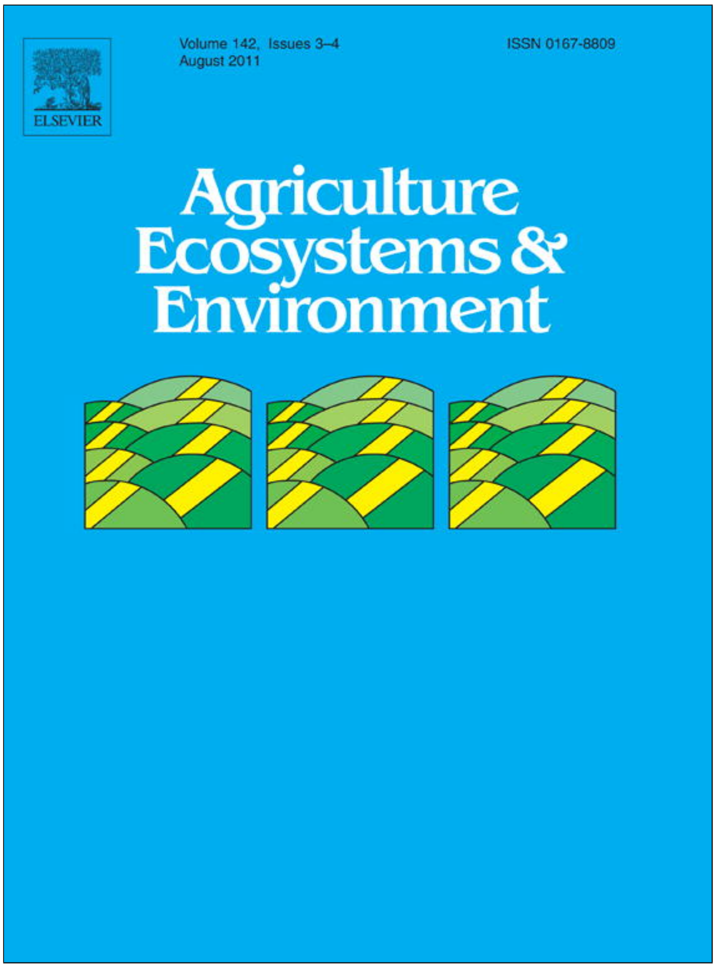
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Review

Biofuels, ecosystem services and human wellbeing: Putting biofuels in the ecosystem services narrative

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ABSTRACT

First generation biofuels provide a number of ecosystem services (e.g., fuel, climate regulation) but they also compromise other ecosystem services (e.g., food, freshwater services) which are of paramount value to human wellbeing. However, this knowledge is fragmented and little is known about how the ecosystem services provided and/or compromised by biofuels link to human wellbeing. In fact, whether biofuels production and use can have a negative or positive impact on the environment and society depends on several interconnected factors. This paper provides a critical review of the drivers, impacts and tradeoffs of biofuel production and use. In particular, it rationalizes the evidence coming from diverse academic disciplines and puts it into perspective by employing the ecosystem services framework popularized by the Millennium Ecosystem Assessment (MA). An outcome of this systematic review is a simplified conceptual framework that illustrates the main trade-offs of biofuel production and use by employing a consistent language grounded on the concepts of ecosystem services. Given the almost complete lack of literature explicitly linking biofuels and ecosystem services, our review concludes by identifying priority research areas on the interface of biofuels, ecosystem services and human wellbeing.

Contents

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1. Introduction

Economic activity and energy demand are bound to increase significantly in the following decades, especially in the developing world (IEA, 2009). At the same time energy security, economic development and environmental protection have become three recurrent and closely intertwined policy themes globally. Fossil fuel combustion is singled as the most important driver of anthropogenic climate change (IPCC, 2007a) with their scarcity and uneven geographical distribution coupled with geopolitical factors severely affecting national economies and international markets. As a result the development of copious amounts of cheap, renewable and environmentally friendly energy has become an integral part of energy strategies in developed and developing countries alike.

Perhaps, the most controversial such energy carrier is first generation biofuels, i.e., biodiesel and bioethanol from "*sugar, starch and oil bearing crops or 'animal fats that in most cases can also be used as food and feed*" (IEA, 2010a: 22).[1] Despite the projected increase in first generation biofuel production and use within the next decade (OECD-FAO, 2010), several studies have confirmed their negative impact on the environment (e.g., SCOPE, 2009), biodiversity (Fitzherbert et al., 2008), the climate (Fargione et al., 2008), food prices (Runge and Senauer, 2008; Mitchell, 2008) and the inclusion of poorer strata of society (Cotula et al., 2008). On the other hand, certain first generation biofuel practices can be net energy suppliers (Hill et al., 2006; Menichetti and Otto, 2009), have a better environmental performance than conventional fossil fuels (Zah et al., 2007) and be economically/socially beneficial (Arndt et al., 2010a; FAO, 2009). There is also significant evidence to suggest that biofuels not only provide several ecosystem services[2] (e.g., fuel, climate regulation) but that they also compromise other ecosystem services (e.g., food, freshwater services) (e.g., SCOPE, 2009; Fischer et al., 2009). However, this knowledge is fragmented and little is known about how the ecosystem services provided and/or compromised by biofuels affect human wellbeing.

It seems that despite the significant knowledge coming from different academic disciplines there is little meaningful integration of the findings. In fact, on several occasions, the findings about biofuels' impacts are contradictory (e.g., GHG emissions, Section 4.2.1). Not surprisingly frameworks and accounting rules that will allow the integrated and consistent evaluation of biofuel production practices are still elusive (Robertson et al., 2008; Tilman et al., 2009). The above indicate two major gaps in the current biofuel literature and practice:

(a) lack of a consistent language that can be used to put biofuels' diverse trade-offs into perspective and frame the biofuel debate;
(b) lack of appropriate integrated tools/toolkits for assessing the sustainability of different biofuel practices during their full lifecycle.

From these starting points the aim of this Review is to address the first point and lay the foundations for the second point by:

- reviewing the drivers and impacts on ecosystem services and human wellbeing of different biofuel production/use practices using the Millennium Ecosystem Assessment (MA) narrative;
- developing a simplified conceptual framework that can be used to illustrate the trade-offs of biofuel production and use using a consistent language grounded on the concept of ecosystem services;
- identifying priority areas for research in the nexus of biofuels, ecosystem services and human wellbeing, particularly for developing appropriate assessment mechanisms.

2. Approach

Various issues have been associated with biofuel sustainability. Hill et al. (2006) suggest that biofuels need to be (a) net energy providers, (b) environmentally sustainable, (c) economically competitive and (d) not compete with food production. Lately additional social criteria have been articulated (e.g., Rist et al., 2009; Borras et al., 2010). Whether biofuel production and use can have a negative or positive impact on the environment and society depends on a multitude of factors that range from the production process adopted, to the characteristics of the surrounding ecosystems and the policies that govern biofuel production and trade.

Currently, numerous initiatives are aiming to promote sustainable biofuel production and use. These initiatives fall broadly within two categories: regulatory/policy initiatives and voluntary standards (Kunen and Chalmers, 2010). Policy/regulatory initiatives essentially provide the incentives and set the boundaries that can influence sustainable biofuel production practices nationally and internationally (Kunen and Chalmers, 2010). They can be biofuel specific, e.g., the EU Renewable Energy Directive—RED (EU, 2009) and the UK Renewable Transport Fuel Obligation—RTFO (RFA, 2010), or target broader sustainability issues and as a result have a ripple effect on biofuel sustainability. Voluntary sustainability standards on the other hand are promoted by multi-stakeholder alliances and can either target biofuels, e.g., Roundtable on Sustainable Biofuels—RSB (RSB, 2010), or specific biofuel feedstocks, e.g., Roundtable on Sustainable Palm Oil—RSPO (RSPO, 2007), Roundtable on Responsible Soy—RTRS (RTRS, 2010).

Most of these initiatives are performance-based as they set specific sustainability targets (e.g., GHG savings) that need to be met if the respective biofuel/feedstock production practices are to be considered sustainable (Kunen and Chalmers, 2010). In the authors'

[1] Second generation biofuels are produced from cellulose, hemicellulose or lignin (IEA, 2010a).
[2] Ecosystem services are broadly defined as the "...*benefits people obtain from ecosystems*" (MA, 2005a: 27).

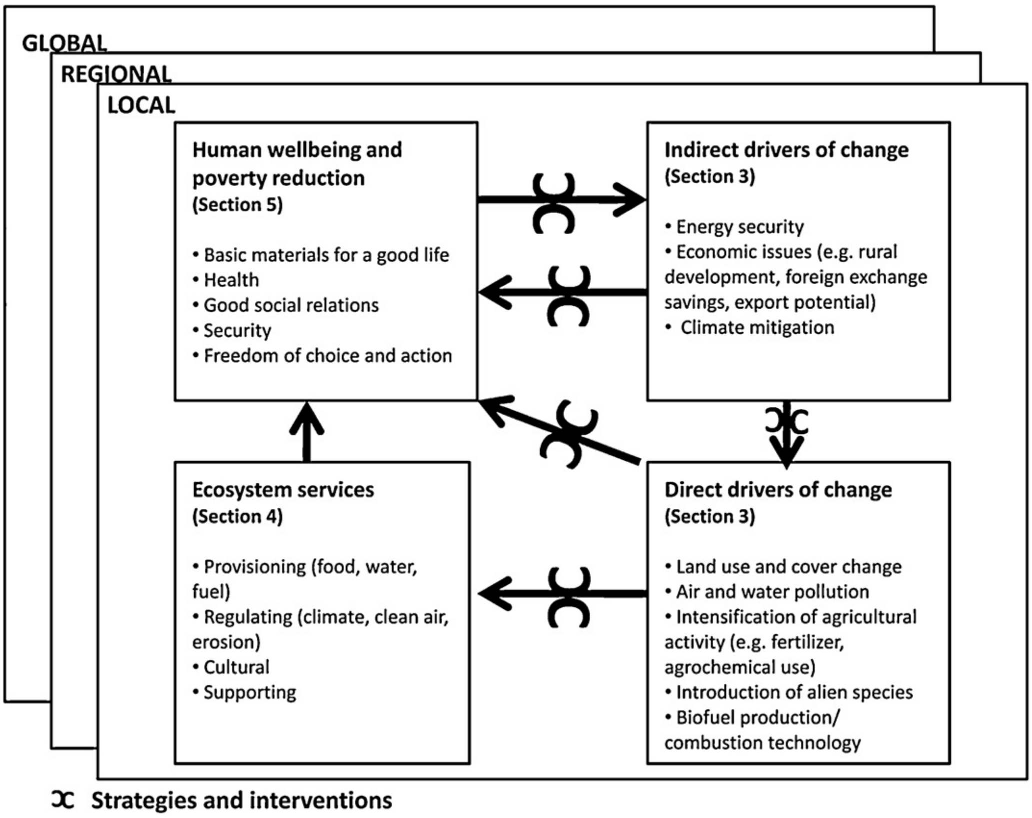

Fig. 1. The MA conceptual framework adapted for biofuel production and use. Adapted from MA (2005a).

opinion the main advantage and limitation of these frameworks is their simplicity. While simplifying and boiling down biofuel sustainability into a discrete list of criteria-targets that have to be met (similar to an indicator list) at the same time they lose information on the interrelations between these different criteria and the dynamics of the social–ecological systems that accommodate biofuel production.

