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Research paper

Mechanisms and indicators for assessing the impact of biofuel feedstock production on ecosystem services

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ABSTRACT

Biofuel feedstock production can be a significant driver of landscape modification, ecosystem change and biodiversity loss. There is growing body of literature that shows how biofuel landscapes provide various ecosystem services (e.g., feedstock for fuel, carbon sequestration) and compromise other ecosystem services (e.g., food, freshwater services). These effects are context-specific and depend largely on prior land use conditions and feedstock production practices. Changes in the flow of ecosystem services due to the conversion of natural and agricultural areas can have ripple effects on human wellbeing. Despite some recent attempts to apply to biofuel settings concepts and methods rooted in the ecosystem services literature, this is the exception rather than the rule within both the biofuel and the ecosystem services research communities. This paper synthesizes the current knowledge about the impact of biofuels on ecosystem services. It focuses especially on the feedstock production phase and outlines the main mechanisms through which landscape conversion affects the provisions of ecosystem services. It proposes conceptually coherent indicators to reflect these mechanisms and offers a critical discussion of key issues at the interface of biofuels and ecosystem services.

1. Introduction

The sustainability impacts of biofuels depend on the cultivation and harvesting of the biofuel crops (referred to as feedstock in this paper). Knowledge syntheses conducted by the Scientific Committee on Problems of the Environment (SCOPE) have outlined some of these diverse social, economic, and environmental impacts around the world [1]. Studies have analyzed the potential conflicts of biofuel production with food production and food security [2,3], while others have addressed concerns over land-grabbing [4,5]. Impacts related to deforestation, biodiversity loss and Greenhouse Gas (GHG) emissions, including those from direct and indirect land use and cover change (LUCC), have also been prevalent [6–8]. While most studies have focused on negative impacts, there is a growing body of literature outlining possible positive impacts on energy security, economic development and climate change mitigation among others [9–15]. Given the diversity of these sustainability impacts, it is challenging to develop a unified framework for biofuel impact assessment and knowledge synthesis [16] [20].

Some recent studies have applied concepts and methods rooted on ecosystem services to synthesise the current knowledge and identify the impacts/trade-offs of biofuel production (see below). The basic premise of the ecosystem services perspective is that ecosystems provide directly and indirectly various benefits to humans (i.e. ecosystem services) [17–19]. For biofuel systems these trade-offs can relate to provisioning ecosystem services (e.g. fuel, food), regulating services (e.g. carbon sequestration, water purification) and cultural services (e.g. religious values) [17,18].

Changes and trade-offs in the flow of these ecosystem services can have important ramifications for human wellbeing (Fig. 1), whether positive or negative [17,18]. Yet there are multiple ways to catalyze these changes in ecosystem services. For example they can be directly

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List of acronyms

CICES	Common International Classification of Ecosystem Services
EU-RED	EU Renewable Energy Directive
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse Gas
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
iLUCC	Indirect Land Use and Cover Change
LCA	Life Cycle Assessment
LUCC	Land Use and Cover Change
MA	Millennium Ecosystem Assessment
NTFP	Non-timber forest product
PES	Payments for Ecosystem Services
RSB	Roundtable for Sustainable Biomaterials
RSPO	Roundtable on Sustainable Palm Oil
TCM	Travel Cost Method
TEEB	The Economics of Ecosystems and Biodiversity
UK NEA	UK National Ecosystem Assessment

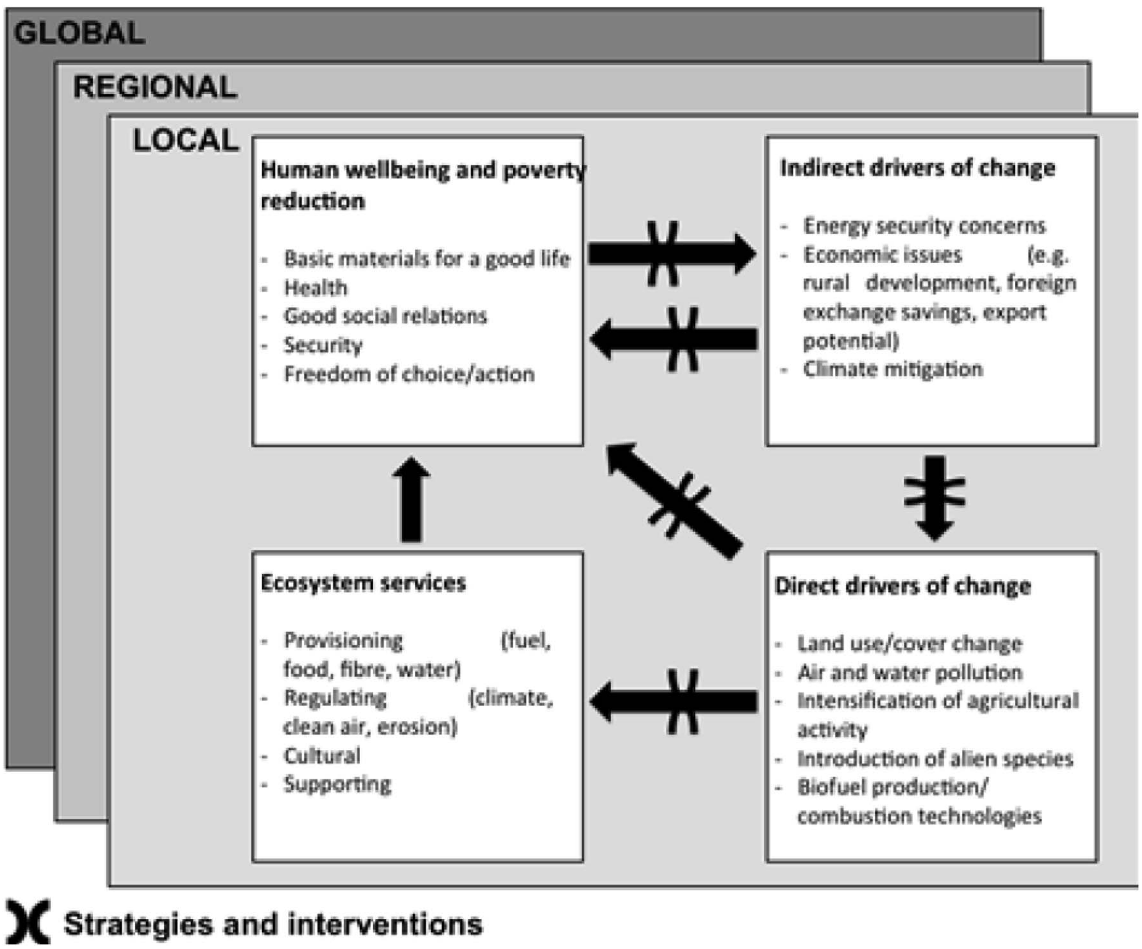

Fig. 1. The Millennium Ecosystem Assessment (MA) conceptual framework adapted for biofuel production and use. Adapted from Refs. [17,25].

induced by multiple mechanisms related to land use change, resource overexploitation or pollution (i.e. direct drivers of ecosystem change) (Fig. 1) or indirect drivers of change such as institutions, technological change and changes in consumption patters.

As it becomes obvious the ecosystem services perspective is particularly strong in making links between ecosystems and humans. However apart from this systematic perspective it has some core elements such as the ability to (a) consider multiple scales, (b) link ecosystem services to different beneficiaries and (c) explicitly identify and consider trade-offs and synergies between ecosystem services (d) acknowledge that different values can be ascribed to ecosystem services [21–24].

This systematic view of the linkages between ecosystems, human activity and human wellbeing can offer an invaluable lens for studying the sustainability of biofuel systems. Further to helping elicit biofuel impacts and trade-offs, an ecosystem services perspective can bring into the equation the different beneficiaries of these ecosystem services and the institutions that govern biofuel production, use and trade.

Recently some studies have adopted an ecosystem services perspective to show how biofuel landscapes can provide various ecosystem services (e.g., fuel, climate regulation) but also compromise a range of provisioning, cultural and regulating services [25–28]. For example, empirical studies have adopted methods and tools rooted on ecosystem services to assess biofuel impacts in the US [29–33], Africa [34,35] and the EU [36,37]. Yet, studies at the interface of biofuels and ecosystem services still remain the exception rather than the rule within both the biofuel and the ecosystem services research communities [38].

Actually, there are significant research gaps at the interface of biofuels and ecosystem services that must be bridged if the ecosystem services perspective is to be successfully applied to study biofuel systems [16,38]. For example, throughout the process of developing this Special Issue we identified a critical lack of literature that systematizes the mechanisms through which biofuel systems either compromise or provide ecosystem services. Furthermore there is a lack of indicators that can reflect in conceptually coherent (and not loosely) these mechanisms [25,39]. This comes to a stark difference to the extensive research on biofuel sustainability impacts and biofuel sustainability indicators [e.g. Refs. [20,40–43].

