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Biofuels: balancing risks and rewards

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This paper describes a framework that can be used to evaluate the environmental risks and benefits associated with biofuel production. It uses the example of biodiesel produced from Argentinean soy to show how such a framework can be used to conceptualize trade-offs between different environmental, social and economic impacts of biofuel production. Results showing the greenhouse-gas savings and overall life-cycle impact of different 'soy-biodiesel' production methods are presented. These impacts and the significance of uncertainty in overall assessments of key parameters, such as greenhouse-gas savings, are discussed. It is shown that, even where sufficient knowledge exists to be able to quantify these impacts, the sustainability of supply of a particular biofuel is inextricably linked to values and ethical judgements. However, tailoring certification efforts to the issues that are most likely to make a significant difference to the overall sustainability could improve the effectiveness of certification efforts. The potential for a framework to guide and focus certification efforts is discussed and future research and policy priorities suggested.

1. Introduction and context for biofuel development

Petroleum-derived liquid hydrocarbons are an integral part of our global economy. Their use is embedded in our transport infrastructure, facilitating personal mobility and global trade; globally, they provide a significant proportion of heat and electricity requirements, and, industrially, they provide a platform for synthesis of a wide range of industrial chemicals and commercial products. However, they are also a key source of global greenhouse-gas emissions, which, because of the scope of international regulatory frameworks, is often underestimated [1]. The significant social, economic and environmental threats associated with climate change have resulted in commitments to substantially reduce the global level of anthropogenic greenhouse-gas emissions [2].

In many cases, it is possible to substitute alternatives for liquid hydrocarbons, for example using natural gas instead of petroleum for chemical synthesis or power generation (provided, of course, that there is sufficient overall availability). However, there are many applications for which a liquid fuel is entrenched in our current infrastructure and user interface. The most obvious of these is use in transportation. There are many options for reducing greenhouse-gas emissions in the transport sector, including demand-reduction measures, engine and efficiency improvements, electric vehicle and hydrogen/fuel-cell development. However, there are some sectors (e.g. aviation) for which a substantial liquid fuel demand is expected to persist in the long term. Biofuels (which use renewable biomass to produce a liquid hydrocarbon with lower greenhouse-gas intensity) can therefore help to reduce greenhouse-gas emissions in the long term and they can also provide an intermediate step towards decarbonization, with transitional use in surface transport required to meet carbon budgets [3].

In the near term, biofuels are particularly useful because they can deliver greenhouse-gas reductions with current technology. This is particularly important when we consider the implications of cumulative emission arguments: that near-term reductions are essential to avoid having to make deeper cuts later on [4]. However, it is absolutely imperative that the biofuels deployed do actually achieve real carbon reductions compared with the fossil fuel alternative. Some markets may have a demand for biofuels that address energy security rather