Using the concept of ecosystem services when discussing the trade-offs of biofuel production and use can bring such interrelations and dynamics into the picture while at the same time maintain a degree of simplicity. This is because the concept of ecosystem services directly links ecosystem impact and human wellbeing, which are two key elements of the biofuel debate evoked by supporters and critics alike. As such it allows for an understanding of the interrelations between ecosystem change and human wellbeing. Additionally, ecosystem services have gained popularity in the academic community (Fisher et al., 2009) and have been accepted by policy makers, e.g., adopted by multilateral environmental agreements such as the United Nations Convention of Biological Diversity (CBD).[3]

Even though the concept of ecosystem services has been used extensively since the MA to understand the impact of numerous human activities on diverse social–ecological systems there is currently almost no literature explicitly linking biofuel production and ecosystem services (e.g., Jakubowski et al., 2010). The exclusion of biofuels from the MA[4] and the subsequent debate on ecosystem services has been a blatant omission given the significant evidence that biofuel production can provide and compromise ecosystem services at various scales.

In this respect this paper is the first attempt in the academic literature to put biofuels within the ecosystem services narrative in a comprehensive manner. For this purpose we have chosen the MA framework (MA, 2005a,b) and the ecosystem services language used during this exercise because the MA has been the most comprehensive attempt to date to identify, define and map ecosystems services and how they contribute to human wellbeing.

Fig. 1 is an adaptation of the MA conceptual framework and illustrates how the review of the academic literature will be approached in this paper. Section 3 collects and discusses the key direct and indirect drivers of ecosystem change that can be attributed to biofuel expansion. Section 4 discusses the main provisioning, regulating and cultural services that are provided and/or compromised by biofuel production and use while Section 5 addresses the subsequent impacts on human wellbeing.

It should be noted that putting biofuels in the ecosystem services narrative using the MA framework is just a first step and far from enough to result in an operational framework for assessing biofuel sustainability using the ecosystem services approach. For this reason Section 6 brings together the main findings of this review and identifies key gaps in the academic literature that need to be addressed before the concept of ecosystem services can be effectively used for the evaluation of different biofuel production and use practices.

The existing literature regarding the impact of biofuels is substantial[5] and spans across several academic disciplines. Additionally there are numerous biofuel production practices which can have radically different impacts across different spatial scales. As

[3] Biofuels are also high in the CBD's agenda (e.g. CBD-COP10 Decision X37).

[4] This exclusion might have been due to the fact that, with the exception of Brazil, global biofuel production was very limited before and during the MA (2001–2005).

[5] Most of the current biofuel literature is concerned with maize bioethanol in the US, sugarcane bioethanol in Brazil and palm oil biodiesel in Indonesia and Malaysia. This literature forms the backbone of this review but significant evidence from other areas and feedstocks (e.g. Jatropha in Africa) is discussed.

Table 1
Key direct and indirect drivers of biofuels' production impact on ecosystem change.

Indirect drivers	Direct drivers
Energy security (mainly at the regional and local level)	Land Use and Cover Change (LUCC)
Economic issues (mainly at the regional and local level)	Air and water pollution
• Rural development	Intensification of agricultural activity (e.g., fertilizers and agrochemical use)
• Savings in foreign exchange	Introduction of alien species
• Export potential	Biofuel production/combustion technology
Climate mitigation (mainly at the global level)	

a result we do not attempt to provide an exhaustive review of the literature but instead to highlight the main impacts of biofuel on ecosystem services and human wellbeing.

In the case of ecosystem services the way the academic literature reports the evidence coincides with the typology of ecosystem services used in the MA (i.e., fuel, food, water, climate change, air quality, soil erosion). However with the exception of "Health" the human wellbeing impacts of biofuels are not reported following the constituents of human wellbeing defined in the MA framework. Furthermore in the case of biofuels the constituents of human wellbeing are interlinked. For example, food (a provisioning service) affects virtually all of the MA constituents of human wellbeing. In order to overcome these challenges we identify the main impacts of biofuels on human wellbeing as reported in the academic literature:

- Rural development (Section 5.1).
- Energy security and access to energy (Section 5.2).
- Food security and access to food (Section 5.3).
- Health (Section 5.4).
- Land tenure (Section 5.5).
- Gender issues (Section 5.6).

We then proceed in each of these sections to discuss which of the MA constituents of human wellbeing are directly[6] impacted and through which mechanisms. This information is also briefly summarized in Section 6 (Table 2).

3. Direct and indirect drivers of ecosystem change related to biofuel production/use

Energy security, climate change mitigation, foreign exchange savings and rural development are commonly identified as justifications for biofuel expansion (Yan and Lin, 2009). In most cases energy security has been the overarching concern (e.g., China, India, Brazil, USA, EU), while in other cases trade balance and rural development have played much more significant roles, e.g., sub-Saharan Africa (Jumbe et al., 2009; Bekunda et al., 2009). While climate change mitigation concerns have been significant driving forces for biofuel expansion in some developed nations (e.g., EU) they have marginally, if at all, influenced developing nations to switch towards greater biofuel production and use (e.g., Zhou and Thomson, 2009).[7] As it is discussed throughout this paper biofuel production and use can affect ecosystems and human wellbeing. In this respect biofuel production and use is an agent of ecosystem change. This ecosystem change is a direct consequence of biofuel induced land use change, pollution, agricultural intensification, introduction of alien invasive species and biofuel production and combustion technology. Following the MA vocabulary we collectively refer to the above factors as the direct drivers of biofuel induced ecosystem change. Consequently the drivers of biofuel expansion itself (i.e., energy security, climate change mitigation, rural development) are perceived as the indirect drivers of biofuel induced ecosystem change (Table 1).

The biofuel lifecycle is rather complicated and includes several stages that range from feedstock production[8] to feedstock transport, biofuel production, biofuel distribution/storage/dispensing and biofuel combustion (Hess et al., 2009; Delucchi, 2006). The different processes adopted at each of these stages can impact ecosystems in differing degrees and can make the difference on whether biofuel production and use can be sustainable.

4. Impacts of biofuel production on ecosystem services and biodiversity

4.1. Provisioning services

4.1.1. Fuel

Liquid biofuels can be used as additives and in some cases they can substitute conventional transport fuels (IEA, 2004). Biofuels can also be used and for other purposes such as rural electrification (FAO, 2009). The two most common forms of liquid biofuels are bioethanol and biodiesel.

Brazil has been a leader in the introduction of biofuels as a transport fuel since the mid-1970s and its pro-Alcool programme. For several interconnected reasons the Brazilian experiment is deemed as an economic and energy security success[9] (e.g., Abramovay, 2008; Fischer et al., 2009) and several other countries are trying to emulate Brazil's success. Currently, a number of countries across the world have mandated the blending of biofuels in differing proportions in conventional transport fuel.

Bioethanol can be obtained from the fermentation of sugar or starch rich crops such as corn, sugarcane, cassava, sugar beet, wheat and molasses (Fischer et al., 2009). Bioethanol is by far the most widely produced biofuel on a global scale with most of it being produced in the US (from corn), Brazil (from sugarcane), China (from corn) and India (from molasses) (IEA, 2010b).

Biodiesel is produced through the transesterification of animal and vegetable fats (Fischer et al., 2009) with the most prevalent feedstocks including rapeseed, soybeans, sunflower seed, palm oil and Jatropha. Numerous other oilseeds are being or have the potential to be used as biodiesel feedstocks. Currently the biggest producer and consumer of biodiesel is the EU (mainly from rapeseed) while emerging players are Brazil (from soybeans), Argentina (from soybeans) and Malaysia/Indonesia (from palm oil). Currently there is also considerable attention in the production of biodiesel from Jatropha in India, China and several sub-Saharan nations. The main reasons behind this interest is Jatropha's small water requirement, ability to be cultivated in marginal lands and not direct

[6] Each of these issues affects indirectly all of the MA constituents of human wellbeing.

[7] One of the potential reasons is the fact that developing nations have been included in Annex A of the United Nations Framework Convention on Climate Change (UNFCCC) and as a result they are not currently bound to reduce their GHG emissions under the Kyoto Protocol.

[8] First generation biofuel feedstock production is essentially an agricultural activity which is in most cases based on monocultures.

[9] It goes without saying that sugarcane ethanol production in Brazil has also significant negative impacts which are discussed throughout this review.

competition with food production (e.g., Achten et al., 2008; Sano et al., 2011; FAO, 2010). In some cases Pure Plant Oil (PPO) from plants such Jatropha can be used as a fuel for transport, cooking and power generation (IEA, 2010a).

As mentioned in the Introduction a key consideration regarding the viability of biofuels is whether they provide net energy gains when compared with conventional fossil fuels. In particular the Energy Return On Investment (EROI) and the percent savings on fossil energy during a biofuel's whole life cycle are considered key indicators of the biofuel's viability. Life Cycle Analysis[10] (LCA) has been identified as the most appropriate tool to answer such questions (e.g., Menichetti and Otto, 2009; Hill et al., 2006; Zah et al., 2007).