The aim of this review is to systematize the current literature at the interface of biofuels and ecosystem services, focusing on the specific mechanisms through which feedstock production affects ecosystem services. We believe that this is an important first step towards unlocking the full potential of the ecosystem services perspective for the study of biofuel systems. Thus this synthesis does not review the magnitude of the ecosystem services impacts of biofuel production (instead see [25,26,28]. In other words this synthesis does not attempt to answer questions of whether "are biofuels good or bad", "what is the magnitude of biofuel impacts on different ecosystem services", or "how can we promote biofuel sustainability", as these can vary considerably across feedstocks, management practices and geographical contexts. Instead we focus on questions of "how (i.e. through which mechanisms) feedstock production affects ecosystem services" and "how can these mechanisms be reflected (i.e. through which indicators)".

We adopt key concepts from the main ecosystem services frameworks, particularly those of the Millennium Ecosystem Assessment (MA) [17], The Economics of Ecosystems and Biodiversity (TEEB) [18] and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) [19].

The different sections of the review reflect an adaptation of the MA framework for biofuels [25,26] (Fig. 1). Initially we identify the direct and indirect drivers of ecosystem change due to biofuel production and use (Section 2.2–2.3). Section 3 unravels the mechanisms through which biofuel expansion affects the flow of the key ecosystem services and proposes conceptually coherent indicators. Section 4.1 summarises the main findings of the review and Section 4.2–4.3 identify key challenges and opportunities for using the ecosystem services perspective to catalyze the progress towards biofuel sustainability.

2. Biofuel expansion as a driver of ecosystem change

2.1. Biofuels and landscape modification

Various factors such as agricultural practices, the previous land use and the socio-ecological context within which feedstock production is pursued affect the extent to which landscape modification due to feedstock production affect ecosystems [25] [44]. This dictates the impacts on biodiversity and the ecosystem services that are provided. To highlight the importance of these factors in this review we use a typology of biofuel systems based on the size of operations and market orientation (sales in national/international markets vs on-site use) (Fig. 2) [45,46].

Type II and IV systems entail feedstock production in large plantations usually following monocultural practices. Type IV systems are essentially commercial plantations that sell feedstock to national/international markets. They have been promoted in several regions of the world and for different feedstocks including maize in the US/China [47,48], switchgrass/miscanthus in the US [49,50], sugarcane in Brazil [51,52], soybeans in Brazil [53], oil palm in Southeast Asia [54,55], rapeseed in the EU [56,57] and sugarcane/jatropha in Africa [45,58]. The sizes of Type IV systems can vary depending on the geographical context and feedstock, but is almost always associated with intensive mono-crop cultivation practices. Type II systems are much rarer and essentially entail the production of feedstock for direct onsite use but at a rather large scale, e.g. large farms in South Africa or mines in Zambia [46].

Type I and III systems entail feedstock production at smaller scales in terms of the amounts of land converted and feedstock produced. Type III systems usually involve small farmers that produce feedstock under contract linked to large plantations (i.e. outgrowers) or smallholders growing independently and linked to feedstock processing plants. Such smallholder/outgrower-based systems have received significant attention in developing countries of Asia [59,60] and Africa [10,11] as a rural development strategy. Some Type III projects are linked to large plantations (i.e. Type IV systems), especially for highly perishable feedstocks such as sugarcane and oil palm that need processing soon after harvesting. Type I projects entail the local production

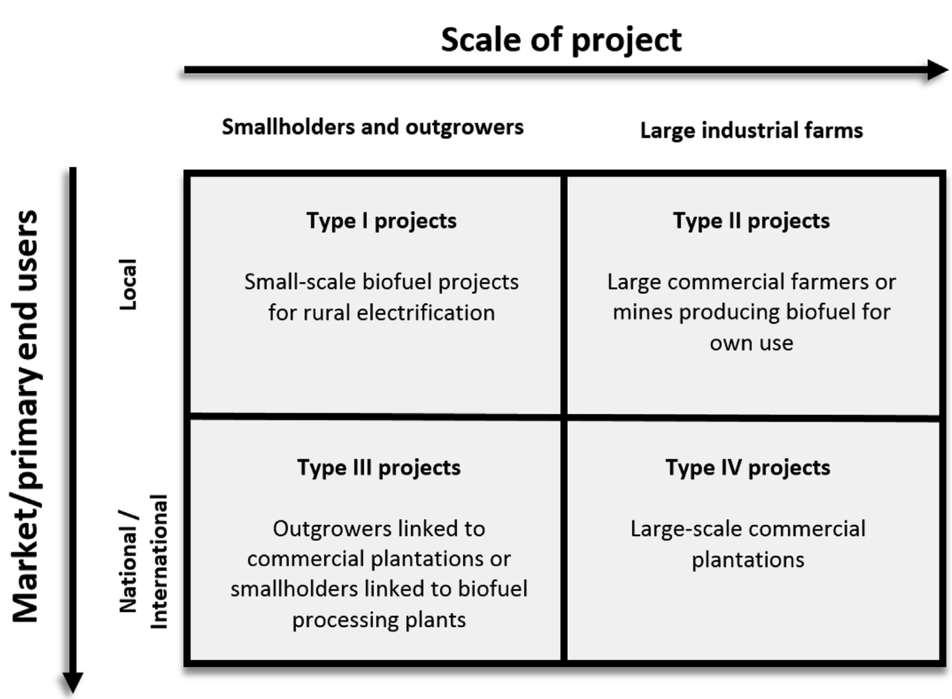

Fig. 2. Typology of feedstock/biofuel projects. Source [45,46].

and consumption of biofuels usually for rural electrification or other local uses. Much like Type III systems, Type I systems have also received some attention in developing countries of Africa and Asia for enhancing rural development usually trough off-grid electrification [61–63].

Depending on the social-ecological context within which these biofuel systems operate, feedstock production can displace directly or indirectly other land uses. For example, several studies have shown how feedstock production has converted agricultural land, natural ecosystems, or a combination of the two [64,65]. Type II and IV systems usually convert large parcels of land exclusively for feedstock production and can be a significant driver of direct LUCC [66,67]. However, to some extent direct LUCC (shown in red in Fig. 3) characterizes virtually every configuration, whether it is large-scale or small-scale.

Apart from the direct LUCC effects, feedstock production can induce indirect LUCC (iLUCC) effects in areas further away from where feedstock production is concentrated [8,68]. This hypothesized effect is thought to be associated with the opening of new agricultural areas [67]. However, the quantification of iLUCC effects is particularly challenging [69] and often controversial due to the complex assumptions that have to be made when estimating such effects [70].

2.2. Biofuels and direct drivers of ecosystem change

Previous studies [26,44] have linked feedstock production to all five MA drivers of biodiversity loss and ecosystem change identified namely (a) habitat change/loss, (b) pollution, (c) global/regional climate change, (d) invasive species, and (e) overexploitation [17].

Habitat loss/change due to LUCC (as outlined in Section 2.1), is perhaps the most important biofuel-related driver of ecosystem change and biodiversity loss [6]. However, the magnitude of habitat loss/change effects depend on, among several other factors, the type of converted land, the feedstock and the vulnerability of the affected species [44,71].

The direct conversion of natural ecosystems such as grassland and forest is usually associated with higher levels of ecosystem change and biodiversity loss when compared to the conversion of cultivated or idle land [71]. Numerous studies have linked feedstock expansion to habitat change and biodiversity loss in highly biodiverse areas such as Brazil (e.g. destruction of riparian forests for sugarcane production) [52,72], Southeast Asia (e.g. destruction of tropical forests for oil palm cultivation [73,74] and Sub-Sahara Africa (e.g. conversion of miombo woodlands for sugarcane/jatropha production) [66,75]. In developed countries such as the EU and the US, most of the production of conventional feedstock such as maize and rapeseed takes place in already converted agricultural areas [56,76]. However, depending on the geography, structure of markets and sustainability safeguards, biofuel policies in developed countries could potentially induce feedstock expansion in developing countries, therefore having faraway impacts on habitats and biodiversity [78].

Ligno-cellulosic biofuel feedstocks such as miscanthus and switchgrass can provide habitat to some insect and bird species, especially if they contain biodiversity-friendly elements such as buffer zones [50].