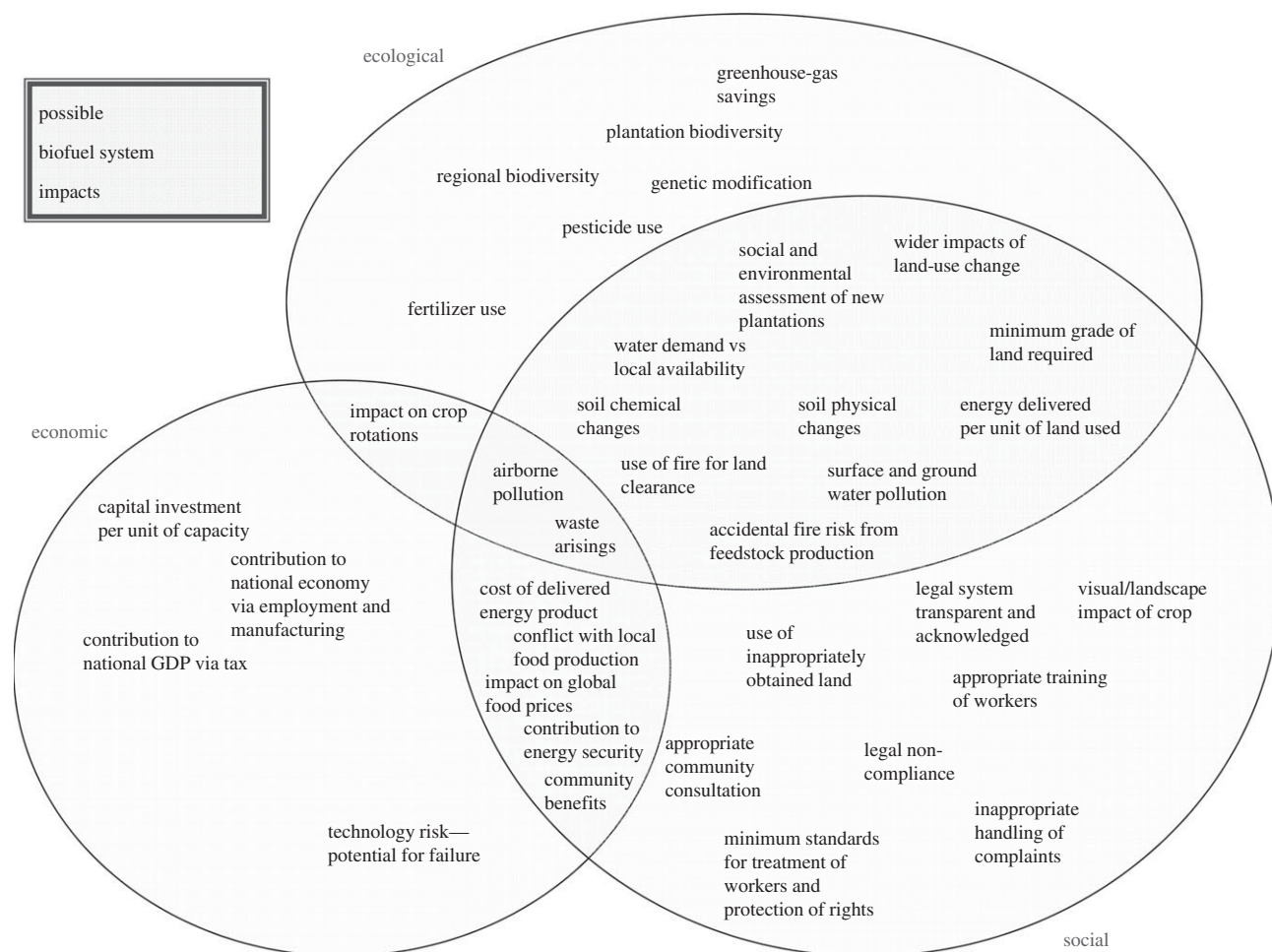


Figure 1. Summary of potential impacts of bioenergy systems.

than climate-change issues, but it is now increasingly accepted in Europe that we should encourage only biofuels that achieve real greenhouse-gas reductions [5].

2. Impacts of biofuel development

While the greenhouse-gas balance is undoubtedly important, the impacts of biofuels extend far beyond this, and due recognition must be given to the full range of social, economic and environmental impacts in any assessment. When taking into account these wider issues, it is particularly important to note that biofuel development becomes contested: there is substantial support for development from some groups, while others consider their overall impact to be so negative that further development should be ceased [6]. This is partly due to differences between stakeholders in terms of values and priorities [7], increasing the importance of comprehensively and transparently assessing all supply-chain impacts.

For the work described in this paper, a wide range of potential bioenergy impacts were therefore identified from a literature review of evolving criteria in certification systems in consultation with stakeholders in the SUPERGEN Bioenergy programme, which was then reduced to the set of mutually exclusive criteria listed in figure 1 to avoid penalizing or crediting a system for the same attribute more than once in an integrated assessment. When considering the overall sustainability of the system and trade-offs between different impacts, it is instructive to group these criteria by the classical social, economic and ecological pillars of

sustainability and the full list of criteria used are illustrated in figure 1, grouped in this manner.

Clearly from figure 1, there are many impacts that straddle the traditional social–economic–ecological distinctions and it is particularly notable that more impacts are considered to have a social dimension than an economic or ecological one.

3. Interfaces of biofuel development with other systems

Biofuels usually have complex integrated supply chains with many interfaces and impacts. The supply chain begins with feedstock production, where there are likely to be interfaces with land, water, ecology and local communities. This can result in complex interfaces with the food system and can have a longer term impact on the carbon sequestration or other functionality of land itself. Feedstocks will then be processed and transported, with further impacts on the environment, interfaces with infrastructure systems, trading routes and economic activity. Conversion of the feedstock to useful product generally results in further ecological, social and economic interfaces at the conversion plant. This may also have indirect impacts in terms of wider induced economic activity or supply-chain activities [8]. The biofuel product will interface with the existing energy market and any co-products will interface with other material/product markets.

Techniques such as life-cycle assessment allow us to quantify the impact of a particular bioenergy system on its environment [9] and, for this reason, are often used as part of regulated impact assessment. However, it is important to realize that the interfaces between bioenergy systems and other systems may not be entirely deterministic. For example, when land is used for biofuel production, there is a deterministic and quantifiable 'land use', but there may also be a response in the land system, for instance agricultural production of certain food commodities may change in response to biofuel production. Therefore, the bioenergy system has direct impacts, but also affects the behaviour of other systems with which it has an interface, leading to indirect impacts within each of those systems.

The key interfacing systems include the following:

- land system—with implications for carbon fluxes, land utilization and food production;
- energy system;
- food system;
- material resources—with implications for competing markets; and
- water system.

Some impacts may be direct; others may be indirect, for example land used for bioenergy production results in another land-use change elsewhere. Some impacts may be physically remote from the cause and often there will be interactions with other systems, resulting in complex, simultaneous evolution. We can therefore evaluate the impact potential and postulate outcomes, but it can be difficult to establish causal links or confidently predict the exact impact of bioenergy systems on other systems. In such an environment, it is appropriate to think of the probability or risk of different outcomes and how they interact. This is considered more carefully below. However, it should be noted that risks may be perceived in different ways by different stakeholders [7]. A methodology for this is described in §4.

4. Methodology

4.1. Principles of risk-assessment methodology

Risk is a concept with which we are all intuitively familiar and that elicits a judgement that is partially context dependent and subjective. For example, every time we cross a busy road, we judge the risk involved and balance it against the reward. We want to get to the other side of the road (the reward), but are aware that we need to avoid a collision with a car (the risk). Our assessment of the risk is affected by two primary factors:

- the probability that a collision will occur;
- the impact that a collision would have if it did occur.

