This was first highlighted by Hill *et al.* (2006), who compared the performance of bioethanol from corn grain with biodiesel from soybeans. It was found that relative to the fossil fuels they displace, GHGs were reduced 12% by the production and combustion of corn ethanol but 41% by soy diesel [6].

These pioneering findings were followed by comparisons that have grown in scope over time. In particular, published LCAs suggest that the GWP of biofuels is highly dependent on how the land was used before the biofuel crop was grown. For example, in an analysis of GWP of biodiesel from palm oil grown on different land that was previously peat land, rainforest, logged over forest, or degraded land, net emission savings were found only in the latter case, with up to 3.5 times more emissions compared to fossil fuels if peat land were drained to make way for palm plantations (Figure 3) [7]. The analysis demonstrated that drainage and destruction of peat lands and rainforests would result in release of a large proportion of carbon stored in these habitats into the atmosphere. It has been estimated that the total CO_2 emissions caused by decomposition of drained peat lands in South East Asia corresponds to ~ 623 Mte/year, with 90% of this originating from Indonesia. In 2006, this practice put Indonesia in 3rd place in global CO_2 emissions, after the USA and China [8]. Even in temperate regions, cultivation of previously undisturbed land results in increased CO_2 release due to aeration of the soil [9].

3. Accounting for emissions from indirect land use change

Further emissions associated with biofuel production can result from displaced land use, referred to as indirect land use change (iLUC), where demand for a particular crop changes the use of land elsewhere. For example, it has been shown that previously uncultured Ukrainian grasslands converted to produce food-grade rapeseed oil, due to increased demand for European biodiesel made from rapeseed cultivated within the EU, has caused the release of carbon trapped in the soil of these grassland ecosystems [10]. Initial concern over GHG emissions from iLUC were raised in a report by Searchinger [11], who argued that iLUC would be the most significant contributing factor to net LCA emission of biofuels. For soy-derived biodiesel it was predicted that emissions would treble if iLUC were included in the analysis. However, methods for calculating emissions from iLUC have been based on agro-economic models informed by emission factor databases that are highly uncertain. Revised databases and models indicate that emissions from iLUC were originally overestimated by approximately a factor of 2 [12].

II. Translating LCA findings into biofuel policy

Prices and demand for liquid biofuels determine where, what type, and how these are produced in the world. Early policies incentivised production through volumetric mandates and subsidies for producers, without specifying a preferred type of biofuel (Table 1). This led to large volumes of liquid biofuels being made available quickly on the market, without the requirement to meet emission standards. The sustainability concerns that this raised instigated legislation changes both in the EU and the USA. In the EU, a set of sustainability criteria have been developed (under Article 17 of the EU RED, Table 1) that liquid biofuels need to meet in order to be awarded subsidies or count towards the renewable energy target of an individual country. A benchmark of 35% GHG emission savings compared with fossil fuels, estimated through a standard LCA, has been set, which will increase to a minimum of 50% savings on 1 January 2017. Currently there is no obligation to account for GHG emissions from iLUC, although this is likely to change in the near future; the EU Parliament is debating changes to the legislation, which would introduce a penalty for use of certain crops based on their iLUC risk factor.

However, opponents argue that it does not make sense to account for GHG emissions from one sector (e.g. biofuel production), whilst ignoring other land users. International agreements such as the Kyoto Protocol, which requires countries to account for emissions from bioenergy in the land use, land-use change and forestry (LULUCF) sector, have provided a first step towards a cohesive emissions policy. Other noteworthy initiatives include the Global Bioenergy Partnership (a body of the UN Food and Agriculture Organisation) and the Roundtable on Sustainable Palm Oil, which have developed a set of sustainability indicators to forge a consensus among a broad range of national governments and international institutions on sustainability. These include indicators for social sustainability alongside environmental and economic ones.

Conclusion

Ensuring that biofuels are sustainable is paramount, if we are not to replace one environmentally damaging practice with another. Development of next generation biofuels, the focus of many plant scientists, may well overcome the issue of competition between food and fuel crops, but large scale cultivation must consider the wider context in terms of other resources and land use. Quantitative assessments of net GHG emissions associated with different biofuels using LCA provide some of the important evidence that can be used to direct policy that discriminates between products based on their sustainability.

References

1. Renewable Fuels Agency. (2008) The Gallagher review of the indirect effects of biofuels production. England, UK.
2. Nuffield Council on Bioethics. (2011). Biofuels: ethical issues. England, UK.
3. National Science Foundation. (2008) Breaking the chemical and engineering barriers to lignocellulosic biofuels: next generation hydrocarbon biorefineries. Washington D.C., USA.
4. Singh, A. et al. (2011) Mechanism and challenges in commercialisation of algal biofuel. *Biores. Technol.* 102: 26-34.