An LCA meta-analysis conducted by Menichetti and Otto (2009) concludes that most current first generation biofuel production practices are net energy providers albeit in differing degrees. Another meta-analysis conducted by de Vries et al. (2010) shows that biofuel production from sugarcane (bioethanol), sweet sorghum (bioethanol) and oil palm (biodiesel) provided significant energy gain when compared to standard transport fuels. Biofuel from sugar beet (bioethanol), cassava (bioethanol), rapeseed (biodiesel) and soybean (biodiesel) had the next highest energy gains while biofuel from corn (bioethanol) and wheat (bioethanol) exhibited the lowest energy gains (de Vries et al., 2010). Finally a comparative LCA study has ranked different biodiesel production chains according to their use of non-renewable energy (Panichelli et al., 2009). The order in decreasing energy consumption is soybean (Argentina), soybean (Brazil), rapeseed (EU), rapeseed (Switzerland), palm oil (Malaysia) and soybeans (USA) (refer to the Supplementary Electronic Material for results of the main LCA studies and meta-analyses).

LCAs for Jatropha biodiesel have shown that this production chain is generally a net energy provider with the biodiesel production stage (transesterification) being the most energy demanding stage (Achten et al., 2008; Reinhardt et al., 2007). Even though Jatropha PPO can be used directly as a fuel without prior processing it is generally accepted that it is not as energy efficient when compared to Jatropha biodiesel while it can cause the combustion engine to malfunction. LCAs on the production and use of Jatropha PPO as a biofuel have shown significant net energy gains when compared with conventional fuels (e.g., Gmunder et al., 2010).

Considering these significant net-energy gains it can be concluded that several different first generation biofuel production practices can meet the "net-energy provision" criterion suggested by Hill et al. (2006) and as such be considered to be feasible energy options in the short-to-medium term. However, current practices rely greatly on fossil fuels for fertilizers and agrochemicals, so biofuels' long term viability following current production practices and technology is debatable. Additionally there are several other non-energy related concerns that need to be considered and are currently far from met as it is discussed in greater length throughout this review.

4.1.2. Food

As already mentioned most of the feedstocks used for first generation biofuel feedstocks are food crops. Indeed some of them are staple crops (e.g., corn, wheat), others are key vegetable oils (e.g., palm oil) while others such as sugarcane and soybeans are important components of the food industry. It has been suggested that biofuel expansion can compete with food production directly (e.g., food crops diverted for biofuel production) and indirectly (e.g., competition for land and agricultural labour).

Fischer et al. (2009) have calculated that as of 2007 1.6% of the cultivated land globally was being used for biofuel feedstock production. When disaggregated, approximately 5.0%, 3.1% and 2.4% of the cultivated area in N. America, S. America and Europe, respectively, was appropriated for biofuel production (Fischer et al., 2009). Simulations conducted by the same authors suggest that if 2020 biofuel penetration targets are to be met then biofuel production from cereals will disrupt significantly the production of food and feed particularly in developing nations. For such reasons, some countries have prohibited the use of food crops for biofuel purposes. India has prohibited the use of edible crops for biofuel production, promoting instead the use of molasses[11] and Jatropha (Zhou and Thomson, 2009). In a similar manner the main feedstock for production of bioethanol in China is low quality corn that is taken from the stockpiles (Zhou and Thomson, 2009).

Biofuel production might also compete with other provisioning services such as fiber and timber. For example Indian Jatropha plantations have been set up on communal land, displacing part of the poor's household needs for food, fuel wood, fodder and timber. Such products often make up the household's largest income source, larger than cash crops and informal cash incomes, and can range from 20 to 40% or more of total household income (Cavendish, 2000; Rajagopal, 2008; Dovie, 2003; Paumgarten and Shackleton, 2003).

4.1.3. Freshwater services

Biofuel production can affect freshwater ecosystem services through overexploitation and degradation (through pollution) (de Fraiture and Berndes, 2009). It is feared that increased feedstock cultivation and biofuel production will increase both water consumption and water pollution.

4.1.3.1. Water quantity. Currently the total water requirement for first generation biofuel production, particularly for irrigated feedstocks, is quite modest when compared to the water appropriated for food production (CA, 2007).[12] However biofuel expansion might result in increased water consumption (e.g., de Fraiture et al., 2008; Berndes, 2002). This might result in a competition between food and biofuel production not only for land and labour but for water as well. This might be potentially serious for countries such as China and India that have mandated the use of biofuels but are under increasing water stress (e.g., de Fraiture et al., 2008). For example, in India the national government currently allows the use of molasses for bioethanol production in order to avoid competition with food production. However, this process is water intensive and a shift towards greater biofuel production might affect the water supply in a country under proven water stress. At the same time the unpredictability of monsoons and droughts can in turn significantly affect the production of molasses that can be used for biofuel production (Agoramoorthy et al., 2009).

It has also been suggested that biofuel expansion might have significant impact on water consumption even in areas that are not currently facing significant water stress (NAP, 2010; Berndes, 2002). For example, embodied water analysis has shown that current bioethanol production practices in the US, such as extensive irrigation, already results in the depletion of vulnerable aquifers with these trends being most prevalent in states that are expected to face water shortages in the future (Chiu et al., 2009).

[10] Among several other unresolved methodological issues, LCA results are sensitive to the allocation methods used.

[11] Molasses can be edible but as a by-product of the sugarcane industry they are not considered edible by the Indian government (Ministry of New and Renewable Energy, undated: 6).

[12] In cases where the feedstocks are primarily rain fed (e.g. rapeseed in Europe, sugarcane in Brazil) then irrigation is even smaller (de Fraiture et al., 2008).

Interestingly, water footprint analysis[13] has shown that for most biofuel feedstocks the total water footprints are consistently larger in developing nations (Gerbens-Leenes et al., 2009a,b). At the same time the water footprint of biofuels[14] can be 70–400 times higher than that of conventional fossil fuels (Gerbens-Leenes et al., 2009b) while it is more water-efficient to use biomass to produce bioelectricity than to produce biofuels (Gerbens-Leenes et al., 2009a). In fact, the total water requirement of biofuel energy is consistently larger, up to two degrees of magnitude, than the water requirement of different forms of conventional energy generation (including hydropower) (Gerbens-Leenes et al., 2009a).

4.1.3.2. Water quality. Feedstock production relies greatly on fertilizers and agrochemicals that can enter water bodies and potentially disrupt ecosystem functioning. At the same time biofuel production practices can produce effluents with high toxicity and Biological Oxygen Demand (BOD).

Gunkel et al. (2007) have highlighted the significant impact of sugarcane production and processing on water quality (water heating, acidification, increased turbidity, oxygen imbalance, and increased coli form bacteria levels) in the Ipojuca River (Brazil). Filoso et al. (2003) have reported high nitrogen loading across rivers with sugarcane plantations in their catchment area. Indeed sugarcane cultivation consumes large amounts of fertilizers and constitutes one of the most fertilizer intensive agricultural practices in Brazil (FAO, 2004a). Martinelli and Filoso (2008) have identified sugarcane expansion as one of the main drivers of fertilizers use increase across Brazil. Similarly, oil palm plantations are also fertilizer intensive and consume by far the largest amount of fertilizers than any other crop in Malaysia (FAO, 2004b; FIAM, 2009) and the third largest in Indonesia (FAO, 2005). Donner and Kucharik (2008) suggest that if US maize production increases in order to meet the 15–36 billion gallons of renewable fuel by 2022, without changing current cultivation practices, then significant added nitrogen loading should be expected along the Mississippi river subsequently increasing hypoxia in the Gulf of Mexico.

In a similar manner Lehtonen (2009) collects evidence of the numerous agrochemicals that are being used in sugarcane agriculture and how they can affect the environment and human health while Lara et al. (2001) have shown the prevalence of agrochemicals in areas that are used for sugarcane cultivation. Martinelli and Filoso (2008) cite several case studies that associate sugarcane burning practices with the acidification of streams/rivers and the detection of Polycyclic Aromatic Hydrocarbons in sediments in lakes in Sao Paulo state.

The palm oil industry has also been identified as a major source of water pollution in Malaysia (Muyibi et al., 2008). Palm Oil Mill Effluent (POME) is characterized by high levels of BOD[15] with approximately 2.5–3 tones of POME being produced for each tone of palm oil (Wu et al., 2010). Effluent from sugarcane mills is also rich in BOD with 12–13 liters of vinasse being generated for each liter of ethanol (Martinelli and Filoso, 2008).

However, there is also evidence that biofuel production can sometimes be beneficial to freshwater ecosystem services. For example, some feedstocks can be used to purify wastewater (Börjesson and Berndes, 2006) and to restore contaminated aquifers and marginal lands (Gopalakrishnan et al., 2009). Finally, POME and sugar cane mill effluent can be used for oil palm and sugar cane irrigation, respectively, but the environmental co-benefits of such practices are debatable.

4.2. Regulating services

4.2.1. Climate regulation

Biofuels have been identified as potential climate change mitigation options (e.g., IPCC, 2007b). Even though biofuel production and use can emit significant amounts of GHGs during their whole lifecycle (Hess et al., 2009; Delucchi, 2006) several LCAs have shown (refer to Tables 1 and 2 in the supplementary electronic material) that biofuels can be emit less GHG than fossil fuels during their whole life cycle.

However, in most LCAs the impact of Land Use and Cover Change (LUCC) on the GHG emission is not properly accounted for. Biofuel expansion can induce direct and indirect LUCC. Considering that LUCC has been identified as a major source of GHG, biofuel production in general, and feedstock production in particular, can be net GHG emitters. For example, oil palm plantations are expected to be net carbon sinks and protect the soil only if they are established on crop/grassland and not on forested or peat land areas (Danielsen et al., 2009; Verwer et al., 2008). Danielsen et al. (2009) calculated that depending on the forest clearing method used, it would take 75–93 years for an oil palm plantation to compensate the carbon lost during the conversion of the initial forest and 600 years if that happens on peatland. On the other hand if that happens on grassland it could take 10 years. Fargione et al. (2008) report similar findings for palm biodiesel production from cleared tropical rainforest and peatland in Indonesia and Malaysia. In the Brazilian context, Fargione et al. (2008) calculate that the time required to repay the biofuel carbon debt would be 17 years (sugarcane substituting woodlands), 37 years (soybean substituting grassland) and 319 years (soybean substituting tropical rainforest). Gibbs et al. (2008) have calculated carbon payback times for several feedstocks in the tropics with their results showing that following present practices it will take decades to offset the carbon lost during the conversion of productive tropical ecosystems (forests, woody savannahs and grassland) in S. America, Africa and Asia.