Mathematically, we think of the risk associated with an event as the product of these two factors. So the highest risk events have both a high risk of occurrence and a high impact when the event occurs, whereas low-risk events have a low risk of occurrence and low impact. This technique is commonly used in the financial and other sectors to carry out risk analyses on projects, investments or actions. In some cases, it is possible to compute the actual probability of the

Table 1. Risk-assessment methodology.

probability of occurrence	severity of impact	combined risk assessment
H(3)	H(3)	HH(9)
H(3)	M(2)	HM(6)
M(3)	H(2)	MH(6)
M(2)	M(2)	MM(4)
H(3)	L(1)	HL(3)
L(1)	H(3)	LH(3)
L(1)	M(2)	LM(2)
M(2)	L(1)	ML(2)
L(1)	L(1)	LL(1)

event and weight it with an impact assessment, but more often a semi-quantitative approach is used where the risk of occurrence and impact are both rated as high, medium or low (HML). The combinations of possible assessment outcomes are then shown in table 1. Risk management is focused on identifying and addressing the events that have the highest combined risk. This can be represented mathematically by assigning absolute values (1, 2 or 3) to the L, M and H probabilities, respectively, and then the product (representing the overall risk) can be computed mathematically. Note that this results in a numerical figure that is higher for higher risks, but that the scale is not linear; so a number twice as large does not represent twice the risk.

4.2. Application of risk assessment to bioenergy systems

When faced with environmental risks and uncertainty, the precautionary principle espoused in article 15 of the Rio Declaration is often invoked [10, p. 22, principle 15, paragraph 80]:

Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.

It could be argued that the threat of climate change is serious and irreversible and that a lack of full certainty on biofuel impacts across all of the earlier mentioned 36 categories should not therefore be used to delay biofuel implementation, where it is clear that cost-effective greenhouse-gas reductions could be delivered. However, a counter argument could be that where there are risks that land-use change might actually negate those carbon savings, this is a threat of serious damage and the cost-effective measure to prevent degradation would be to not act. The balance here revolves around the degree of uncertainty associated with the impacts. It is important to balance risks and rewards, but this is complicated by the fact that environmental risk is perceived differently by different stakeholders in the face of uncertainty [7].

In order to assess biodiesel production from Argentinean soy, the system was defined as described in §4.3 and, a wide range of possible sustainability parameters/impacts were considered as listed in figure 1. Life-cycle assessment was used to determine the quantitative impacts of the biodiesel production system, which are presented in §5.1 for

greenhouse-gas savings and \$5.2 for wider ecological impacts. A literature review of socio-economic impacts of soy production in Argentina was collated, and a number of interviews with Argentinean stakeholders were carried out during a field trip to Argentinean plantations [11]. These were synthesized and then presented to a group of industrial, academic and commercial stakeholders in a workshop, who each scored the impacts of the soy-biodiesel system. Stakeholders from government departments, biofuel businesses, consultants, non-governmental organizations and trade organizations were invited to the workshop, based on the prior contacts of the organizers. However, at the same time, the organizers tried to ensure that a balance of views and backgrounds were represented. This resulted in 12 attendees from 17 invites. For each 'issue', the participants decided whether it was a risk or a benefit, and then rated the occurrence as high, medium or low and the impact as high, medium or low, with corresponding scores assigned as in table 1. Benefits were assigned positive numbers; risks negative numbers. It was necessary to represent the views of all stakeholders involved by a single rating (H, M, L) for each of the 36 criteria, and so the modal figure was chosen where this clearly had support of over 50 per cent of participants; but where there were less conclusive (and usually more divergent) opinions, the mean was adopted as a fairer reflection of polarized opinions.

4.3. System definition for life-cycle assessment

The soybeans are produced from transgenic Round-up Ready seeds on a farm of 500 ha (quite small for Argentina), growing 200 ha of soybeans in monoculture, in the Pampas agricultural region of Argentina [12]. A no-till agricultural approach has been assumed with minimal ground preparation, but with utilization of glyphosate as a broad-spectrum herbicide post-planting. This no-till approach is common in Argentina, with 16 Mha or 60 per cent of agricultural land farmed this way in 2005. The soy is cropped with another rotation crop, but the focus of the sustainability assessment is on soy production only. It is assumed that no pre-planting removal, cultivation or preparation is undertaken after harvesting of the rotation crop each year, which would be the case for rotations involving oilseed rape, an alternative oilseed for biodiesel production.

Soy expansion in Argentina has resulted in significant new land areas coming into soy production, and so two production variants were modelled to assess the impact of this. In option A, it was assumed that previous agricultural land was used and there was no fertilizer application, as is common practice, whereas, in option B, a land-use change is required to facilitate soy expansion, which is included in the greenhouse-gas balance and allowance has been made for fertilizer application, as this is more likely to be required when switching land into cultivation. Planting using a mechanized row crop planter is assumed on good alluvial soil, with high organic content, which will facilitate high crop yields when there is adequate rainfall of 500–750 mm [13]. No-till agricultural techniques are used, as is commonplace in Argentina and elsewhere, including Canada and Australia. A summary of the key agricultural steps modelled for option A and option B is given in table 2.