5. DfT. (2008) Carbon and sustainability reporting within the Renewable Transport Obligation. Government recommendations to the Office of the Renewable Fuels Agency, London. England.
6. Hill, J. et al. (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. *PNAS* 103: 11206–11210.
7. Wicke, B et al. (2008) Different palm oil production systems for energy purposes and their greenhouse gas implications. *Biomass & Bioenergy* 32: 1322 - 1337.
8. Hooijer, A. et al. (2006) Assessment of CO_2 emissions from drained peatlands in SE Asia, *Delft Hydraulics Report Q3943*.
9. Vellinga, T.V. et al. (2004) The impact of grassland ploughing on CO_2 and N_2O emissions in the Netherlands. *Nutr. Cycl. Agroecosys.* 70: 33–45.
10. E4tech. (2010) A causal descriptive approach to modelling the GHG emissions associated with the indirect land use impacts of biofuels.
11. Searchinger, T. et al. (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319: 1238–1240.
12. Broch et al. (2013) A review of variability in indirect land use change assessment and modeling in biofuel policy. *Envir. Sci. Pol.* 29: 147-157.
13. Luo et al. (2009) Life cycle assessment and life cycle costing of bioethanol from sugarcane in Brazil. *Renew. Sustain. Energ. Rev.* 13: 1613–1619.
14. Stephenson et al. (2008) Improving the sustainability of the production of biodiesel from oilseed rape in the UK. *Proc. Saf. Environ. Protect.* 86: 427-440.

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Table 1. Examples of biofuel policies

	Early policies	Current policies	Planned changes
EU	Biofuels Directive (2003/30/EC) required that 5.75% of all transport fuel by volume is biofuel by 2010. There were no sustainability considerations in the directive.	The Biofuels Directive was superseded by *The Renewable Energy Directive* (EU RED*,* 2009/28/EC), which requires that 20% of all energy delivered to EU consumers by 2020 comes from renewable sources. The EU RED does not specify the proportion that has to come from individual countries, the transport sector, or indeed from biofuel. Mandatory environmental sustainability criteria impose restrictions on using materials sourced from land with high biodiversity value (e.g. rainforests), or high carbon stock (e.g. peat lands). There are minimum requirements for lifecycle GHG savings compared with fossil fuels. The Fuel Quality Directive (2009/30/EC) requires fuel suppliers to reduce the GHG emissions of transport fuels by 6% by 2020 compared to the EU-average level of emissions from fossil fuels in 2010. Biofuels can be blended with fossil fuels to achieve this reduction, as long as they meet sustainability criteria included in the Directive (same as in the EU RED).	Incorporation of iLUC factor penalty for biofuels. Double or triple credits for second generation biofuels, including those made from lignocellulosic material, and algae
USA	US Renewable Fuel Standard (RFS1) effective from 2005, required 7.5 billion gallons (34 billion litres) of renewable fuel to be blended into gasoline (petrol) by 2012. There were no sustainability standards described for the biofuels	Under the Energy Independence and Security Act (2007) the programme was revised (RFS2) and expanded to require 36 billion gallons of biofuels on the market by 2022. RSF2 includes new definitions and criteria for both renewable fuels and the feedstocks used to produce them, which include GHG thresholds for renewable fuels	Several states (e.g California) are adopting Low Carbon Fuel Standards which have more stringent requirements than those of RSF2.

Brazil	National Alcohol Program (Pró-Álcool) decreed by the President (Decreto No. 76.593) in 1975 set a goal of 3.5 billion liters of ethanol to be produced by 1980. In 1979 the Brazilian car manufacturers signed an agreement with the federal government to produce vehicles that ran on ethanol only (rather then a fossil fuel blend). By 1984, the sale of ethanol-powered cars had reached 84% of total vehicle sales in Brazil. Bioethanol produced from sugar cane in Brazil has been reported to have a GWP ~ 70% lower than gasoline [13].

Figure legends

Figure 1. The three faces of sustainability

Sustainability is a multifaceted concept that relies on the successful maintenance and enhancement of environmental, social and economic resources. A healthy economy generates wealth, creates opportunities for investment and employment, whilst social sustainability prioritises human well-being and social capital. To ensure environmental sustainability it is essential that the natural capital of the environment remains intact. True sustainability can only be achieved when these three drivers of sustainability overlap and do not infringe on one another.

Figure 2. Life cycle assessment of biodiesel production from oilseed rape grown in the UK [14]. The schematic shows a summary of the production pipeline required to produce 1 te of biodiesel, assuming productivity of the crop as 3.4 te/ha. Other inputs into the process such as fertilisers and water during cultivation are shown, as well as the various co-products of downstream processing. For each stage in the lifecycle of the fuel the global warming potential (GWP) and net energy balance (MJ) was determined using agreed international methodology. The GWP at the end use stage is assumed to be zero, because CO_2 absorbed

during growth is emitted here upon combustion. The data are reported in Stephenson et al. 2008 [14].

Figure 3.

GWP of biodiesel produced from palm oil, with different previous land uses. Global warming potential here is reported based on kilograms of CO_2 equivalents emitted per GJ of fuel combusted (kgCO_2-eq/GJ). The data are reported in Wicke et al. 2008 [7].