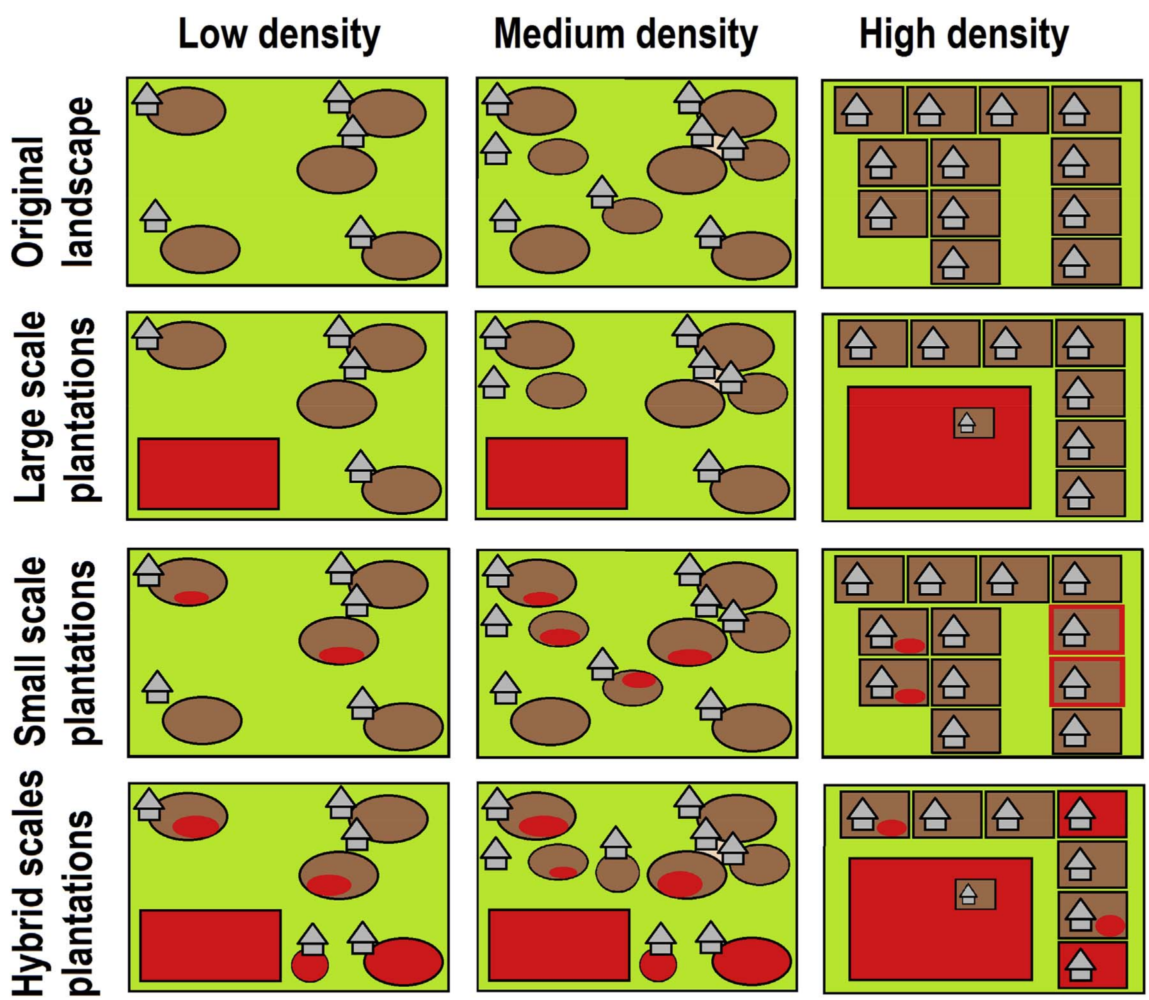

Fig. 3. Common biofuel-related landscape modifications.
Note: Green denotes natural ecosystems (e.g. woodland, grassland), brown denotes agricultural land, and red feedstock production. In some cases feedstock production can replace poorly producing crops or pasture on marginal lands. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

While such landscapes are often more biodiversity-friendly when compared to conventional feedstocks such as maize, wheat, soy and rapeseed [50,79], they can still trigger habitat change and biodiversity loss if they displace indigenous vegetation [77].

Feedstock production can also be a major source of water pollution. For example, large-scale feedstock production in Type IV systems (Fig. 2) often requires large quantities of fertilizers and agrochemicals, which can have important pollution effects to aquatic ecosystems [80,81]. Effluents from biofuel refineries can further exacerbate impacts on aquatic habitats [47,82]. Studies from Brazil [51,52,83], Southeast Asia [73,84], the US [85,86] and the EU [87], have shown the negative water pollution outcomes of some biofuel practices. On the other hand some lingo-cellulosic feedstocks require lower amounts of fertilizers and pesticides compared to the intensive production of annual crops (e.g. maize), thereby having positive effects on water quality [76]. It is worth noting that these effects on aquatic ecosystems can materialize far away from the areas of feedstock/biofuel production [76,88,89]. For example, maize production following current agricultural management practices can increase nutrient loading along the Mississippi basin, leading to higher levels of hypoxia in the Gulf of Mexico [90–92].

As with any agro-industrial activity and/or combustion process, biofuel production and use can emit different ambient air pollutants such as particulate matter, nitrogen oxides, volatile organic compounds (VOCs) and tropospheric ozone. However, the type and magnitude of emissions varies between different biofuel pathways [1,93,94]. For example, for some atmospheric pollutants and geographical contexts biofuel pathways can have higher emissions than conventional fossil fuels, especially when practices such as agricultural burning are used [73,95]. Some studies have linked such emissions to negative outcomes on human health either through observed trends such as prevalence of pulmonary diseases around feedstock-producing sites [96] or estimated through modeling exercises [49]. While it is difficult to observe the direct effects of increased air pollution on ecosystems/biodiversity, studies in Europe and Southeast Asia have modeled increases to tropospheric ozone due to feedstock production, and linked it to negative effect on plants [97].

Several studies have also confirmed that different biofuel pathways can have radically different GHG emissions. The magnitude and type of these emissions depends on multiple factors such as the type of converted land, feedstock and agricultural production practices [e.g. 1,98]. Landscape conversion for feedstock production can substantially alter carbon balances due to changes in carbon stocks in standing biomass and soil [7]. As a rule of thumb, biofuel pathways that entail the conversion of natural habitats with high carbon stocks (e.g. forests, peatlands) tend to have the higher carbon debts and payback periods [7,66,67,74,99,100].

Careful selection of feedstock and management practices can lead to emission savings for atmospheric pollutants and GHGs. For example, using agricultural residues (e.g. wheat/maize/rice straw, sugarcane bagasse) for energy production [101] and adopting advanced agricultural practices and integrated production configurations [102] can have substantial emission savings. Furthermore, perennial crops can improve carbon balances as they sequester more carbon compared to annual crops [103].

LUCC can also have localized climatic effects. In particular, changes in vegetation type and density can change surface albedo, temperature and evapotranspiration, affecting thus the local climate [104–106]. There has not been any explicit research on how changes in local microclimate due to feedstock production affect ecosystems and biodiversity. However research in non-biofuel contexts has shown that some significant effects on biodiversity and ecosystem services might occur [107,108].

Some lignocellulosic feedstocks, especially perennial grasses such as miscanthus and switchgrass, might become invasive and compete with local vegetation [109–111]. This competition can have particularly negative effects to biodiversity if it occurs in riparian habitats that harbor significant biodiversity [112,113]. Jatropha has also been identified as a potentially invasive species in Africa, however its invasive potential is still unclear or possibly overestimated [114–117].

Finally, following landscape conversion some localized over-exploitation effects can be triggered for species of economic value. This mechanism is difficult to delineate but in theory it is due to the displacement of natural resource harvesting (e.g. forest products) from converted areas, to ever diminishing unconverted areas. This can be particularly significant in contexts where local communities rely significantly on ecosystem services for their livelihoods [26,45]. Some studies have used qualitative approaches to elicit such causal effects but, as mentioned above, they are very difficult to unravel [118].

2.3. Biofuels and indirect drivers of ecosystem change

As already discussed in Section 1, the main drivers of biofuel production and use are energy security, economic development and climate change mitigation. Apart from these generic drivers, there are some context-specific drivers such as national policies that promote improvement in ambient air quality (e.g. Ref. [119]). Such policy imperatives feature in various regional and national plans that promote biofuels [1,120]. While it is not the purpose of this review to delve into institutional aspects, it is must be mentioned that such policies and institutions can affect the environmental and socioeconomic performance of biofuel systems. For example, they can dictate the preferred feedstock, origin (e.g. domestic production vs imports), the mode of production, the markets targeted for energy and non-energy products, the funding mechanism for agro-industrial and biofuel projects, and the mechanisms to share the costs and benefits of biofuel production and use [1,120].

The IPBES Conceptual Framework views such policies and institutions as important indirect drivers of ecosystem change [19]. The 2009 EU Renewable Energy Directive (EU-RED) is an example of how institutions and policies can indirectly drive ecosystem change. EU-RED originally required a share of 10% renewable energy in the transport sector in the EU by 2020 [121]. It was expected that a significant share of the mandate would be met through imports (such as soy from Argentina and palm oil from Indonesia/Malaysia) if domestic production was not enough. The significant expansion of jatropha in Africa was largely driven by expectations to export in EU markets [45]. This export-oriented feedstock production had the potential to trigger significant LUCC in the exporting countries [122,123], but the actual quantification was very difficult, especially for multi-functional feedstock such as oil palm [124]. This expectation for feedstock export to the EU triggered the interest of foreign investors in leasing or buying large tracts of land [120,127].