In both cases, once the leaves fall, harvesting takes place using a large combine harvester, which threshes the seeds internally and outputs beans to a transporter truck, whereas

Table 2. Agronomic regime modelled.

option A	option B
production on previous agricultural land with no land-use change	production on previous scrub land with inclusion of land-use change greenhouse-gas emissions
no-till planting	no-till planting
two applications of post-emergence herbicide	two applications of post-emergence herbicide
no fertilizer or soil conditioner application	single annual application of a compound fertilizer application of lime once every 5 years
combining of crop at harvest	combining of crop at harvest

all other parts of the plant are blown back on to the field [14]. After harvesting, the soybeans are dried in a grain drier using diesel fuel, before being transported 500 km by road, using a 40 tonne maximum capacity truck to a crushing plant.

At the crushing plant the beans are taken from the silo and crushed and separated by solvent extraction (using hexane) into soyoil and soymeal. The soyoil is then shipped from Argentina to the UK (14 500 km). Trans-esterification to produce biodiesel then takes place at a facility in the UK, whereby the soyoil is reacted with methanol in the presence of a potassium hydroxide catalyst to produce glycerol and a fatty-acid methyl ester biodiesel product. Finally, the biodiesel is transported to the point of sale (distance: 200 km) within the UK, via a pipeline.

This system was modelled using the Renewable Fuels Agency's (RFA) carbon calculator for greenhouse-gas balances and the Sima Pro life-cycle assessment software for other life-cycle ecological impacts. The RFA is responsible for ensuring that UK biofuels meet minimum sustainability standards. As part of this, it requires that life-cycle greenhouse-gas balances are carried out on all regulated feedstocks, using the RFA calculator, which has been developed for this purpose and contains a large number of corresponding default assumptions and figures that users may either accept or replace with their own figures. Their calculator was used to provide an indication of the results that would be achieved by companies that were not proactive in investigating their supply chain. The Sima Pro model is a more sophisticated life-cycle assessment tool that allows the impact of different assumptions and approaches to be investigated more thoroughly.

5. Results

5.1. Greenhouse-gas savings

Table 3 shows the calculated greenhouse-gas savings for the two options considered, compared with the default figures assumed by the RFA, and a breakdown of the origin of the figures is given in figure 2.

The RFA default figures indicate greenhouse-gas emission savings over the life-cycle of 39.8 per cent. From figure 2, it can be seen that the largest contributor to carbon emissions is the crop production phase. It should be noted that

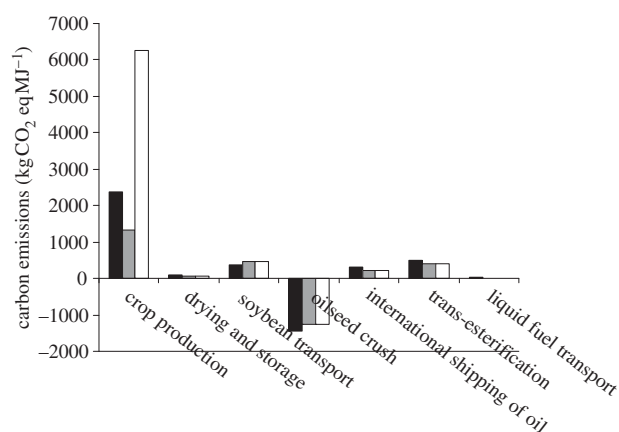


Figure 2. Carbon emissions from soy biodiesel supply chain. Black bars, RFA default values; grey bars, soy option A; white bars, soy option B.

Table 3. Greenhouse-gas savings for biodiesel production from Argentinean soy compared with mineral diesel.

	RFA default	option A	option B
carbon savings (%)	39.8	65.9	-66.5

analysis of the inputs for this phase revealed that the RFA default figures are not typical of no-till systems but conventional production. Therefore, the no-till production on previous agricultural land (option A) modelled in this work indicated a much higher greenhouse-gas reduction of 65.9 per cent. This illustrates the importance of knowing the production steps to accurately quantify greenhouse-gas emissions and of encouraging production regimes that minimize greenhouse-gas emissions where that is a key priority. However, they also do not include any land-use change, which would significantly increase the emission from this phase and is discussed below. Option B does include the greenhouse-gas emissions associated with land-use change and from table 3 shows no decrease in greenhouse-gas emissions, but a net increase of 66.5 per cent compared with conventional diesel production.

The value of offset emissions at the step oilseed crush mill is also significant in the overall greenhouse-gas balance. If CO₂ credits were not applied for the soymeal co-product, then the greenhouse-gas savings fall to only 19.3 per cent. This is because production of meal for animal feed often uses cereals such as wheat which have high rates of fertilizer application and are therefore more carbon intensive than soymeal production. This is a good example of how bioenergy-system performance depends on the response of systems with which it interacts. Including a credit for soymeal is equivalent to claiming that the bioenergy system has interacted with the food system so that the physical exchange of soymeal between the two systems has resulted in a net reduction in greenhouse-gas emission for the food system. This is justified if a demand for the soymeal co-product exists that would be satisfied by alternative production if not obtained from the soy-biodiesel system. In reality, it is impossible to 'know' whether or not that will be the case, without considering the food production system and its demand/supply balance. The validity of the assumption is also scale dependent because small amounts

of soymeal could be considered to displace the market in this way, but this may not continue if soy-biodiesel production is expanded significantly.