Indirect land impacts can also affect significantly GHG emissions. Lapola et al. (2010) have calculated that by 2020 biofuel expansion in Brazil might create a carbon debt of up to 250 years mainly due to indirect LUCC (direct LUCC will also contribute but not significantly). In their model they suggest that, among other processes, the replacement of rangeland in the south of the country with sugarcane cultivation might push the rangeland frontier in the Amazon and cause significant deforestation (Lapola et al., 2010). It should be noted that the calculation of carbon payback time depends on several assumptions and as a result can be highly uncertain (Upham et al., 2009).

Biofuel production can also emit nitrous oxide (N_2O), another potent GHG, mainly through the use of fertilizer during feedstock cultivation (Menichetti and Otto, 2009). Even though N_2O emissions are routinely considered in biofuel LCAs, their inclusion is a major source of uncertainty given some unresolved methodological issues (Menichetti and Otto, 2009). For example, Crutzen et al. (2008) have suggested that the emission of N_2O during feedstock production might be 3–5 times greater than initially assumed in such LCAs, resulting in maize, sugracane and rapeseed biofuels having a considerably reduced climate cooling effect (or even a climate warming effect). Some of the methodological choices made by Crutzen et al. (2008) have been contested and updated calculations have shown that N_2O can contribute 10–80% of total GHG emissions during biofuel production with sugarcane ethanol, sugar beet bioethanol and palm oil biodiesel providing robust GHG sav-

[13] The water footprint is expressed in m^3 (of water consumed) per GJ (of energy produced) and depends on numerous factors such as the type of crop, the agricultural production system and the climate (Gerbens-Leenes et al., 2009b). However, even within the same country the water requirement of biofuel production can depend on other factors such as the regional water use practices (Chiu et al., 2009).

[14] The water used during the transformation of the feedstock into is much lower than the water consumed for the production of the feedstock itself (IATP, 2010).

[15] POME has a BOD of 21,500–24,500 mg/L which is several times higher than that of sewage water.

Table 2
Key sustainability issues associated with biofuel production, from an ecosystem services perspective.

Sustainability issue	Main ecosystem services	Main constituents of well-being
Energy security	Fuel (provisioning service)	Energy security (Security) Access to fuel, (Basic materials for good life)
Climate change	Climate change regulation (regulatory service)	Secure resource access and security from disasters (Security) Access to basic materials, e.g., sufficient nutritious food (Basic materials for a good life)
Economic development (rural development)	Fuel (provisioning service)	Security, Basic materials for a good life and Health
Food production	Food (provisioning service), Erosion regulation (regulatory service)	Sufficient and accessible nutritious food (Security, Basic materials for a good life, Health and Good social relationships)
Ecosystem conservation	Services from conserved ecosystems: pollination of crops and other vegetation (regulatory service), climate change regulation (regulatory service), timber and forest non timber products (provisioning services), aesthetic value (cultural service)	Basic materials for a good life, Good social relations
Water provision	Steady and clean water supply (provisioning)	Basic materials for a good life, Health, Good social relations
Health	Food (provisioning services), water (provisioning services), clean air (regulatory service)	Health
Social cohesion	Sufficient and equitable supply of ecosystem services (provisioning, regulatory, supporting and cultural)	Good social relations
Biodiversity decline	Biodiversity is not an ecosystem service per se but "*the foundation of ecosystem services to which human well-being is intimately linked*" (MA, 2005c: 18).	Security, Basic materials for good life, Health, Good social relations

ings (Smeets et al., 2009). On the other hand wheat ethanol, maize ethanol and rapeseed biodiesel can, under certain scenarios, produce up to 53%, 11% and 72% more GHGs than conventional fossil fuels (Smeets et al., 2009).

Finally, apart from GHG emission, biofuel expansion can affect regional climate through land cover conversion. Georgescu et al. (2009) have found that biofuel expansion in the US Corn Belt might affect regional climate as a result of conversion of land cover from one crop type to another and the associated changes in energy and moisture balance of the surface upon conversion to biofuel crops.

4.2.2. *Air quality regulation*

Atmospheric pollutants are emitted from several processes during the biofuel's life cycle. Feedstock cultivation can be a particularly polluting due to fertilizers use, land-clearing through fire, other feedstock-specific activities such as sugar-cane burning (to assist harvesting) and the feedstock itself.

Biofuel feedstocks, like all other plants, are emitters of Volatile Organic Compounds (VOCs), isoprene in particular. Even though there is limited knowledge regarding VOC emissions from biofuel feedstock, there is a concern that biofuel expansion, especially from tree plantations such as oil palm, might result in greater VOC emissions (Royal Society, 2008; Hewitt et al., 2009). Hewitt et al. (2009) have shown that indeed VOC and nitrogen oxides (NOx) emissions, which are tropospheric ozone precursors (O_3), are greater from oil palm plantations than from primary rainforest. NOx are mainly emitted mainly through the application of fertilizers and combustion in farm activities, such as mechanized agriculture (Hess et al., 2009).

Martinelli et al. (2002) have identified sugar cane burning[16] as a major source particulate matter with aerodynamic diameter <2.5 μm (PM2.5) and <10 μm (PM10) (Cancado et al., 2006; Lara et al., 2005; Martinelli et al., 2002; Castanho and Artaxo, 2001), Polycyclic Aromatic Hydrocarbons (PAHs) (Martinelli and Filoso, 2008) and NOx (Oppenheimer et al., 2004). Sometimes the land that is used for feedstock production, particularly for oil palm cultivation, is cleared through the use of fire (e.g., van der Werf et al., 2008). Biomass burning has been identified as a major source of atmospheric pollution and GHGs, thus affecting significantly atmospheric chemistry and biogeochemical cycles among other impacts (Bytnerowicz et al., 2009; Crutzen and Andreae, 1990).

Delucchi (2006) has found out that US maize ethanol and soy biodiesel have higher carbon monoxide (CO), nitrogen dioxide (NO_2), non methane organic compound (NMOC), sulphur dioxide (SO_2) and particulate matter (PM) emissions during the whole lifecycle of the fuel when compared to conventional gasoline. In particular fuel production, feedstock recovery, cultivation and fertilizer manufacture were the processes that were identified as those processes responsible for the bulk of the pollutant emission.

However biofuels can have positive impacts on ambient air quality. For example the introduction of biofuels in Brazil has been partly credited for the improvement of air quality in the city of Sao Paulo (Goldemberg, 2008). The rapid introduction of cars which run on ethanol (flex-fuel vehicles) since 2003 has led to the gradual dephasing of older more polluting and less energy efficient vehicles. In this respect biofuel introduction as an alternative transport fuel can be viewed as a potential opportunity for the introduction of cleaner technology, something that can have ripple effects on ambient air quality, particularly in cities situated in the developing world (IEA, 2004).

4.2.3. *Erosion control*

In order of decreasing soil erosion hazard[17] de Vries et al. (2010) ranked the most commonly used feedstocks as follows: cassava, soybean, sugarcane, sorghum, corn, sugar beet, winter wheat, oil palm and winter rapeseed. Martinelli and Filoso (2008), mention that sugarcane cultivation is a significant driver of soil erosion in Brazil. In fact in several areas of the state of Sao Paulo high erosion rates have been observed in land that is consistently under sugarcane cultivation (Martinelli and Filoso, 2008). Soybean cultivation for biodiesel in Argentina exhibits greater soil erosion potential and greater negative effect on soil nutrients than switchgrass (van Dam

[16] Sugarcane burning assists harvesting and about 80% of the sugarcane crops in Brazil are burned for this purpose each year.

[17] This is an indicative ranking that can depend on the characteristics of the soil itself and the cultivation method adopted among other factors.

et al., 2009). Soil erosion potential is further increased if soybean is cultivated at degraded grassland rather than abandoned cropland (ibid). Valentin et al. (2008) suggest that if a biofuel-driven expansion of maize and cassava production takes place into already degraded upland agricultural systems in S.E. Asia then an increased risk of higher runoff and sediment generation is to be expected.

On the other hand feedstocks that can be grown in marginal lands, such as Jatropha, can improve soil quality and control erosion in marginal lands (Achten et al., 2008; Gmunder et al., 2010). It is interesting to note that agricultural practices such as sugarcane burning which can have been associated with negative effects on ambient air quality and human health can reduce the risk of erosion if the residues are left on the soil (Smeets et al., 2008).

4.3. Cultural services

Ecosystems provide cultural services (e.g., spiritual, aesthetic, educational and recreational services) which are sometimes highly valued in monetary terms (MA, 2005a). For local communities and indigenous people such services frequently form an important element of their culture and can be threatened by several factors such as LUCC (MA, 2005a). Sometimes, maintaining the traditional land use and the local customs is often held more important than material gains even in industrialised countries (e.g., Raish and McSweeney, 2003). At the same time, certain plants are important ceremonial elements while high biodiversity agriculture (e.g., for maize) can have important aesthetic and cultural value that cannot be provided by monoculture cropping systems (MA, 2005a).

Changes in ecosystem conditions can alter the values that people derive from cultural ecosystem services (Rodriguez et al., 2006). Even though in some occasions ecosystem change may increase cultural value[18], it is most likely that the opposite phenomenon might occur. Biofuel induced LUCC may diminish the cultural value people receive from landscapes and ecosystems, by destroying habitat and displacing traditional crops (Friends of the Earth, 2008). Feedstocks, such as oil palm, are frequently planted on forest land and as a result often cause deforestation (refer to Section 4.4). It has been suggested that biofuel induced deforestation can affect indigenous people disproportionately. For example, almost half of Indonesia's population depends on ecosystem goods and services from forests with approximately 40 million of these people being indigenous and having been already affected (Tauli-Corpuz and Tamang, 2007).

Several biofuel feedstocks are associated with invasive behaviour, refer to Section 4.4. However, invasive plant species may eliminate traditional plant species with high cultural value, with potentially severe impacts especially for the poor in tropical countries (MA, 2005b).

Finally, marginal lands have been targeted as the most appropriate areas for producing biofuels in a sustainable manner. Economically, land is marginal if it is not profitable, e.g., when crop prices and yield do not cover production cost (Dale et al., 2010). However, marginal land often provides other ecosystem services including space for politically and economically marginalized populations with the cultural and spiritual values derived from the land not always being acknowledged when assessing the costs and benefits of biofuel production (Dale et al., 2010).