However, the 2009 EU-RED required minimum lifecycle GHG emission reductions. This included emissions from LUCC, and feedstock transport in the EU, which complicated imports from developing countries. This marked the first time that exporting countries were held responsible for GHG emissions at the point of production, as such emissions had always been accounted for at the point of consumption [125]. This shifted the burden for LUCC impacts onto developing exporting countries that previously had no such responsibility under the Kyoto Protocol [126]. This shift in responsibility for land use emissions seems to have curbed the enthusiasm for international biofuels trade as independent certification schemes arose to enforce the EU regulations [128]. The increasing difficulty to export feedstock to EU markets possibly contributed to the collapse of biofuel projects, mainly jatropha projects in Africa [45,129]. Essentially feedstock production driven by such policies did not necessarily materialize into local economic benefits, while the loss of ecosystem services due to land conversion took in some cases a further toll on local livelihoods [118].

3. Impacts of biofuel feedstock production on ecosystem services

3.1. Provisioning services

3.1.1. Feedstock

Feedstock for biofuels is the main ecosystem service obtained after the conversion of agricultural land and/or ecosystems for biofuel production (Section 2.1) [25,34]. This feedstock can be transformed into liquid fuel such as ethanol, biodiesel and straight vegetable oil (i.e. not converted to biodiesel) that can be used for transport, rural electrification and cooking [1]. As discussed further below, the same feedstock conversion processes provide other potentially marketable bio-based products such as fertilisers, animal feed and organic materials.

Feedstock production and biofuel use can contribute in multiple ways to human wellbeing. Most commonly this happens through rural development and the generation of income and employment for those involved into feedstock production (Section 4). A secondary avenue is through enhancing energy security locally (Type I and II systems) or nationally/internationally (Type III and IV systems) (Section 2.1, Fig. 2) [1,45]. Considering the largely urban focus of modern economic policies, biofuels (and the bio-economy more broadly) is one of the few options to boost economic development in depressed rural areas [130].

An appropriate indicator to assess feedstock production as a provisioning service is the "mass of feedstock production per unit area annually" (e.g. measured in kg km^{-2} y^{-1}), see Ref. [47]. However, the use of such indicator can be misleading considering the multi-functional nature of most feedstocks. For example, sugarcane can be a raw material for multiple products such as sugar, ethanol, co-generated electricity and biomaterials. Often a combination of products is developed based on market signals [131]. Furthermore, some biofuels are produced from the by-products or residues of other industrial processes. For example, in countries such as Malawi ethanol is commonly produced from molasses, which is a by-product of sugar production [132]. For biodiesel crops this can be even more complex as due to their high protein content, oilseeds can be used as animal feed. Thus feedstock is often a co-product, and sometimes not even the most economically valuable co-product.

Furthermore, while feedstock is the main ecosystem service provided by converted biofuel landscapes, the actual energy carrier (i.e. liquid biofuel) is produced through various feedstock treatment processes. The technological options that can increase (or decrease) the final energy provision from biofuel systems cannot be easily considered through an ecosystem services perspective (see Section 4.2.2).

This means that while an indicator as above might offer a good estimate of the overall potential for biofuel production from a given area [56], it might end up overestimating the actual feedstock related-ecosystem services, especially in contexts where the biofuel is a by-product of other industrial processes. In such contexts a more appropriate indicator can be one that denotes the "fraction of the plant component (e.g. sugar content) that is actually used for biofuel production per unit area annually" (e.g. measured in kg km^{-2} y^{-1}). In this sense the ecosystem service perspective could borrow from LCA practices in which different products from a process are divided according to their value in economic, energy or system terms [133], see Section 4.2.3.

3.1.2. Food crops, feed and livestock

Several types of feedstock are either staple food crops (e.g. maize, wheat) or crops that are important in the food industry (e.g. sugarcane, oil palm). As a result biofuel production can sometimes entail the direct diversion of crops from food-related uses. This can potentially contribute to, among others, reduced local availability of food and food price increases (e.g. Refs. [134–136]) (see Section 4.2.4).

However, when adopting an ecosystem services perspective, biofuel impacts on food and feed (a provisioning ecosystem service) should be initially understood through land use change [137]. Feedstock production can compete for land with food crop or livestock production [56,66,135]. The conversion of agricultural and/or pasture land can result in the loss of provisioning ecosystem services such as food, feed and livestock, which can affect human wellbeing in multiple ways [25] (Section 4.2.4). Due to the significant LUCC effects associated with large-scale feedstock production (Section 2.2), this loss of ecosystem services can be extensive for Type IV systems. However even when feedstock production is undertaken in smallholder/outgrower settings (Type I and III systems), then those households produce feedstock households may divert labour, water and/or other agricultural inputs from agricultural activities [11,134], possibly affecting food crop production from family farms.

This competition for land and other inputs can result either in the total halting of food/feed/livestock production in the converted landscape (i.e. total loss of ecosystem services), or in a displacement, (i.e. food/feed/livestock production moves somewhere else in the landscape possibly at a reduced scale). This partial displacement relates to iLUCC effects (Section 2.1).

As the main mechanism of ecosystem services impact is that of loss/displacement of food/feed/livestock production from the converted landscape, then appropriate indicators to capture this loss could be related to "mass of food crop/feed/livestock forgone per unit area annually" or "calorific content forgone per unit area annually" (e.g. measured in t km^{-2} y^{-1}, or MJ km^{-2} y^{-1}). However, if ecosystem services trade-offs are being captured (Section 4.1), then a more appropriate indicator would be related to the actual provision and change of food/feed/livestock ecosystem service between the two landscape states (i.e. pre- and post-conversion) such as "mass or calorific value of food crops/feed/livestock per unit area annually" for each state (e.g. measured in t km^{-2} y^{-1} or MJ km^{-2} y^{-1}).

Some agricultural practices can minimise the competition between feedstock and food crop production. For example, intercropping feedstock with food crops, or growing feedstock on farm boundaries (e.g. jatropha fences) can reduce land diversion from food crop production [34,66,138]. Still growing biofuel crops at farm boundaries might displace to some extent food crops and/or timber, but quantifying these trade-offs can be complicated [59].

3.1.3. Woodland and grassland products

The conversion of some natural land uses such as woodlands and grasslands can decrease the provision of some natural product that offer important provisioning ecosystem services in some sociocultural settings (see below). This includes ecosystem services associated with timber, and non-timber forest products (NTFP) used, among others, for construction, fuel, wild food, and medicinal purposes. Several studies have linked biofuel expansion with the loss of such ecosystem services [34,118]. The main mechanism behind the loss of ecosystem services can be (a) the actual loss of woodland/grassland habitats, and/or (b) the over-exploitation of ever-declining woodland/grassland habitats around converted feedstock production sites (Section 2.2).

At the same time there are different ways to reflect the loss of these woodland/grassland ecosystem services. For example it can be understood as the "actual loss or scarcity of the service", or the "changes in the access to the service".

When considering physical scarcity, it is appropriate to estimate changes in the "availability/stocks/prevalence/existence of socially and economically important woodland/grassland products" following landscape conversion (e.g. measured in kg km^{-2} y^{-1}). Ecological modeling can provide useful tools for the predictive assessment of such indicators. For example, species distribution models have estimated how feedstock production in different parts of South Africa can increase the vulnerability or induce the loss of certain woodland plant species [139]. Even though this approach has not been used for ecosystem services derived from woodland/grassland products, it is in theory flexible enough for such applications.

When considering the loss/change of access to woodland/grassland products following landscape conversion, then it is key to quantify changes in the consumption patterns of these products. A relevant indicator is for example change in the "amount of woodland/grassland product consumed per unit area annually" (e.g. measured in t km^{-2} y^{-1}) for the two landscape states. Household surveys and focus group discussions have elicited such changes in consumption patterns following forest conversion for large-scale jatropha production in Sub-Sahara Africa [34,118]. However, it can be difficult to link directly changes in the consumption of woodland/grassland products to landscape conversion. This is because indirect drivers of ecosystem change such as population increase and changes in consumption preferences can also affect the consumption of woodland and grassland products (Section 2.2–2.3). For example, plantations can cause population increase through providing employment opportunities, and developing ancillary infrastructure (e.g. roads) that can further facilitate access to woodland/grassland products [34].

3.1.4. Freshwater

Biofuel crops require water for their production. This water can be diverted from other human uses (e.g. cultivation of other crops, livestock, human consumption, industrial uses), as well as natural processes within ecosystems. Depending on feedstock type and agricultural practices there can be different degrees of water diversion.