It should also be noted that the crop nutrition options presented in option A are considered typical of practice in Argentina, but do not promote long-term soil productivity. Adding in application of the same nutrients as in option B results in a reduction in greenhouse-gas savings from 65.9 per cent to 51.3 per cent.

Soy option B has very much higher emissions associated with crop production than the other cases. Over 70 per cent of these emissions come from the land transformation, using Intergovernmental Panel on Climate Change (IPCC) standard values for Argentinean agricultural and ecological zone for scrubland [15]. It should be noted that there can be significant variations in these values and the actual applicable value could be considerably higher or lower, depending on the previous land condition. Also, no allowance is made for any increase in soil carbon resulting from the establishment of the crop, which might be the case if the land was previously a particularly poor soil. Similarly, no allowance has been made for the direct emissions associated with the actual land transformation. The contribution of soil nitrous oxide emissions is also significant within the figures for crop production, being over 20 per cent of the total for the crop production step. These releases occur when plant growth converts nitrogen in soil to nitrous oxide and are generally higher when nitrogen fertilizer is applied.

Overall, the results show that it is possible to obtain very significant reductions in greenhouse-gas emissions by using soy-derived biodiesel. However, there are several important assumptions that could make a significant difference to the overall greenhouse-gas balance. Some of these are dependent upon systems that interface with the bioenergy system, but are largely beyond its sphere of influence, namely the food system (which dictates demand for soymeal for animal feed) and the land system (availability of suitable land). It is important to realize that these factors (such as the carbon intensity of the animal feed displaced) influence the bioenergy-system results and to realize that these parameters themselves exhibit interdependencies. For example, the energy-system and food-system assumptions both affect the results for the biodiesel greenhouse-gas balance, but they also affect each other because some energy-system decarbonization pathways might focus on fertilizer production and liquid fuels, substantially reducing some food-system emissions, while others might focus on electricity, having less of an impact on the food-system emissions.

From a risk management perspective, it is reassuring that substantial greenhouse-gas savings can be achieved and most stakeholders prioritized the greenhouse-gas savings parameter very highly. The variations in the magnitude of savings achieved with different land and substitution assumptions indicate that there is potential to achieve a significant reward, but it is affected by specific areas of uncertainty, related to the production regime. The important thing then is to consider how to mitigate that risk or uncertainty. Unfortunately, many of the key parameters here are actually part of the interfacing food and land systems rather than that of the bioenergy system. This is disconcerting because it will be difficult for the biofuel supplier to control those risks. Also, it is worth noting that the rationale for soymeal credit is predicated upon a demand for carbon-intensive animal-feed production in future. Therefore, the

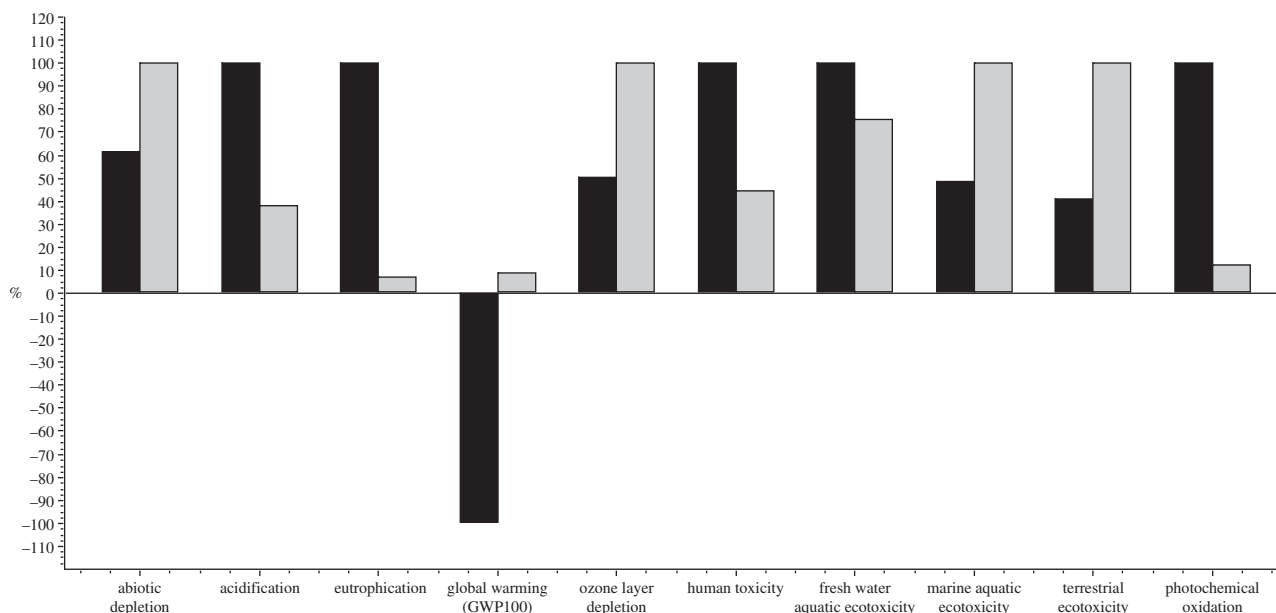


Figure 3. Life-cycle ecological impacts of soy biodiesel compared with mineral diesel. Black bars, soy biodiesel, option A, Argentina; grey bars, conventional diesel, at regional storage.