4.4. Biodiversity

Biofuel production (feedstock cultivation in particular) is considered a potentially significant emerging threat to biodiversity (Groom et al., 2008). Six main direct drivers of biodiversity loss have been identified in the academic literature; habitat destruction, overexploitation, invasive species, disease, pollution and climate change (MA, 2005a). Biofuel production has been linked to four of these drivers namely habitat destruction, invasive species, pollution and climate change. The impact of biofuel production on pollution (Sections 4.1.3 and 4.2.2) and the climate (Section 4.2.1) have already been discussed.

Of these four drivers, biofuel induced habitat destruction is considered as perhaps the most important threat to biodiversity. Generally speaking the magnitude of biodiversity loss depends on the type of land that was converted for feedstock production. The conversion of natural ecosystems (e.g., grassland, forest) results in higher levels of biodiversity loss when compared to the conversion of cultivated land (Fischer et al., 2009). However, with the exception of oil palm agriculture, very few biodiversity loss assessments have been conducted for biofuel feedstocks.

Oil palm plantations are believed to have a significant impact on biodiversity in a region that contains a significant portion of the planet's remaining tropical forests as well as two of the world's twenty five biodiversity hotspots.[19] Koh and Wilcove (2008), report that oil palm plantations in Malaysia and Indonesia have mainly replaced primary and secondary tropical forest rather than pre-existing cropland. According to their calculations 55–59% of oil palm expansion in Malaysia and at least 56% in Indonesia occurred at the expense of primary forest. Reviews of academic studies have shown that indeed oil palm plantations contain much fewer species than primary forests (e.g., Fitzherbert et al., 2008; Danielsen et al., 2009). For example, oil palm plantations harbor fewer bird (Peh et al., 2005) and butterfly species (Hamer et al., 2003; Dumbrell and Hill, 2005) than primary forest, logged forest and rubber plantations.[20] In most studies it was found that the majority of the forest species was lost and replaced by smaller numbers of nonforest species. More importantly the subsequent animal communities were dominated by a few generalist species of low conservation value (Danielsen et al., 2009). It is hypothesized that biodiversity loss in oil palm plantations happens because such habitats are structurally less complex than primary forests, have a shorter life span[21] and are major landscape fragmentation factors (Fitzherbert et al., 2008).

Martinelli and Filoso (2008) cite several cases that show how the destruction of riparian ecosystems due to their conversion to sugarcane plantations can decrease biodiversity. Interestingly the destruction of such riparian ecosystems results in reduced water quality that can further affect biodiversity and human wellbeing (Martinelli and Filoso, 2008). However it is the future biofuel expansion in Brazil (the combined effect of sugarcane, soybean and oil palm expansion) that can pose an even more significant threat to biodiversity through direct and indirect LUCC effects in the Cerrado (Smeets et al., 2008; Sparovek et al., 2007) and the Amazon (Lapola et al., 2010).

In a similar manner the EU biofuel mandates are expected to result in cropland expansion throughout the world and particularly within the EU, Brazil and sub-Saharan Africa (Britz and Hertel, in press). Hellmann and Verburg (2010) have shown that this biofuel expansion can significantly impact biodiversity throughout Europe by 2030 mainly due to indirect LUCC. McDonald et al. (2009) have estimated under several different scenarios that bioenergy, particularly biodiesel from soybeans and ethanol from maize/sugarcane, will consistently have the largest impact on LUCC in the US by 2030.

[18] e.g. as exhibited in high land rents surrounding in areas built environment projects (MA, 2003; Peterson et al., 2003).

[19] Sundaland and Wallacea as designated by Conservation International.

[20] For a summary of the results of the meta-analysis conducted by Danielsen et al. (2009) refer to the Supplementary Electronic Material.

[21] Oil palm plantations are usually cleared and replanted every 25–30 years (Fitzherbert et al., 2008).

Most of this new area will be directly claimed in temperate forest (deciduous and conifers) and temperate grassland and will amount between 141,000 km^2 and 247,000 km^2 having significant impacts on biodiversity (McDonald et al., 2009).

In some cases LUCC impacts on biodiversity have been associated with the cultivation method adopted with monocultural systems deemed as particularly harmful to biodiversity (e.g., Groom et al., 2008; Tilman et al., 2006). It has been suggested that feedstock cultivation methods that do not rely on extensive monoculture (e.g., Tilman et al., 2006) or that employ land sparing and wildlife-friendly farming techniques (e.g. Koh et al., 2009) can have a lower negative impact on biodiversity.

Finally, there are fears that certain biofuel crops might end up becoming invasive. Currently the feedstocks that are mostly associated with invasiveness are Jatropha in certain parts of Australia (FAO, 2010) and perennial grasses (Pyke et al., 2008; Raghu et al., 2006; Buddenhagen et al., 2009).

5. Human wellbeing

5.1. Rural development

One of the main drivers of biofuel production in developed and developing nations alike is rural development. In macroeconomic terms the production of feedstock and biofuel can contribute to rural employment and rural income creation. In this respect biofuels can contribute significantly to all aspects of human wellbeing as designated by the MA[22] and be an agent of poverty alleviation.

Biofuel policies often aim to promote rural development by supporting rural employment.[23] This is often achieved by addressing the issue of crop overproduction and idle production capacity (Dillon et al., 2008; Javier, 2008). For example, the Philippines biofuel program is planned to target sugarcane in order to make use of idle production capacity in sugar distilleries (Javier, 2008). Brazil, Malaysia and Indonesia currently have substantial and highly competitive biofuel feedstock production sectors which is a legacy of their plantation crops industry (sugarcane and oil palm, respectively). In these countries the biofuel industry has contributed significantly to income and employment creation, not least through the recent boom in the prices of these crops. While biofuel manufacturing/processing/distribution directly employed only around 1000 people in Indonesia (Dillon et al., 2008) it is believed that in 2001 up to 4.5 million Indonesians depend on the country's palm oil industry, including palm oil for biofuel feedstock (Sargeant, 2001). This includes employees and family dependants in downstream processing and associated services. In fact it has been suggested that the Indonesian biodiesel production alone could provide 2.5 m jobs over the coming few years (Cassman and Liska, 2007; Sargeant, 2001). Biofuel production can contribute to rural employment in industrialised countries as well. By 2006 approximately 100 corn ethanol plants existed in the US. These plants are often located in rural areas as a means of addressing depopulation and supporting local economies. Parcell and Westhoff (2006) estimated that one plant generates 54 direct jobs in biofuel distillation and 210 indirect jobs. However, it should be noted that the academic literature often fails to assess the net contribution of feedstock cultivation to employment, as compared to other types of agricultural production with similar labour intensity (Rajagopal, 2008).

Apart from employment opportunities, feedstock production can prove to be a profitable activity in its own right. It has been suggested that higher prices on agricultural commodities would benefit developing countries by increasing the profitability for farmers and thus increase their income (OECD, 2008). Farmers, plantation owners and exporters are expected to gain from such high prices while processors and net food purchasers further downstream are expected to be negatively affected (Dillon et al., 2008). Smeets et al. (2008) mention that the average salary in sugarcane agriculture in Sao Paulo state is generally higher when compared to the production of other crops. The same applies to the ethanol industry when compared with other industries in the state (Smeets et al., 2008). However even though in most cases the offered wage for sugarcane cutters is above the minimum wage mandated by the government it is still not high enough to escape the poverty level (e.g., Martinelli and Filoso, 2008).

However, the direct effect of higher feedstock prices on human wellbeing is not necessarily positive for everybody. For example higher feedstock prices can drive up food prices, e.g., for sugar, grains and vegetable oils, hence increasing households' living expenditures (OECD, 2008). The biofuel programs in Brazil, US and increasingly in China are predicted to further affect international corn and sugar prices (Koizumi, 2009; Koizumi and Ohga, 2009). Higher food prices might significantly affect human wellbeing negatively as it will be discussed in more depth in Section 5.3.

The positive or negative impact of biofuel production (and its magnitude) on employment and income depends greatly on the kind of biofuel production system adopted. Arndt et al. (2010a) assessed Mozambique's planned biofuel program using a general equilibrium simulation and found that the GDP positive effect would be higher if an outgrower approach with decentralised small production units (rather than large scale plantations) is adopted. This was also confirmed for the Tanzanian biofuel program (Arndt et al., 2010b). In the Mozambique study the program could contribute up to 0.6% of the GDP and even accounting for some food displacement effects, the program could reduce poverty incidence by approximately 6% over a 12-year phase-in period. The advantage of the outgrower approach is explained by the greater use of unskilled labour and the fact that land rents are appropriated by smallholders rather than plantation owners. In particular, the outgrower approach causes more evenly distributed income while it is more likely to provide technology spillovers (Arndt et al., 2010a).

However, the nature of biofuel production favours economies of scale, and without specific intervention smallholders find it difficult to compete with large scale plantations (Royal Society, 2008). High production costs, such as technology and seed, is another reason that smallholders may have difficulty to compete. One extreme example is the case of genetically modified crops where one company alone controls 33% for genetically modified soybean seeds, hence having a large influence on the price formation of these seeds (FAO, 2002a).

Additionally, often the negotiation power of small holders is low due to asymmetric information and transaction costs restricting market access. As a result, land owners and actors further down the production chain are likely to capture the rents from higher world market prices on crops, while farmers may not benefit (Taheripour and Tyner, 2007). For example during the high commodity prices in 2007 farmers in Kenya gained very little from the increased food prices while for African farmers the negative effect from high food prices is likely to outweigh the benefits of potentially higher sales price of agricultural commodities (Wodon and Zaman, 2008; Hoffler and Owour Ochieng, 2008).

In fact, shifting to biofuel feedstock production can be a risky endeavour particularly for small holders. High market and production chain uncertainty makes biofuel production risky, exposing farmers to the financial risk of not getting adequate returns on their investment. During the past decade price volatility has increased for

[22] i.e. security, basic materials for good life, health and social cohesion.