For example, feedstocks that are conservative water users under non-irrigated conditions (e.g. jatropha under rainfed conditions) can divert lower quantities of water from other human and natural uses (e.g. Ref. [140]), when compared to dense feedstock monocultures under irrigation (e.g. large irrigated sugarcane plantations). At the same time this water diversion needs to be considered based on the previous land use. For example, dense jatropha monocultures in dryland conditions characterized by sparse tree vegetation will most likely affect hydrogeological cycles given the sheer number of trees incorporated in the converted landscape [118,138].

Water footprint analysis can be used to quantify the overall appropriation of freshwater services for feedstock production (and essentially the loss of freshwater services for other uses) [e.g. 141–143]. An appropriate indicator in this case could be the overall water requirement for the production of feedstock, e.g. "water use per unit area of feedstock production annually" (e.g. measured in m^3 km^{-2} y^{-1}), or "water use per unit mass of feedstock production annually" (e.g. measured in m^3 t^{-1} y^{-1}).

While water footprint analysis has been used to compare different feedstocks or biofuel options (e.g. Refs. [141,142]), in reality certain water use takes place in the landscape regardless of feedstock production. A potential indicator to reflect this could relate to changes in freshwater availability in the converted landscape for other uses, i.e. "volume of water left for other uses within the landscape annually" (e.g. measured in m^3 y^{-1}).

However, both approaches discussed above reflect the consumption of an ecosystem service (freshwater) for the production of feedstock. For the assessment of ecosystem services trade-offs following landscape modification, a more appropriate approach would be to capture the ability of the ecosystem to provide freshwater pre- and post-conversion. In this case, a more appropriate approach would be to quantify changes in freshwater recharge expressed in "volume of water provided from the entire landscape annually" (e.g. measured in m^3 km^{-2} y^{-1}) (e.g. Refs. [29,78]).

3.2. Regulating services

3.2.1. Water quality and purification

Studies have shown that agrochemicals, fertilizers and industrial effluents associated with feedstock cultivation and treatment can degrade aquatic ecosystems (Section 2.2). Often these effects on water quality can manifest far away from where biofuel production takes place [76,88,89].

The effects of biofuel production on water quality are conceptually difficult to be captured through conventional ecosystem services frameworks such as MA or TEEB (Section 1). This is because this impact does not reflect so much the diversion of an ecosystem service as for provisioning services (see Section 3.1), but reflects the degradation (loss of quality) of an ecosystem service (clean water in this case). In this context, the impact mechanism is more akin to an ecosystem disservice (Section 4.2.2). For this type of mechanism, potential indicators could be the "concentration of chemicals and suspended sediment downstream of biofuel activities" (e.g. measured in mg m^{-3}), or the "export of chemicals and suspended sediment from biofuel producing areas" (e.g. measured in kg km-^{2} y^{-1}) [47].

However, some aspects of water quality degradation can be captured through a conventional ecosystem services perspective. In particular landscape conversion for feedstock cultivation can change (whether decrease or increase) the ability of the converted landscape to purify water. This can be due to the loss or gain of landscape elements such as wetlands and riparian vegetation or even the characteristics of the feedstock itself [76,83,144,145]. In this case, the impact mechanism is more akin to the loss or provision of a regulating ecosystem service [146].

A potential approach for capturing the loss or gain of water purification ecosystem services is to start by identifying the loss or gain of landscape elements that can act as water purification zones (e.g. wetlands, riparian vegetation). Subsequently, this could be linked to the loss or gain of water purification potential expressed as changes in the "volume of purified water per unit area annually" before and after conversion (e.g. measured in m^3 km^{-2} y^{-1}) or even better linked to specific pollutants and purification processes such as nutrient retention in terms of changes in "mass of nutrient retained per unit area annually" (e.g. measured in t km^{-2} y^{-1}) (e.g. Ref. [29]). It is worth mentioning that some studies have used indicators related to soil buffer capacity to reflect groundwater quality protection from nutrient leaching [56].

3.2.2. Climate regulation

Life Cycle Assessment (LCA) has been widely used to quantify the GHG emissions of different biofuel value chains around the world [1,98]. This usually entails the quantification of GHG emission at each stage of the biofuel lifecycle, and the comparison of the overall emissions with an appropriate baseline/alternative fuel, most commonly conventional transport fossil fuels (e.g. gasoline, diesel). If a biofuel value chain emits lower amounts of GHGs throughout its lifecycle (including from LUCC effects) than conventional fuels, then it can provide benefits to the global climate. In the opposite case they provide a disservice to the global climate. However, different biofuel value chains have very different emission profiles so it is not possible to distil a common conclusion for all [1].

What is interesting to notice is that as with energy provision (Section 3.1.1), overall GHG emissions are affected substantially by technological processes both in the production side and the consumption side of biofuel value chains. Furthermore, GHG emissions are measured in relation to the baseline energy type and level of use, which also changes and differs depending on the end-use application.

As a result, the climatic impacts of biofuels are difficult to be explained solely through an ecosystem service perspective (Section 4.2.2) [147]. While some conceptual frameworks such as the UK National Ecosystem Assessment (UK-NAE) have tried to factor (even if conceptually) the role of technologies in transforming ecosystem services to final goods [148], the most commonly used frameworks such as MA, TEEB and IPBES (Section 1) fail to make this distinction. As a result there are important conceptual challenges that prohibit the direct use of an ecosystem services perspective to capture climate regulation services from the entire biofuel value chain.

However there is a particular stage of the biofuel life cycle whose climate change mitigation effects can be explained through an ecosystems services lens. This relates to changes in carbon stocks due to LUCC effects, which can affect significantly the overall GHG balances of biofuel value chains (Section 2.2) (e.g. Refs. [149,150]).

In short, the LUCC effects of feedstock production can induce negative or positive changes in the carbon stored in above/below ground biomass and soil, indicating gains or losses in carbon sequestration services [66]. An appropriate indicator can be the changes in "carbon stored in the above/below ground biomass and soil per unit area over a specified amount of time (e.g. 20-years)", (e.g. measured in t km-2). The appropriate time period can differ somewhat for different feedstocks, climatic conditions and landscapes, and can be chosen with reference to the Intergovernmental Panel on Climate Change (IPCC) guidelines [151]. Considering that soil carbon is a significant carbon pool that can vary substantially between localities, it is important to the extent possible to use values obtained from local soil analysis (e.g. Ref. [66]), rather than use standardised values.

Such data can be linked to conventional LCAs to calculate the years required to compensate for the loss of stored carbon (i.e. payback period) [7,67,74,99]. It must be noted that feedstock landscapes that might initially incur a carbon debt may ultimately be more effective carbon sinks than the landscape they replace. This has been shown in landscapes where dense perennial crops such as sugarcane replace degraded or sparsely wooded areas [66].

3.2.3. Soil erosion regulation

Often extensive areas of bare soil can be left exposed to rain and wind in agricultural areas, especially during the initial land conversion and the period between harvest and regrowth. This can result in soil loss, which is another important environmental impact related to feedstock production [1].

The ability of different feedstock production systems to retain soil depends on various factors, including the feedstock and agricultural practices. For example, soil erosion tends to be higher in extensive sugarcane monocultures compared to adjacent pasturelands, grasslands and forests, due to the extensive areas of exposed bare soil to intense rain and wind [152,153]. Similar points have been made for other feedstocks such as maize [e.g. Ref. [154]. On the other hand some feedstocks such as jatropha and perennial crops (e.g. switchgrass, miscanthus) do not need to be planted annually and have deeper roots that can bind soil better. For example jatropha has been used for erosion control and rehabilitation with the justification that its root system may help in binding the soil [63,156], but the proper quantification of these benefits is still lacking. Perennial grasses such as miscanthus and switchgrass have also been reported to have soil erosion control potential [157].

Conversion for feedstock production can thus affect the ability of the landscape to retain soil, i.e. provide regulating ecosystem services related to erosion control. An appropriate indicator to quantify such services can be changes in the "mass of retained soil per unit area annually" (e.g. measured in t km^{-2} y^{-1}).

3.2.4. Pest regulation and bio-control services

Landscape modification can lead to the gain or loss of habitat for pest predators. This can in turn affect predator prevalence, and thus the ability to provide or compromise wider pest regulation and bio-control services. Several studies have shown how landscapes dominated by lingocellulosic feedstocks or mixed agricultural landscapes that contain buffers of natural vegetation can indeed offer habitat to such predators compared to crop monocultures such as maize [32,50,158,159]. Studies in such biofuel settings have adopted an experimental approach in measuring bio-control services [50], using indicators such as "natural enemy biomass" or "pest egg predation" [159,160].

Some biofuel feedstocks such as castor bean have certain insecticidal properties for pests that target surrounding food crops [138]. In this case these crops can offer directly bio-control regulating services. Appropriate indicators could assess the insecticidal properties of these crops such as "mass of active ingredient per unit area" (e.g. measured in kg km^{-2}).