savings in the transport sector are obtained only if the food sector maintains high-carbon-intensity levels. Reductions in the latter would seriously impact upon the biofuel carbon savings, and these reductions are being sought in an overall greenhouse-gas reduction context. In other words, some successful policy initiatives to reduce greenhouse gases from the food system could reduce the greenhouse-gas savings achieved by this bioenergy system. Conversely, though, development and investment of techniques such as no-till agriculture could be incentivized by biofuel incentivization schemes and transferred into wider agricultural production with greenhouse-gas reduction benefits. There is a two-way, symbiotic relationship between the bioenergy system and the food system, physically mediated by land use, and changes in one system can have an impact on the other, including changing greenhouse-gas emissions. It is important therefore to take a holistic view, which considers the net changes in greenhouse-gas emissions across the different interacting sectors.

It is also interesting to note the geographical origin of the carbon emissions. From figure 2, most of the emissions are in production in Argentina. Therefore, from an IPCC inventory perspective, they would be counted in Argentina's national inventory and thereby increase their national emissions inventory, even though they are providing carbon reductions in the UK. The supply-chain accounting methodology that facilitates validation of whether or not 'real' greenhouse-gas savings are being achieved along the supply chain also allows biofuel importers to effectively export their greenhouse-gas reduction obligations.

5.2. Other life-cycle environmental impacts

Going beyond carbon emissions, wider impacts of soy can also be compared: figure 3 shows the performance of the same biodiesel system compared with conventional diesel across a range of ecological impact categories. These ecological impacts are related to some of the impacts identified in figure 1; for example, regional biodiversity will be impacted by terrestrial ecotoxicity. Therefore, these calculations were

presented to stakeholders at the workshop to inform their assessment of the impacts.

The greenhouse-gas emissions (global warming potential) have been discussed in detail in §5.1, but, from figure 3, it can be seen that the soy-biodiesel system has significantly lower impact figures and therefore shows better environmental performance than the mineral diesel equivalent in the following categories:

- abiotic depletion;
- ozone layer depletion;
- marine aquatic ecotoxicity; and
- terrestrial ecotoxicity.

In the following categories, the soy-biodiesel has higher impact figures, which indicate significantly worse environmental performance than the mineral diesel equivalent:

- acidification;
- eutrophication;
- human toxicity;
- freshwater aquatic ecotoxicity; and
- photochemical oxidation.

This split performance against different impact categories clearly shows the ecological trade-offs involved in substituting biodiesel for mineral diesel. It is important to balance the risks of acting against not acting and, while it is desirable to support reductions in greenhouse-gas emissions, it must also be acknowledged that these are obtained at the expense of undesirable impacts in other categories. This is particularly of concern with respect to the location of impacts. Greenhouse-gas levels are a global environmental challenge and so, in one sense, it does not matter where geographically the emissions are incurred or reductions are achieved, and global trade in products inevitably spreads the emission burdens of consumption across geographically distinct producer countries that then benefit from trade income. However, impact categories such as human toxicity and eutrophication have negative impacts that are location-specific. The

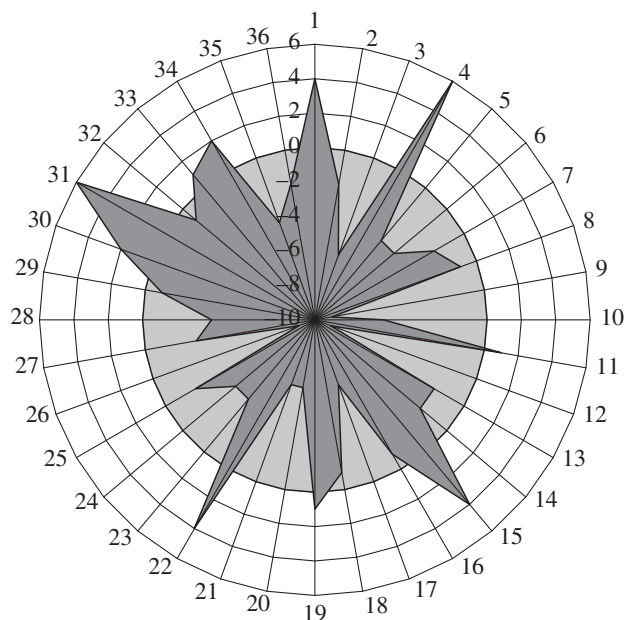


Figure 4. Radar diagram showing overall sustainability assessment of biodiesel from Argentinean soy compared with mineral diesel. Light grey, reference level; dark grey, scores for Argentinean soy system.

application of supply-chain accounting procedures means that greenhouse-gas obligations can effectively be traded so that countries that import biofuels are effectively exporting their own reduction commitments. It could be argued that this is an integral part of the global trading system—if products can be exchanged for financial compensation, then it seems equally reasonable that greenhouse-gas reductions should be financially purchasable. However, where there are less transparent environmental costs, such as local toxicity impacts wrapped up with the financial transaction, this raises ethical concerns.