[23] Smeets et al. (2008) distinguish between three types of impacts of biofuel policies on employment; direct, indirect and induced.

food commodities while adding the generally high volatile nature of energy markets in the equation can make decision regarding a shift towards biofuel production more difficult to handle particularly for small producers (Woods, 2006; Robles et al., 2009). Additionally, the 2007 food crisis diminished worldwide stocks of agricultural commodities hence making them more exposed to supply and demand shocks from, for example, unfavourable weather (Wright, 2009). Furthermore, production risks stem from the fact that new knowledge about the yield performance of certain feedstocks is still emerging while in some cases the farmers might be altogether missing the necessary knowledge for cultivating their feedstock, e.g., Jatropha in rural India (Agoramoorthy et al., 2009). Additionally, infrastructure and marketing channels may cause production risks due to the production chain being vulnerable to interruptions. For example, transport interruption and capacity constraints of palm oil plants have in some cases resulted in the harvested crops perishing before being processed, causing subsequent income loss to small scale farmers in parts of Africa (FAO, 2002b).

With the exception of Brazil, biofuel programs in most countries are supported by subsidies (GSI, 2011; OECD, 2008). When subsidies are used to enable the biofuel programs, the opportunity cost of these fiscal resources should be assessed. For example, subsidizing biofuel programs is sometimes held to be the most cost effective way to achieve energy security when compared to subsidizing programs on other fuel supplies (or of facing the risk of unsteady supply and price of imported fossil fuel). When rural development is a goal of the biofuel program, then the cost effectiveness of the program needs to be compared to other means of fighting poverty or creating employment. In this respect subsidies can have a positive or negative net effect on human wellbeing and significant attention should be paid by policy makers when adopting biofuel strategies based on subsidies. In fact, while the production of biofuel feedstock is economically viable if corresponding food feedstock prices are high enough, the step from feedstock to ready-to-use biofuel is in general not cost competitive when compared with its market substitute, fossil fuels. While subsidised programs may generate employment and income, it is not clear to what extent they contribute to net public welfare. However, from a public welfare point of view, biofuel programs should account for the opportunity cost of subsidies that could have been used for other measures, such as direct investment in rural development (OECD, 2008).

For example, in 2006, biofuel subsidies in the US, EU and Canada amounted to USD 11 billion per year and are expected to increase to USD 25 billion per year in the 2013–2017 period (OECD, 2008). Rajagopal et al. (2007) conducted a simple welfare analysis of the direct effects of the US biofuel subsidies for maize ethanol. Excluding environmental and other long term effects, they found that in the short term the US biofuel subsidies paid out, by benefitting fuel consumers through lower fuel prices. However, other studies have found that the US biofuel subsidies have highly negative welfare effects (e.g., de Gorter and Just, 2010). Kretschmer et al. (2009) used a general equilibrium simulation of EU's 2020 biofuel target. Taking into account feed-in effects of the program across various economic sectors, they found it unlikely to reach the target without substantial subsidies being added to the program. The program was estimated to increase European agricultural prices by 7%, and would benefit EU farmers selling such products. The same source found that world commodity prices would likely be further affected as other countries increase their renewable energy targets.

In 2008 Indonesia subsidised its biofuel sector with USD 40 million excluding infrastructure investments (Dillon et al., 2008). However there is some evidence that biofuel subsidies may worsen income distribution in the country. For example, in Indonesia 60% of the highest income Indonesians received 83% of subsidies for fuel (gasoline and biofuels), while 40% of the lowest income group received only 17% (Dillon et al., 2008).

Finally, the net contribution of biofuels to income and employment depends on among other the opportunity cost in terms of foregone alternative uses of land, technology, labour and capital, both in the short and long term. This trade off in the use of productive resources is often not highlighted in the literature, and it is both dynamic (with differentiated impact across time) and with distributional consequences (with differentiated impact across countries, economic sectors and population groups).

There is also a growing body of literature that indicates how small scale biofuel initiatives can contribute positively to human wellbeing through better access to energy, capacity building, poverty reduction and rural development (e.g., FAO, 2009; Energia, 2009). Examples of small scale initiatives include rural electrification in Mali, Cambodia, Uganda and India (from Jatropha), biodiesel water pumping/irrigation in India and Nepal (from Jatropha and other local underutilized seeds) and biodiesel production in Guatemala, Thailand and South Africa (from Jatropha, sunflower seeds and soya).

It is sometimes perceived that biofuel expansion on forested land will be economically beneficial. However, while this may be the case at the macro level (when excluding environmental externalities) it is not always the case at the local level. In a recent study, Rodrigues et al. (2009) found some counterevidence to this assumption, in a cross sectional analysis of 286 Brazilian municipalities. It was shown that deforestation causes a boom and bust pattern: deforestation was initially associated with increases in several indicators of rural development (Human Development Index, literacy, standard of living and life expectancy) followed by a decrease to approximately the initial levels in these indicators. This may be a result of initial increases in income due to mechanization of agriculture and land use by newly arrived immigrants which are nullified by the subsequent exhaustion of the natural resources (causing declining land productivity), increasing population pressure.[24]

5.2. *Energy security and access to energy resources*

Fuel provided by biofuels impact directly two of the MA constituents of human wellbeing: security (energy security) and basic materials for a good life (access to energy). These impacts can be observed in different spatial scales (national vs. local).

5.2.1. *National level*

As it has been discussed earlier energy security is one of the main driving forces of biofuel production in several areas of the world. In fact numerous countries seem to have initiated their biofuel programs as a response to fears over energy security.

First generation biofuels that are net energy providers (refer to Section 3.1.1) can provide a dependable and renewable energy source. Brazil is such an example where bioethanol from sugarcane constitutes a significant fraction of all the transport fuel consumed in the country in part due to its significant energy gains (IEA, 2010b). However, biofuels can also promote energy even in cases where they do not provide a net energy gain. For example, Khatiwada and Silveira (2009) report the case of molasses-based bioethanol in Nepal which is not a net energy provider. However, given that the non-renewable energy used for the production of the biofuel comprises only about 8.3% of the total energy used it has been suggested that bioethanol can be used as a transport fuel in Nepal given the abundance of the required renewable resources. The pro-biofuel argument in that case has to do with the economic burden that fossil fuel import entails in the national economy.

[24] However, that study did not fully adjust for population size.

5.2.2. Local level

Biofuel may also contribute to local energy security. For example the Indonesian government has committed to promote energy security in the country through the Energy Self-Sufficient Villages (ESSV) programme. This programme aims to create the capability in 1000 villages to meet their own energy demand from locally available renewable resources such as biofuels, hydropower and wind energy (Kusdiana and Saptono, 2008). Biofuel based energy solutions are one of the main avenues explored with several different feedstocks being explored, i.e., Jatropha, coconut, oil palm, cassava and sugarcane (Kusdiana and Saptono, 2008). FAO (2009) also collects a number of cases in Africa, Asia and Latin America where energy security at the local level (usually the village level) was improved through small scale biofuel projects.

Access to liquid biofuel for rural households can contribute to energy security in the household level and as such have a ripple effect on poverty alleviation. It is standard practice in some of the least developed countries for people to source their energy from fuel wood collected by them. This activity carries a high shadow cost in terms of time and energy invested (Ewing and Msangi, 2009). The contribution of liquid biofuels on energy is especially high when transport costs of imported fossil fuel are high, such as in landlocked countries or when road infrastructure is poorly developed (Kojima and Johnson, 2005).

5.3. Food security and access to food

Several studies suggest that biofuel expansion competes and will increasingly compete directly and indirectly in the future with food production. A manifestation of this competition is the increase of food prices. While the impact of food price increases for rural development was discussed in Section 5.1, this section focuses specifically on the impact of food prices at the national and household level.

Food price increases can affect all aspects of human wellbeing as designated by the MA (i.e., security, basic materials for good life, health and social cohesion) and a key question is how the welfare effects of higher food and feedstock prices are distributed among small and large scale production units, and between net producers and net consumers of those crops (Ewing and Msangi, 2009).

Increased biofuel demand and production, particularly in the US and the EU, has indeed been identified as one of the main interconnected reasons behind the sharp increase of food commodities prices since 2002 (Mitchell, 2008; RFA, 2008). High food prices were most dramatically witnessed during the 2007 food crisis and even though the exact mechanisms of how biofuels affect food prices cannot be easily delineated, it is believed that biofuel subsidies in developed countries, globalised trade, speculation and high fossil fuel prices play significant roles (Runge and Senauer, 2008; RFA, 2008; Mitchell, 2008). Various sources have estimated that biofuels might have contributed up to 30% of the weighted average increase of cereal prices between 2000–2007 while it is expected that biofuels will continue to affect food prices (von Braun et al., 2008; OECD, 2008; Rosegrant, 2008; Kretschmer et al., 2009; Fabiosa et al., 2009). At the same time high feedstock prices can affect negatively biofuels production in its own right. For example, de Fraiture et al. (2008) cite studies in the US and China which show how the increases in corn price are linked to increased bioethanol demand in the former case (US) and have resulted in a decrease in the bioethanol production targets in the latter case (China).

Many developing countries are net food importers, especially in Sub-Saharan Africa. These countries may face hardship due to higher food and biofuel prices (FAO, 2002a). For example, the national economies of low income and food deficit countries[25] have already experienced falls of greater than 1% in their economic activity with a 10% increase in food prices (RFA, 2008). Higher biofuel prices may also divert agricultural production originally serving domestic food demand to export markets resulting in food shortages and malnutrition (Ewing and Msangi, 2009). Msangi et al. (2008) estimate that calorie intake in Sub-Saharan Africa may decrease by 11% by 2020, as a consequence of the food-biofuel competition. A global modeling exercise concluded by IIASA concluded that biofuels can have a significant negative impact on access to food by 2020. In particular it was projected that if first generation biofuels are to constitute 2%, 4% or 6% of transport fuel then cereal price increases in the order of 5%, 20% and 34%, respectively, are to be expected by 2020 (Fischer et al., 2009). This might increase the number of people (mostly in developing countries) at risk of hunger by an additional 140 million people (Fischer et al., 2009). The stress is set to increase after that year, due to the climate change effect on cropland and increasing demand (e.g., RFA, 2008; Stromberg et al., 2009).

Despite these macro-scale effects the food-biofuel competition can have significant impacts at the household level. First of all, like every type of market integration biofuels cause market dependence in the sense that households that switch from subsistence food production to biofuel feedstock production become dependent on international commodity markets. As a consequence such households can potentially get negatively affected by feedstock price increases in the sense that they are not compensated by a larger increase in the prices they receive from middlemen (Agoramoorthy et al., 2009). The sources and type of food can indeed be such that increasing fuel prices, and their indirect effects on, for example, fertilizer prices, can have a larger effect on poverty than increasing food prices, as shown in an economic simulation of the Mozambique biofuel program (Arndt et al., 2010a).