Apart from direct measures of pest regulation and bio-control services as discussed above, some studies have used proxy indicators as changes in the use of insecticide per unit area, pre- and post-conversion, (e.g. measured in t km^{-2} y^{-1}) [161,162].

However while some feedstock landscapes can provide some level of pest regulation and bio-control services, it is highly likely that previous non-agricultural land uses provided the same or even higher extent/quality of habitat for predator species (or even had no need for these services). To test such dynamics long-term studies would be necessary but this remains a major gap in the literature.

3.2.5. Pollination

As with bio-control services the interplay between feedstock production and pollination is complicated (Section 3.2.4). Landscape modification can lead to the gain or loss of habitats for pollinators. This can affect pollinator prevalence, and as an extent the provision or loss of pollination services from the wider landscape. For example, the large-scale land conversion for maize and soy production in the US has decreased suitable habitat for key pollinators such as wild bees and honeybees, taking a significant toll on pollination services [163,164]. On the contrary, some lignocellulosic feedstocks such as switchgrass and miscanthus can be more attractive to some insect species (Section 2.2), including pollinators, having a positive effect for the provision of pollination services [30,50].

However, the extent of delivery/loss of pollination services can depend on several factors including the pollinator/pollinating species, their abundance and distance of habitat areas (e.g. Ref. [165]). As a result, it is considerably complicated to select an indicator that meaningfully captures all these factors.

Studies in biofuel settings have adopted an experimental approach when assessing pollination services across different landscape transitions [50]. Such studies have used directly observed indicators usually related to the "added seed weight of pollinated plants per unit area annually" (e.g. measured in t km^{-2} y^{-1}) [30], [32]. However, as discussed above multiple factors affect the delivery of pollination services. As a result alternative assessment approaches could rely on pollination indices that can consider some (or all) of these factors (e.g. Ref. [165]).

3.3. Cultural services

Feedstock production can affect cultural ecosystem services if areas of cultural significance are converted. Areas of cultural significance can cater to recreational, spiritual, religious or educational activities, among others. While a burgeoning literature identifies how the loss of such landscape elements can catalyze the loss of cultural ecosystem services [18], cultural impact is a very under-researched topic in the biofuel literature.

Some recent studies have, however, discussed the loss of cultural ecosystem services due to feedstock production. These include the loss of graveyard sites [34] and sacred groves [118] around jatropha plantations in Mozambique and Ghana, respectively. Loss of some cultural ecosystem services has also been observed around sugarcane plantations in Brazil [51]. Conversely, other studies have found some positive effects of feedstock production on cultural ecosystem services, such as the popularisation of honge oil for sacred lamps or the strengthening of cultural association with the honge tree in India [59].

The valuation of cultural ecosystem services is particularly challenging [18]. Some cultural ecosystem services, such as recreation, can be readily monetised. In such cases an appropriate indicator can be the monetary value of lost cultural services measured in "economic value per unit area annually" (e.g. measured in USD km^{-2} y^{-1}). As recreational services can be very context-specific the period of time could vary between areas. Thus the period that binds the indicator needs to be considered subject to the study context. A wealth of monetary tools such as the Travel Cost Method (TCM) and Hedonic Pricing can be applied to value in economic terms changes in the provision of cultural ecosystem services following landscape conversion [18].

However, impacts on some cultural services cannot be easily quantified (e.g. Ref. [166]). In these cases the elicitation of qualitative estimates of change in cultural value might be more appropriate [51,118]. This can be achieved through the elicitation of qualitative metrics that capture respondent perceptions (e.g. Likert-scales), through interviews, focus group discussions or participatory mapping [e.g. Ref. [118]]. In any case the loss of landscape diversity can be an indicator proxy for the loss of cultural services at the landscape scale [36], so a good starting point is to identify landscape elements that provide different cultural services such as sacred groves or areas of recreational potential. Subsequently the cultural impacts of conversion to local communities and visitors can be elicited as discussed above.

4. Discussion

4.1. Synthesis of mechanisms, indicators and trade-offs

Tables 1 and 2 summarize the key mechanisms of biofuel expansion on ecosystem change/biodiversity loss (Table 1) and ecosystem services (Table 2) as identified in Sections 2–3. We identify eight important observations that emanated through this literature review.

First, in this paper we outlined and summarised mechanisms for the most common ecosystem services impacts as identified in the academic literature, e.g. Refs. [25,26]. However, it is often the case that context-specific ecosystem services and/or impact mechanisms might exist. Thus, this paper should not be viewed as a comprehensive or binding typology of ecosystem services for biofuel landscapes, as such choices should be reflexive of local contexts and user needs [167]. It should be used to understand the key mechanisms for some of the most commonly studied ecosystem services in the academic literature.

Second, the proposed indicators can be used ex-ante (i.e. as predictive tools for planning biofuel projects) or ex-post (i.e. for monitoring impacts following landscape conversion and operation). Table 2 shows that some indicators are more appropriate for ex-post purposes, especially for those ecosystem services related to the consumption of woodland/grassland products (Section 3.1.3). Such considerations should be important for choosing the appropriate set of indicators for a given application.

Third the proposed indicators reflect the main mechanisms of ecosystem services impacts focusing as identified in the current literature, and are based on the expert opinion of the authoring team. This neither reflects local specific contexts (see above), nor the priorities, needs and expectations of affected stakeholders. Participatory methods for identifying important local impacts and appropriate indicators can help reflect better the perspectives of stakeholders, potentially increasing their usefulness in local contexts [47,59,168].

Fourth, there are substantial knowledge gaps about biofuel impacts on most non-provisioning ecosystem services, and especially pollination and pest regulation. It is important to develop further the evidence base about impacts on such ecosystem services to both understand better the underlying impact mechanisms, as well as choose the most appropriate indicators.

Fifth, biofuel value chains have several stages such as land preparation, feedstock cultivation, biofuel production, transport, and final biofuel use [1]. The ecosystem services perspective has a great explanatory power for the early stages of biofuel life cycles such as land conversion and feedstock production (Section 3.2–3.3). It has conceptual limitations in capturing properly impacts of later stages that are not strongly linked to land transformation. In this paper we have focused overwhelmingly on these early stages, but we acknowledge that other stages in the biofuel value chain (e.g. feedstock refinement, transport, end-use) can have important interactions with ecosystem services (e.g. Refs. [25,26]).

Sixth, as biofuel feedstock production is primarily an agricultural activity, we focused on mechanisms related to agricultural feedstock production systems (see Section 2.1). Even though some biofuel feedstocks can be harvested from wild trees (e.g. croton) [59,169], such approaches are relatively uncommon and operate at extremely small scales (Section 2.1). While we do not discuss such systems in this synthesis, we expect that a lot of the impact mechanisms will be similar with tree biofuel feedstocks such as jatropha. Furthermore, some promising feedstocks such as agricultural co-products and residues [47] are conceptually difficult to be considered through an ecosystem services perspective. While we acknowledge their growing importance in improving the efficiency of biofuel value chains, we do not discuss them thoroughly in this review apart from highlighting the limitations of the ecosystem services perspective to fully consider them (e.g. Section 3.1.1 and 4.2.2).

Seventh, most of the feedstocks discussed in this paper are multifunctional. Apart from bioenergy generation they can be used directly for food (e.g. maize), be used in the food industry (e.g. sugarcane, soybeans, oil palm) or be used for biomaterials (e.g. sugarcane). Only a few of the feedstocks discussed in this review such as jatropha and perennial grasses can be used solely for bioenergy. This means that with the exception of pure bioenergy crops, the expansion of multi-functional biofuel crops could also be driven by demand for food, animal feed or other products, with biofuel/bioenergy being a secondary factor. In such cases if the aim of a study is to allocate biofuel impacts across products or uses, then approaches similar to attributional life-cycle analysis should be adopted [133,170].

Table 1
Biofuel-related mechanisms of ecosystem change and biodiversity loss.
Source: Adapted from Ref. [44].

Mechanism	Scale of effect
Loss and fragmentation of habitats due to their conversion into agricultural landscapes dominated by a single crop (usually associated with Type IV systems)	Local/landscape
Simplification and homogenization of habitats due to the modification/loss of landscape elements (e.g. riparian forests) and ecosystem processes (e.g. soil loss) (usually associated with Type IV systems)	Local/landscape
Biofuel landscapes dominated by ligno-cellulosic feedstock (e.g. miscanthus, switchgrass) or that contain biodiversity-friendly landscape elements (e.g. buffer strips) can provide habitat to various species	Local/landscape
Pollution of soil and water from fertiliser/pesticide use causes toxicity, eutrophication and other negative environmental effects (usually associated with Type IV systems)	Local/landscape, Regional
Emission of ambient air pollutants contributes to acidification and tropospheric ozone formation	Local/landscape, Regional
Net-emissions or reductions of GHGs during the entire life-cycle of bioenergy generation (including from direct and indirect LUCC) contributes to anthropogenic climate change (or its mitigation)	Global
Effects to local micro-climates due to changes in albedo and evapotranspiration	Local/landscape, Regional
Invasive behavior of some feedstocks that compete with native vegetation	Local/landscape, Regional
Overexploitation of genetic resources from ever-declining habitats in/around feedstock-dominated landscapes	Local/landscape

Table 2
Mechanisms and indicators of the ecosystem services impacts of feedstock production.