5.3. Balancing sustainability risks and rewards

As described earlier, stakeholders were convened to assess the overall trade-offs in accordance with the risk methodology. The outcomes were then synthesized in a radar diagram, as shown in figure 4.

Using this representation, the circle is the reference level that represents doing nothing—no bioenergy system is implemented. The bioenergy system is then evaluated by comparison with the reference level of doing nothing (i.e. continuing to use fossil fuel diesel). A wholly sustainable solution would involve stretching that circle to increase the positive impacts while minimizing the inward incursions. Clearly, there are some parameters for which utilization of biodiesel from soy is providing a net sustainability benefit but there are many others where the net impact is viewed by stakeholders as negative—an increase in environmental risk.

In this framework, the highest and lowest achievable scores are +9 and -9, and figure 4 shows that the soy system carries what could be thought of as ‘maximum risk’ (-9) in some areas, but no ‘maximum rewards’ (+9). Therefore, figure 4 effectively illustrates the trade-offs associated with bioenergy development—in a bid to address one issue or need, actions are taken that have negative repercussions in other areas, which should also be taken into account.

Where such diversity of impacts exists, deciding whether or not development should proceed or be halted is fraught

with difficulty. The decision is not simply of whether or not carbon savings are achieved, but involves much more complex issues of how carbon reductions should be prioritized compared with other impacts (and from whose perspective these impacts should be assessed): equity and accessibility issues for different communities; the extent to which precautionary principles should apply; the ethics of negative impacts in one part of the world supporting positive impacts elsewhere and equitable sharing of burdens. For example, genetically modified Round-Up Ready soybeans facilitate the substantial global greenhouse-gas reductions achievable via no-till agriculture in soy-biodiesel production, but also tend to result in higher levels of herbicide use [12], resulting in greater toxicity impacts local to the production sites. In addition, the high mechanization associated with no-till approaches tends to be associated with large-scale production, with local smallholders unable to easily benefit as a result of the high capital cost of no-till drills. So, incentivizing or requiring higher levels of greenhouse-gas reductions could sacrifice potential for social benefits for local communities. Biodiesel production can deliver multiple system benefits but only if certification frameworks encourage these. Focus on a single objective could impair performance in other areas and these areas may be of more immediate relevance to local producers.

6. Discussion

At an international level, significant efforts are being made to ensure the sustainability of international biofuel supply/trade by development of legislative frameworks and certification methodologies whereby only ‘approved’ biofuels that meet certain minimum standards will be accepted. In the context of the methodology presented in this study, this is akin to drawing a fixed circle on top of figure 4 and excluding biofuels that do not have that minimum radius for any parameter, regardless of how well they may perform against other parameters. In some cases, this may be appropriate to remove the risk of unacceptable impacts, but setting that threshold too high will remove the opportunity of obtaining some highly valuable rewards (job creation, income generation and trade opportunities) in some contexts. Also focusing on minimum standards does not encourage improvement or maximization of important parameters, such as greenhouse-gas reductions.

The analysis carried out earlier for soy has shown the importance of certain parameters to the overall system sustainability and it would, therefore, be appropriate for sustainability certification or assessment of renewable biodiesel to take those parameters into account for soy. However, it is important to realize that these certification schemes require substantial effort and actually add to the cost of the commodity produced [16]. There is therefore a need to balance the requirements to be diligent with regard to potential impacts with the requirement to ensure economic sustainability by not overburdening the product with certification elements that will not actually make a difference to the overall fuel sustainability. A good example here is the use of fertilizer. The application of N fertilizer, in particular, has a very significant impact on the greenhouse-gas balances of annual biofuel crops and so should rightly be scrutinized for those crops. However, the fertilizers applied to soy have much more limited greenhouse-gas impacts and so there is little point in chasing evidence, records and calculations to support the exact

greenhouse-gas balance for this feedstock in cases where it is clear that, for the vast majority of production options, this will not result in a significant sustainability risk. It would make much more sense to focus efforts on the areas that give most cause for concern. The earlier mentioned risk framework suggests that this would equate to identifying the issues for a particular feedstock that carry a high sustainability risk either because the impact could be substantial or because the probability of an impact occurring is high and then focusing on the certification of those supply chains. For example, in the case of soy-biodiesel production, greenhouse-gas balance results are obviously highly variable but key drivers include land-use change, yield and the use or otherwise of no-till agriculture. Therefore, focusing on these parameters in supplier certification would make more sense than requiring detailed information on all aspects of production.

Such an approach could readily be combined with existing certification approaches by carrying out 'screening' assessments for different feedstocks and then only requiring producers to focus on the most significant areas when assessing their feedstock sustainability. It is acknowledged that there would, of course, be challenges associated with issues such as the choice of stakeholders to ensure inclusivity and cross-representation. However, these challenges are common to many approaches for increased stakeholder inclusivity in biofuel development and so need to be addressed, regardless of methodology or approach.