While subsistence farmers may not be directly affected by changes in international commodity prices, poor people in food deficit developing nations are considered as particularly vulnerable considering that they use a very large fraction of their income on food (e.g., Runge and Senauer, 2008). People in such countries often spend 50% of their income on food with Sub-Saharan Africa being the region with the highest household food expenditure share. For example, the average Ghanaian household spends 67% of its income on food, while Rwandan households spend 86% (Ahmed et al., 2007; von Braun, 2008). Generally speaking the food security of poor urban net buyers of food can be particularly threatened from biofuel induced high food prices (Wodon and Zaman, 2008). For example, survey data from Uganda has indicated that urban households have significantly higher food expenditures in absolute terms than do rural households (Maltsoglou, 2007). RFA (2008) suggests that biofuels induced food price increases can significantly affect the economic wellbeing urban poor (e.g., predicting a 2% poverty increase in Nicaragua), but are expected to be a much less significant determinants of economic wellbeing in the longer term. However, data from 73 developing countries show that while for most countries it would cost 0.1% of GDP to eliminate the part of urban poverty caused by the rising food prices since 2005 for some countries (e.g., Nigeria, Nicaragua, Haiti) it could cost more than 3% of GDP (Dessus et al., 2008).

It should be noted that the highest increases in food prices was most strongly experienced in developing nations and could be a driver of social unrest as manifested by food riots in countries such as Egypt, Mexico, Indonesia and several Sub-Saharan African nations (Runge and Senauer, 2008).

[25] e.g. Armenia, Egypt, Haiti, Honduras, Mongolia, and several Sub-Saharan countries (RFA, 2008).

5.4. Health

In the previous section it was discussed how biofuels can be an agent of malnutrition (e.g., Ewing and Msangi, 2009; Fischer et al., 2009). Malnutrition is considered as one of the most leading threats on human health globally.

Atmospheric emissions associated biofuel production and combustion can also severely affect human health. For example, Jacobson (2007) suggests that if E85 was to substitute conventional gasoline by 2020, the tropospheric ozone-related mortality and other health effects associated with the direct atmospheric emissions of bioethanol will increase by 9% in Los Angeles and by 4% in the rest of the US. Hill et al. (2009) have shown that the health related costs associated with the emission of M2.5, a potent health hazard, from maize-ethanol during its whole life-cycle is comparable and in most cases greater than the costs associated with PM2.5 emissions from conventional gasoline.[26]

It has been shown that respiratory related hospital admissions are increasing during the sugarcane burning season in parts of Brazil (e.g., Cancado et al., 2006; Uriarte et al., 2009). These trends are more evident for children with two to three times more hospital admissions during the burning season. As already mentioned land clearing by fire is a common method used in oil palm plantations in S.E. Asia. The forest fire induced air pollution health effects in S.E. Asia have been thoroughly documented in the academic literature, (e.g., Frankenberg et al., 2005; Sastry, 2002; Emmanuel, 2000). Finally, particulate matter and mites released during the storage, moving, drying and cleaning of soybeans in the Argentinean context is also associated with negative health impacts (Lerda et al., 2001 as cited in Tomei and Upham, 2009).

Human health can also be affected by pesticides and other agrochemicals that are used during feedstock production. Lehtonen (2009) cites a number of acute and chronic symptoms associated with short-term and long-term exposure to pesticides and tracked studies where bad practices in the application of pesticides in intensive sugarcane cultivation areas in Brazil have resulted in water and soil contamination. Smeets et al. (2008) provides evidence of poisoning and death due to bad pesticide application practices in sugarcane farming while Martinelli and Filoso (2008) have identified banned agrochemicals associated with biofuel sugarcane production in sediments and fish in the Piracibaba River (Sao Paulo state). Tomei and Upham (2009) report that agrochemicals associated with biofuel feedstock production are frequently applied too close to rural communities in Argentina, causing negative possibly causing cancer, respiratory illnesses and foetal abnormalities.

In some occasions the feedstock itself can be harmful to human health. The toxicity of Jatropha's seeds, oils and products (e.g., seed oil cake) have been highlighted as potential health threats and caution has been suggested during the production and use of such biofuels particularly in enclosed spaces (Achten et al., 2008).

Finally the manual and intensive nature of manual jobs associated with feedstock production in some parts of the world can also impact health in a negative manner. Martinelli and Filoso (2008) collect numerous studies that have reported the health effects on sugarcane cutters leading on several occasions to death.

5.5. Land tenure and displacement

In a number of cases the access of poor people on land has been compromised due to biofuel expansion. Some such 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/lack of information in Indonesia and even aggressive land seizures in Colombia (Cotula et al., 2008). On the other hand Smeets et al. (2008) attribute the apparent lack of land tenure conflicts in Sao Paulo state in the prior consolidation of the industry with the land owned by a few large land owners.

Another example is the case of Jatropha plantations in India that have been set up on communal land, displacing part of the poor's household needs for food, fuel wood, fodder and timber. Agoramoorthy et al. (2009) suggest that the aggressive approach of the Indian government and the biofuel industry towards Jagtropha may displace millions of poor rural farmers.

Africa has received much interest lately from foreign governments and firms, for leasing land for different uses, including feedstock production. For example, China's has acquired the right to grow 2.8 million hectares with oil palm in the Congo and 2 million hectares in Zambia (The Economist, 2009). There are even cases in which foreign interests are leasing land from governments in drought struck countries such as Ethiopia and Sudan, sometimes even using foreign labour thus leaving as the only benefit the hope that the land rent is invested in welfare enhancing projects. In Sudan, a net receiver of food aid, 70% of the crops produced by foreign interests is exported (The Economist, 2009).

Eliminating ecosystem services can affect the well-being of people and can be an agent of social conflict. An example of this are oil palm plantations established without a recognition of the traditional land borders, rights and interests (WWF, 2006). In Indonesia, logging companies and plantations owners have displaced indigenous people when establishing new oil palm plantations (USAID, 2009).

5.6. Gender issues

It is interesting to note that the negative effects of biofuel production on human wellbeing might not be proportionate between genders. Araujo and Quesada-Aguilar (2007) make the case that biofuel initiatives have the potential to benefit women but if gender considerations are left out when planning biofuel policies then the livelihoods of women and their families might be threatened.

Rossi and Lambrou (2008) discuss several potential risks of first generation biofuel expansion in developing regions such as Brazil, India and Sub-Saharan Africa suggesting that in several occasions these risks are gender-differentiated with women being more likely to face the negative socioeconomic and environmental impacts associated with biofuel expansion. For example evidence suggests that when food prices rose in Indonesia (partly due to biofuel expansion, refer to Section 5.3) mothers in poor families decreased their food intake in order to feed their children (Actionaid, 2010).

Nevertheless there are also cases where both small and large scale biofuel initiatives have contributed significantly to the wellbeing of women (e.g., Energia, 2009; FAO, 2009). Actually understanding the net welfare contribution of biofuels across genders can be very complicated. Very little research has been conducted to understand the trade-offs of increasing women's participation on biofuel production. Arndt et al. (2010c) have shown that significant trade-offs are to be expected if women are more actively involved in feedstock production in Mozambique. Increasing women's participation is not expected to affect overall economic growth in the country (also see Arndt et al., 2010a) but it is expected to curb the effects of biofuel production on poverty alleviation as a result of higher food prices (Arndt et al., 2010c).

[26] Costs from cellulosic ethanol emissions are much lower.

6. Discussion

In this paper we make the case that it is both possible and justified to make explicit the trade-offs associated with biofuel production and use by using the concept of ecosystem services considering that this concept links ecosystem functioning and human wellbeing and has gained recognition by academics and policy makers.

The MA which has been the major scientific assessment of ecosystem services to date and the subsequent related literature has failed to note the substantial impact of biofuel production and use on the provision of ecosystem services and human wellbeing. Table 2 identifies the main sustainability issues related to biofuel production, the ecosystem services affected and the links to the constituents of human wellbeing articulated by the MA. Figs. 1 and 2 adapt the MA typology of ecosystem services to account for the drivers, impacts, and trade-offs of biofuel production and use as related to ecosystem services and human wellbeing.

Even though biofuels' negative impacts have attracted most of the attention there are also examples of biofuel production and use providing, enhancing or restoring ecosystem services and thus contributing positively to human wellbeing. In fact the term biofuels includes vastly different production practices that take place in different ecosystems, for different reasons and compete with other human activities. For example, the drivers, impacts and trade-offs of large scale sugarcane bioethanol production in Brazil are most certainly different from the drivers, impacts and trade-offs of small scale biodiesel production in rural Sub-Saharan Africa or India. Further to the environmental and socioeconomic context it is fair to say that in most cases the difference on whether biofuel production can provide a net benefit on the environment and human wellbeing also depends on the technological processes and the policy instruments adopted during biofuel production, use and trade.

As a result it is important to clarify the associated trade-offs which are context specific when attempting to promote biofuel sustainability. With that in mind Figs. 1 and 2 and Tables 1 and 2 should be seen as a synthesis of the reviewed literature whose aim is to put biofuels in the ecosystem services narrative and to provide a simplified conceptual framework that illustrates the main tradeoffs of biofuel production using a consistent language. As such they can be used as a first step when assessing the sustainability of different biofuel production practices by framing the debate.

In this sense the ecosystem services approach and the simplified conceptual framework provided in this paper rather than acting antagonistically, they can complement and improve the quality of existing initiatives and frameworks that aim to enhance biofuel sustainability (refer to Section 2). In particular the ecosystem services approach, and the immersion of biofuels within it, can assist policy makers to obtain a better grasp of the trade-offs associated with biofuel production and use. Understanding and communicating the dynamics and trade-offs of biofuel production is something that other current frameworks through their current format (similar to an indicator list) miss.

However significant research is needed before ecosystem service-based frameworks are to be used effectively for assessing different biofuel practices. Based on our review we identify three priority research areas in the confluence of biofuels, ecosystem services and human wellbeing: evidence, valuation, policy implications.