Category	Ecosystem service	Mechanism	Possible indicators	Functionality	Possible monetary valuation technique
Provisioning (Section 3.1)	Biofuel feedstock	Converted landscape provides feedstock that can be used to produce fuel for transport, cooking and rural electrification	Fraction of the plant component (e.g. sugar content) that is actually used for biofuel production per unit area (e.g. measured in kg km^{-2} y^{-1})	ex ante, ex post	Market prices
	Food, feed, livestock	Converted landscape loses the ability (partially or fully) to produce food, feed, and livestock	Mass or calorific value of food crops/feed/livestock per unit area, pre- and post-conversion (e.g. measured in t km^{-2} y^{-1} or MJ km^{-2} y^{-1})	ex ante, ex post	Market prices
	Woodland/grassland products	The conversion of woodland/grassland (both direct and indirect) can decrease the availability of (and access to) natural products such as timber/grass for construction, fuelwood, medicinal plants and wild food.	Availability/stocks/prevalence/existence of socially and economically important woodland/grassland products, pre- and post-conversion (e.g. measured in kg km^{-2} y^{-1}). Amount of woodland/grassland product consumed per unit area, pre- and post-conversion (e.g. measured in kg km^{-2} y^{-1})	ex post	Market prices
	Freshwater	Landscape conversion can increase or decrease the ability of the landscape to provide freshwater	Freshwater recharge from the entire landscape, pre- and post-conversion (e.g. measured in m^3 km^{-2} y^{-1})	ex ante, ex post	Market prices
Regulating (Section 3.2)	Water purification	Loss or gain of landscape elements such as wetlands and riparian forests can decrease or increase the ability of the converted landscape to purify water	Loss or gain of water purification potential in terms of volume of purified water per unit area, pre- and post-conversion (e.g. measured in m^3 km^{-2} y^{-1}) Indicators that reflects specific pollutants and purification processes, e.g. changes in mass of nutrient retained per unit area, pre- and post-conversion (e.g. measured in t km^{-2} y^{-1})	ex ante, ex post	Replacement cost
	Climate regulation	Landscape conversion can increase or reduce the amount of carbon stored in above/below ground biomass and soil.	Amount of carbon stored in the above/below ground biomass and soil per unit area over a specified amount of time (e.g. 20-years), pre- and post-conversion (e.g. measured in t km-2).	ex ante, ex post	Market prices
	Erosion regulation	Landscape conversion can increase or reduce the ability of the landscape to retain soil	Amount of retained soil per unit area annually, pre- and post-conversion (e.g. measured in t km^{-2} y^{-1}).	ex ante, ex post	Avoided cost
	Bio-control and pest regulation	Landscape modification can lead to the loss or gain of habitats for pest predators Certain crops such as castor bean can have direct insecticidal properties to insects that target surrounding crops	*Direct measures* For feedstock landscapes that provide habitats to natural predators: "natural enemy biomass" or "pest egg predation" For feedstocks that have direct insecticidal properties: amount of active ingredient per unit area (e.g. measured in kg km^{-2}). *Proxy measures* For either landscapes that provide habitat or feedstocks that have insecticidal properties: amount of insecticide used per unit area, pre- and post-conversion (e.g. measured in t km^{-2} y^{-1})	ex ante, ex post	Replacement cost
	Pollination	Landscape modification can lead to the loss or gain of habitats for pollinators	Direct measures of pollination services related to the benefits of pollination for plant growth such as "added seed weight of pollinated plants" Pollination indices that consider some (or all) of the factors that affect the delivery of pollination services	ex ante, ex post	Market prices
Cultural (Section 3.3)	Recreation Religious values Education	Landscape conversion can lead to the loss of landscape elements that have cultural significance (e.g. sacred groves, areas with recreational/educational potential) Feedstock and/or its production practices can have cultural value (e.g. use of feedstock or co-products in cultural activities)	*Cultural services that can be monetised* Monetary value of cultural services per unit area, pre- and post-conversion (e.g. measured in USD km^{-2} y^{-1}) Cultural services that cannot be monetised Qualitative estimates of cultural value, pre- and post-conversion, e.g. through Likert-scales	ex ante, ex post ex post	Contingent Valuation Method (CVM) Travel Cost Method Hedonic Pricing Deliberative Monetary Valuation (DMV)

Finally, we do not delve into the human wellbeing outcomes of biofuel-driven changes in the flow of ecosystem services. This is because the mechanisms of human wellbeing impacts tend to be highly context-specific, depending not only on feedstock production decisions, but also on the different affected groups, prevailing institutions and broader socioeconomic dynamics of the area within which feedstock production is pursued (to name just a few). Instead we outline their, often complicated, nature using food security and poverty alleviation as examples (Section 4.2.4). Significant research would be needed to fully understand the context-specific linkages between biofuels, ecosystem services and human wellbeing.

4.2. Promises and gaps of an ecosystem services perspective for biofuel value chains

4.2.1. Ecosystem services as an additional lens for assessing biofuel sustainability

The concept of ecosystem services has the relevance, theoretical foundations, versatility and acceptability amongst academics and policy-makers to assess and put into perspective the trade-offs of biofuel production and use [25]. The ecosystem services approach can have various benefits for studying biofuel systems [16,38] such as the:

- ability to study coupled social-ecological systems
- ability to connect the environmental and socioeconomic impacts of biofuels
- ability to integrate insights from different knowledge sources
- user-oriented approach
- international acceptance by academics, practitioners and policy-makers.

The ecosystem services perspective can capture most of the sustainability impacts considered by the main biofuel-related certifications schemes [39]. However, such certification schemes have limitations in their representation of the environmental systems affected by feedstock production. This is because they use predominantly feasible causal indicators rather than more reliable but less feasible effect indicators [39]. Similarly environmental assessments do not provide an overarching picture of biofuel impacts, compared to ecosystem services studies, as they tend to focus on selected cause-effect relationships (i.e., selected environmental impact categories) [38]. On the contrary, ecosystem services studies have the potential to provide a holistic view of the cause-effect relationships of biofuel production [38].

The ecosystem services perspective could thus assist stakeholders in obtaining a better understanding of some of the key biofuel trade-offs across different spatial and temporal scales [56]. It offers a particularly strong lens to identify trade-offs in the flow of benefits (i.e. ecosystem services) associated with LUCC during the conversion of agricultural and natural areas (e.g. forests, grasslands). Synthesizing and communicating the complex dynamics and trade-offs of biofuel production and use in a robust, yet understandable manner, is something that other biofuel sustainability assessment frameworks miss in their current format [25,39]. Another appropriate use of the ecosystem services perspective could be to apply its underlying principles (Section 1) to broader land use policies/strategies that are linked to biofuels through the application of policy coherence [171,172].

However the ecosystem services perspective is not a panacea. It lacks explanatory power for key aspects of biofuel value chains such GHG/pollution emissions (Section 4.2.2) and is not easily compatible with some standard tools such as LCA (Section 4.2.3). Furthermore it requires substantial effort to link in practice the biofuel-driven changes in ecosystem services, with human wellbeing (Section 4.2.4).

4.2.2. Low explanatory power for important biofuel impacts

Pollution and climate change are direct drivers of ecosystem change (Section 2.2). As such they are conceptually akin to ecosystem disservices [173,174]. However, fertiliser/agrochemical run-off or GHG/air pollutant emissions further down the biofuel chain (i.e. from the conversion and combustion of biofuel) cannot be classified as ecosystem disservices as they are not linked to the actual ecological functioning of the modified landscape [155]. This means that important impacts of biofuel value chains cannot be captured properly through an ecosystem services perspective.

In a similar manner, through an ecosystem services perspective, feedstock is the main service provided by converted landscapes (Section 3.1.1). The actual energy carrier (i.e. ethanol, biodiesel) is produced through feedstock treatment, and thus cannot be considered as an ecosystem service per se. This means that while various technological options can increase (or decrease) the final provision of energy from biofuel systems, they cannot be easily captured from an ecosystem services perspective. This can decrease the ability of the ecosystem services perspective to inform biofuel policy and practice, as the actual end-products (i.e. liquid biofuels, co-products), are usually the focus of biofuel policies or national future energy scenarios [120].

In any case, air/water pollution, GHG emissions and energy provision are major aspects of the biofuel sustainability discourse as they are practically present in every indicator list, whether this includes certification schemes [175–177], academic studies [42,47] or legislation (e.g. EU-RED). The inability of the ecosystem services perspective to capture these aspects properly can raise some concerns about its true ability to inform biofuel decision-making.