The relevant issues will be different for different feedstocks. For example, an analysis of American commercial forest residue supply chains showed that key risks focus mostly on the carbon and nutrient balance implications, whereas for Brazilian eucalyptus the key issues are land-use change and hydrological impacts [17]. There are also variations between locations, for example land-use change may be extremely important in some contexts; but if dealing with a high-yielding perennial crop, where long-term soil carbon is likely to increase and there is not significant pressure on the same land area for food production, this will be much less important. Despite this, significant efforts and costs may be incurred in documenting how, for a particular supply chain, the impacts are relatively small. While it is an attractive ideology to compare all supply chains on a common basis, it does not make practical sense to burden all commercial supply chains with the same evidential requirements, particularly if this detracts from the economic sustainability of the resource. The earlier mentioned risk profile showed that there are some positive aspects of biomass supply chains. These could be reduced global greenhouse-gas emissions or socio-economic benefits. In some locations, these could have very significant, welcome impacts, but this will happen only if significant supply chains and markets are developed. Certification requirements should therefore be proportionate to the potential risk posed by supply chains to ensure that positive impacts are actually encouraged rather than supply being deterred. A more pragmatic approach, which prioritized the key risk factors for different supply chains, would be more likely to result in a delivery of the much-needed benefits (including reduced greenhouse-gas emissions).

However, the risk profiles are critically dependent upon the assessment of the likelihood of an impact occurring and the assessment of the severity of that impact. Both of these parameters can be greatly influenced by different types of

uncertainty. In some cases, these may be endemic to particular supply chains; for example, in countries with weak institutional regimes, verification of land-use and ownership may be very challenging and supply-chain specific. In these cases, conformity and confidence could be gradually increased by certification schemes. However, for this to take place, it is again key that the most significant parameters are prioritized, for example land use and soil carbon content.

It is also important to realize that global bioenergy supply certification and assessment does not act only to exclude certain supply chains, but actively shapes a dynamic producer market. For example, imposition of European agricultural norms that may not be readily achievable in some producer countries does not allow the potential positive impacts of biomass supply to be experienced.

Uncertainty takes different forms and that should dictate the management approach. A detailed look at key supply chains highlights many areas where understanding of the processes and interactions is lacking, or quantification of the impacts could be significantly under- or overestimated. For example, even small levels of N₂O releases along the chain could be highly detrimental to the overall greenhouse-gas balance; yet, estimates for this figure are highly uncertain and projections for future levels (e.g. in response to climate-change impacts such as increases in global mean surface temperatures) are barely considered. The impact of different forest harvesting and management techniques on long-term soil carbon appears to be very significant and yet relatively poorly understood. It is imperative that scientific research focuses on these and other potentially significant impacts to reduce the level of uncertainty, allowing better prioritization and management of key risks.

Normally when risk assessments are carried out in a commercial context, the aim is to identify key risks and then to ensure that these are mitigated either by reducing the likelihood of occurrence or by limiting the impact. If we are to improve the sustainability of bioenergy supply chains, it is imperative that this logic is carried through to sustainability assessment. Certification schemes should encourage benefit maximization and risk minimization, not simply maintaining levels of mediocrity. Setting minimum thresholds (e.g. for carbon savings) may ensure that the worst impacts are avoided but does not necessarily encourage maximization of the overall benefits.

For the case of Argentinean soy, discussed in this study, the most significant drivers of the greenhouse-gas balances are not the bioenergy system, but the food and land systems. It is important that this is recognized, and appropriate consideration is given to these systems (as well as the energy system) in a research context. This requires much more than consideration of how bioenergy systems impact on land and food systems, but an adequate consideration of these complex systems in their own right. Land use is an important physical resource which sits at the nexus of food production, carbon sequestration and energy provision and therefore warrants specific consideration in its own right, not just as an adjunct to bioenergy system evaluation.

7. Conclusions

- Supplying energy has an impact—different systems have different impacts and the prioritization of one system,

energy resource or technology over another should take into account the multiplicity of impacts.

- Impacts of bioenergy systems are perhaps more wide ranging than for other energy resources, and are different for different feedstocks, conversion technologies and scales.
- Bioenergy systems interact in a complex way with the food and land systems, and improved understanding of these interactions is key to being able to confidently predict the actual impact of bioenergy systems.
- Balancing risks and rewards is an essential part of biofuel development, and risk-assessment techniques can be used to conceptualize the balancing and trade-offs, but still present a considerable challenge
- In particular, the challenge may be simplified by focusing on key supply chains and tailoring certification efforts for those supply chains to the issues that are most likely to make a significant difference to the overall sustainability. This could be done by regulatory bodies carrying out generic assessments of supply chains for producer regions

that would highlight the most relevant issues and then suppliers would be required to report only on these, reducing the administrative burden and cost of certification schemes.

- Uncertainty complicates risk balancing, and research to reduce uncertainty in key areas should be prioritized, for example nitrous oxide emissions, soil carbon dynamics, forest management impacts, losses and decomposition pathways.
- The desire to establish that 'real' greenhouse-gas reductions are being achieved with biofuels has resulted in the adoption of a consumption-based approach to greenhouse-gas calculations, which may not always be consistent with the scope, or support the objectives, of the established territorial-based greenhouse-gas emissions inventory reporting.

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