Evidence: There are significant knowledge gaps regarding (a) the impact of biofuel production and use on certain types of ecosystem services (e.g., cultural services) and constituents of human wellbeing (e.g., gender issues) and (b) the links between those ecosystem services compromised and/or provided by biofuels and human wellbeing. The newly established Intergovernmental Science-Policy Platform on Ecosystem Services and Biodiversity (IPBES, refer to http://ipbes.net/) should consider addressing such knowledge gaps.

Valuation: It has been suggested that the MA classification of ecosystem services used in this paper is appropriately simple to illustrate the tradeoffs between ecosystem services and human wellbeing (Costanza, 2008). However, it fails to address issues of valuation very well given that it allows for a certain degree of double counting (Wallace, 2007; Boyd and Banzhaf, 2007; Costanza, 2008). Lately other classifications of ecosystem, services have

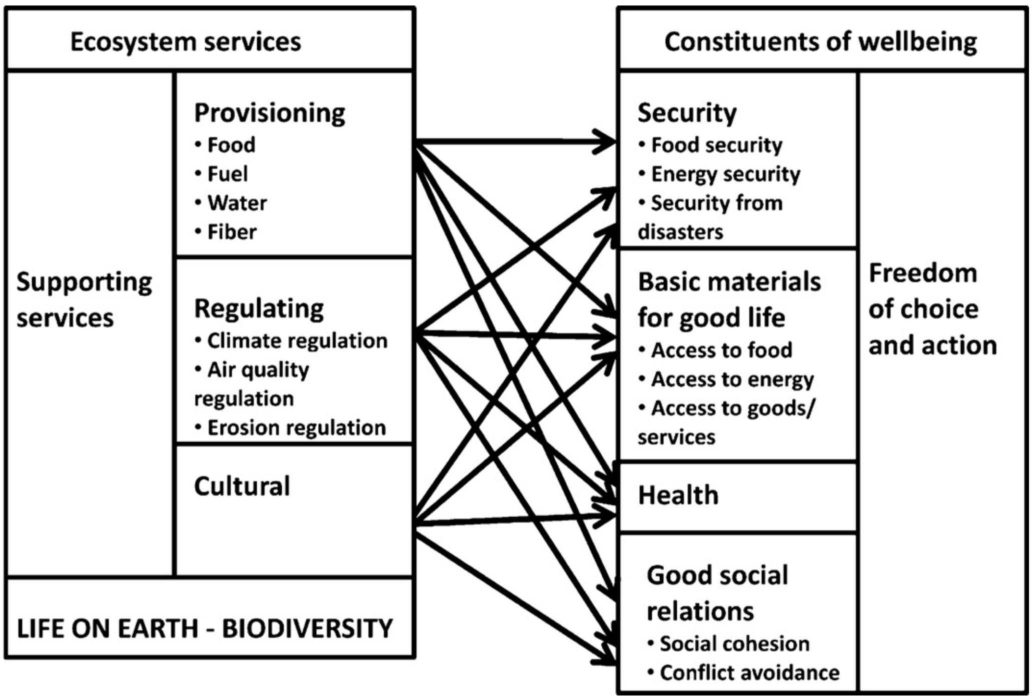

Fig. 2. Linkages between biofuel production, ecosystem services and human wellbeing. Adapted from MA (2005a).

been suggested when the aim is not only to highlight the associated tradeoffs but to also valuate the ecosystem services (e.g., Wallace, 2007; Boyd and Banzhaf, 2007; Fisher et al., 2009; Kumar, 2010). It is thus important to develop typologies of ecosystem services that are be biofuel specific and context sensitive in order for ecosystem service based frameworks to be developed. Furthermore, given the nature of the provided and/or compromised services both biophysical and monetary tools become relevant (Ecological Economics, 2002; Kumar, 2010). It seems that integration of thermodynamic models (e.g., exergy and embodied energy) with monetary valuation tools is essential, particularly for the fuel related ecosystem services. However, a robust framework that could combine such tools in a meaningful manner has not yet been developed (Gasparatos et al., 2009). A challenge for developing this framework stems from the different concepts of value that these tools employ (Farber et al., 2002; Kumar, 2010) and the difficulty in defining what constitutes an ecosystem service that ought to be valuated (Boyd and Banzhaf, 2007). Certain concepts of value seem to be more relevant to certain ecosystem services so there need to be a good theoretical basis behind the choice of valuation tools. However, most ecosystem services valuation methodologies disregard this fact by indiscriminately choosing only monetary valuation, something that can result in distorted valuations. Hybrid biophysical-monetary valuation frameworks and/or indicator based multi-criteria analysis can be particularly promising.

Policy implications: If biofuels are placed in the ecosystem services narrative then certain policy implications are expected to arise. Such implications can range from the local scale (e.g., payment for ecosystem services schemes) to the international scale, e.g., potential interlinkages between the CBD and the UN Framework Convention on Climate Change (UNFCCC). Research aiming to identify, explain and overcome such policy implications will go a long way towards unlocking the full potential of ecosystem services-based frameworks for assessing biofuel sustainability.

7. Conclusions

This paper has provided a systematic review of the drivers, impacts and tradeoffs of biofuel production on ecosystem services and human wellbeing and has placed biofuel production in the ecosystem services narrative following the MA framework. The evidence collected suggests that biofuel production and use can indeed affect several types of ecosystem services negatively or positively: provisioning services (e.g., fuel, food, freshwater), regulating services (e.g., climate regulation, air quality regulation, erosion regulation), and cultural services. At the same time biofuel production can be an agent of rural development and affect access to energy/energy security, access to food/food security, health, land tenure and gender equality. As such biofuel production and use can impact directly and indirectly all aspects of human wellbeing as designated by the MA.

Fuel: Biofuels have been proposed as alternative transport fuels. Several biofuel practices are net energy suppliers and as a result can contribute positively to energy security in the short-to-medium term. However, overreliance on fertilisers and agrochemicals for feedstock production casts doubt on their long term potential.

Food: First generation biofuel feedstocks are essentially food crops and can compete directly and indirectly with food production. It is feared that biofuel expansion will compromise significantly food and feed production globally. For this reason, certain countries such as India have enforced a moratorium in the domestic production of biofuels from edible crops.

Freshwater: Biofuel production can affect both the quantity and quality of freshwater. Biofuels exhibit higher water footprints than fossil fuels and other renewable energy sources. Fertilisers, agrochemicals and effluent from biofuel refineries can pollute water bodies. However, with adequate management practices some biofuel feedstocks can provide environmentally friendly water sewage treatment and improve water quality in aquifers.

Climate regulation: Several LCAs have suggested that biofuels generally emit less GHG during their full life cycle than conventional fossil fuels. However, LCAs usually do not factor the GHG emissions through direct and indirect LUCC. Biofuels grown on former agricultural land seem to result in smaller carbon debts.

Air quality regulation: The emission of atmospheric pollutants takes place at several stages of the biofuel's life cycle and depends on several factors such as the agricultural practices used during feedstock production (e.g., fertiliser use, land clearing through burning, etc.) and the combustion technology.

Erosion regulation: The extensive cultivation of the main biofuel feedstocks such as sugar cane, soybeans and oil palm are major causes of soil erosion. Other feedstocks such as Jatropha can improve soil quality and control erosion in marginal lands.

Cultural services: Studies that link biofuel production and cultural services are currently lacking. Nevertheless biofuels are usually grown in extensive monocultures which are thought to affect negatively cultural ecosystem services.

Biodiversity: Biofuel expansion, particularly in the tropics, is considered to be an emerging threat to biodiversity. Biofuels have been linked to four of the six main drivers of biodiversity loss identified in the MA, namely habitat loss, pollution, invasive species and climate change.

Rural development: The net contribution of biofuels to income and rural employment depends on the opportunity cost in terms of foregone alternative uses of land, technology, labour and capital. Biofuel policies often aim to promote rural development by supporting rural employment but the positive or negative impact of biofuel production (and its magnitude) depends greatly on the kind of biofuel production system adopted (e.g., large plantations vs. small holders). On the other hand, there is evidence to suggest that small scale biofuel initiatives can contribute positively to human wellbeing through better access to energy, capacity building, poverty reduction and rural development.

Energy security/access to energy: Certain biofuel production practices can promote energy security both at the national and the local level. Small scale biofuel projects have been successful in providing rural populations in developing nations with reliable access to energy, e.g., through rural electrification projects.

Food security/access to food: The increase in food prices during the past few years has partly been attributed to the biofuel-food competition. The highest increases in food prices were observed in developing nations and were drivers of social unrest (food riots).

Health: Atmospheric emissions associated with biofuel production and combustion can affect human health. Pesticides and other agrochemicals that are used during feedstock production are also potent health threats. The manual and intensive nature of jobs associated with feedstock production, particularly in developing nations, can also impact health in a negative manner.

Land tenure: There are numerous examples where the access of poor people on land has been compromised through displacement of poor families, concentration of land to powerful actors, loss of land rights through coercion/lack of information and aggressive land seizures.

Gender issues: The risks of biofuel expansion might be gender-differentiated with women being more likely to face the negative impacts associated with biofuel expansion. However there are also several cases where small and large scale biofuel initiatives have contributed to the wellbeing of women. Understanding the net welfare contribution of biofuels across genders can be very complicated and very little research has been conducted for this purpose.

It is evident that biofuels include vastly different production practices that take place in different ecosystems, for different reasons and compete with other human activities. The complexity of biofuels' production chains, the multiple uses of the land appropriated for the production of feedstock and the many different incentives that drive the biofuel market, contribute to the difficulty of designing and implementing policies for sustainable biofuels. Markets alone do not provide the sufficient institutional framework to make explicit and to communicate effectively the many values of ecosystems in a way to promote biofuel sustainability. Coordinated action for the development and enforcement of biofuel-related sustainability standards is needed. The concept of ecosystem services and its great explanatory power can help towards this end.

We conclude that by taking the opportunity cost of ecosystems in terms of their contribution to human wellbeing as a starting point, the concept of ecosystem services can be easily communicated and assist policy makers to identify the trade-offs of biofuel production. Considering the almost complete lack of academic literature explicitly linking biofuels, ecosystem services and human wellbeing significant future research must be conducted before operational frameworks based on the concept of ecosystem services are realistically able to assess biofuel sustainability. Research should not only focus on increasing our knowledge about the impact of biofuels on ecosystem services and how it links to human wellbeing but also to develop appropriate valuation mechanisms and to identify the policy implications that will arise if biofuels are put in the ecosystem services narrative.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.agee.2011.04.020.

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