4.2.3. Low compatibility with key tools applied in biofuel value chains

As already discussed the ecosystem services perspective is particularly strong for explaining impacts only during some life-cycle stages, and in particular feedstock production. This can complicate efforts to reconcile the outputs of ecosystem services studies with some standard and well-established tools for biofuel value chains such as the LCA. Actually there are significant challenges for reconciling LCAs with ecosystem services assessments, [178–180]. Central to this low compatibility in the context of biofuels is the fact that they capture key impacts such as energy provision, climate mitigation and water services through different perspectives (Section 3).

However, in smallholder settings (Type I and III systems, Section 2.1), where feedstock is produced either on the boundaries of farms (e.g. jatropha hedges) or by intercropping with other food crops (e.g. Ref. [34]) the ecosystem services perspective has benefits over LCAs. In such agricultural systems it is very difficult to estimate land requirement or allocate which agricultural inputs relate to the food crop and which to the feedstock in standard LCAs [133,170]. In our opinion in such contexts the ecosystem services perspective has a higher explanatory power than standard tools such as the LCA. The ecosystem services perspective tends to capture multiple benefits (or bundles of ecosystem services) without the need to delineate them [29,32]. Thus it does not need to consider the outputs (i.e. ecosystem services) as discrete units to allocate appropriately the inputs between them in order to quantify properly the resulting impacts.

4.2.4. Difficulty to establish links to human wellbeing and poverty alleviation

A key premise of the ecosystem services perspective is that changes in the flow of ecosystem services can affect different constituents of human wellbeing [17–19] and poverty [181–185]. Studies have attempted to draw these links more closely both conceptually and empirically [186–188]. For example changes in the flow of ecosystem services can have a positive or negative effect on the wellbeing and livelihoods of local communities around feedstock plantation [34], [118]. Sometimes, the income that local communities receive through biofuel-related activities can contribute to poverty alleviation [10].

However, while it is relatively straightforward to employ current ecosystem services frameworks to explain the effect of landscape conversion on the flow of ecosystem services (Section 3), it harder to identify the actual linkages to human wellbeing. This is particularly true for multi-dimensional concepts such as food security, energy security and poverty alleviation, among others.

For example there are several mechanisms through which feedstock production can affect the four pillars of food security (i.e. availability, access, utilization and stability) [134]. For example in Section 3.1.1-3.1.2 it was shown how feedstock production can divert food crop production, essentially reducing food availability through trade-offs between two provisioning ecosystem services. At the same time, the income received from feedstock production (i.e. the monetary outcome of a provisioning ecosystem service), can be used to buy food, thus increasing access to food [189]. Furthermore, this added income can be used to buy agricultural inputs or to implement integrated food-fuel systems to create positive synergies between feedstock and food production even in highly food insecure areas [9,190,191]. Additionally, feedstock producers in outgrower schemes may have better access to inputs, even for food crops, due to credit access because of their secure outgrower contracts that function as collateral [11].

Previous reviews at the interface of ecosystem services and human wellbeing have suggested that the constituents of human wellbeing of the MA framework do not reflect well the major human wellbeing impacts of biofuels [25,26]. Specific modifications in commonly used conceptual frameworks need to be made to reflect better the key impacts of biofuels on rural development (i.e. employment and income generation), food security, energy security, health and social cohesion, as well as overarching themes such as gender and land tenure [25,26].

Linking biofuel-induced changes in ecosystem services and human wellbeing remains a big research gap. It can be very complicated to establish such linkages considering the diversity of feedstocks, modes of production (Section 2.1) and social-ecological contexts within which feedstock production is pursued. These links can be very context-specific and should be considered carefully in efforts to promote biofuel feedstock production, especially areas where poor local communities over-rely on ecosystem services for their livelihoods.

4.3. Applications for policy and practice

4.3.1. Biofuel certification

There are various certification schemes that aim to promote biofuel sustainability. While some of the indicators in these certification schemes reflect certain ecosystem services [192], ecosystem services have not been properly integrated into such schemes [39]. Only recently have concepts from the ecosystem services literature and practice began featuring in some relevant certification schemes such as the Roundtable for Sustainable Palm Oil (RSPO), Bonsucro and the Roundtable for Sustainable Biomaterials (RSB) [175,176,193]. The meaningful integration of an ecosystem services perspective in such schemes will entail the selection of fit-for-purpose indicators for the ecosystem services component of these schemes (Section 4.2.1). Considering the more system-oriented lens of the ecosystem services perspective (Section 1), this could curb criticisms that "*indicators in certification schemes tend to demonstrate compliance with underlying legislation rather than ensure environmental sustainability*" [39].

4.3.2. Marginal land identification

There is a complex interface between biofuel production and food security (Section 4.2.3). Some of the more critical literature usually focuses and raises concerns on how biofuel production can compete with food production (Section 3.1.2), and how this can affect negatively food security [136]. This, often simplistic understanding, has coalesced in the "food vs fuel" debate and has been a major criticism of biofuels [2,194].

To avoid the competition between feedstock and food crop production (two provisioning ecosystem services), there have been suggestions to locate feedstock production in marginal lands [118,195,196,199]. The two major definitions of marginal land are (a) lands of low suitability for food crop production, and (b) land with limited possibilities for cost-effective agricultural production [197,198]. However, such uni-dimensional definitions disregard the multiple other benefits that humans may derive from marginal lands. It has been shown that areas considered marginal (and earmarked as such for bioenergy expansion) can harbor significant biodiversity and provide valuable ecosystem services [139,200]. These ecosystem services can be particularly important in poor rural areas where people often depend substantially on these services for their livelihoods.

The ecosystem services perspective is ideal for identifying the multiple benefits derived or lost from the conversion, conservation or restoration of marginal lands [201]. Essentially the ecosystem services perspective can move beyond the mono-dimensional understanding of the current marginal land discourse, to a more multi-dimensional understanding [118]. This can offer a better lens for appreciating the trade-offs of marginal land conversion for feedstock production.

4.3.3. Market-based instruments

There is a large debate about the potential of market-based instruments in promoting biodiversity conservation, e.g. Refs. [202–204]. Payment for Ecosystem Services (PES) schemes is a type of market-based instruments, where buyers of an ecosystem service (e.g. clean water) pay providers for this service essentially safeguarding it [205]. While it is not the purpose of this paper to delve into whether PES schemes actually perform well (see more comprehensive publications [206–211]), the fact remains that PES schemes have received significant traction in current environmental discourses such as the Green Economy [212].

Some literature has investigated whether PES schemes can help reduce the environmental burden of feedstock production. For example there is potential to establish PES schemes to incentivise feedstock producers to adopt feedstocks and production practices (e.g. reduced fertiliser use) that reduce high nutrient loading and the deterioration of downstream water quality [76] [88] [213].

However, as large-scale feedstock producers (Type IV systems) are usually private companies, their effective participation in PES schemes can be complicated [214]. For example, it has been suggested that several barriers might prohibit the involvement of large-scale sugarcane companies in Malawi in PES schemes, such as the fact that they can be both sellers and buyers of ecosystem services [215].

5. Conclusions

This review has highlighted that biofuel feedstock production can be a major driver of landscape modification. As such it can have ripple effects on ecosystems and the services they provide. Biofuel feedstock production can be linked to each of the five drivers of ecosystem change and biodiversity loss outlined in the Millennium Ecosystem Assessment. While habitat loss/change is possibly the most important driver, some feedstock production practices have been associated with pollution, invasiveness, overexploitation of biological resources and contribution to global/regional climate change.

Landscape modification due to feedstock production can also affect the provision of various provisioning, regulating and cultural ecosystem services. Despite the growing evidence about these impacts, some of the underlying impact mechanisms are context-specific and not well-understood. Elucidating the mechanisms through which these impacts emerge is important for understanding the full effect of feedstock production on human wellbeing.

Developing indicators that reflect such impacts is an important step towards unlocking the potential of the ecosystem services perspective for assessing the impacts of biofuel production and use. This review offered a set of conceptually coherent indicators (Table 2). However, it should be stressed that apart from conceptual coherence further criteria need to be considered when deciding such indicators for real-life application, such as their usefulness, ability to represent all key sustainability impacts and acceptability to stakeholders.

Despite its strengths for elucidating the trade-offs of biofuel expansion, the ecosystem services perspective has several limitations. Some of the most important are its inability to capture appropriately important biofuel sustainability impacts related to energy provision, GHG emissions and pollution, and its partially low incompatibility with some standard tools such as the LCA. On the other hand, the ecosystem services perspective can have some important applications such as (a) improving the prevailing marginal land discourse for selecting biofuel sites, (b) expanding biofuel/feedstock certification standards and (c) inform the development of market-based conservation instruments (e.g. PES schemes). However, further conceptual and empirical work would be needed to properly apply the ecosystem services perspective and unlock its full potential for promoting biofuel sustainability.

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