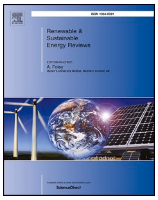
Renewable and Sustainable Energy Reviews 161 (2022) 112409

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Land use for bioenergy: Synergies and trade-offs between sustainable development goals

Ivan Vera [a,*], Birka Wicke [a], Patrick Lamers [b], Annette Cowie [c], Anna Repo [d], Bas Heukels [e], Colleen Zumpf [f], David Styles [g], Esther Parish [h], Francesco Cherubini [i], Göran Berndes [j], Henriette Jager [h], Luis Schiesari [k], Martin Junginger [a], Miguel Brandão [l], Niclas Scott Bentsen [m], Vassilis Daioglou [a,n], Zoe Harris [o,p], Floor van der Hilst [a]

[a] *Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 CB, Utrecht, the Netherlands*
[b] *National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO, 80401, USA*
[c] *NSW Department of Primary Industries, University of New England, Trevenna Rd, Armidale, NSW, 2351, Australia*
[d] *Natural Resources Institute Finland (Luke), PO Box 2, FI-00791, Helsinki, Finland*
[e] *Rijksdienst voor Ondernemend Nederland, Prinses Beatrixlaan 2, 2595 AL, The Hague, the Netherlands*
[f] *Argonne National Laboratory, Environmental Science Division, 9700 S. Cass Avenue, Lemont, IL, 60439, USA*
[g] *School of Engineering, University of Limerick, V94 T9PX, Limerick, Ireland*
[h] *Environmental Sciences Division, Oak Ridge National Laboratory, 1 Bethel Valley Road, Oak Ridge, TN, 37831, USA*
[i] *Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology, 7491, Trondheim, Norway*
[j] *Division of Physical Resource Theory, Department of Space, Earth and Environment, Chalmers University of Technology, Göteborg, Sweden*
[k] *Gestão Ambiental, Escola de Artes, Ciências e Humanidades, Universidade de São Paulo, São Paulo, SP, 03828-000, Brazil*
[l] *Department of Sustainable Development, Environmental Science and Engineering (SEED), School of Architecture and the Built Environment (ABE), KTH - Royal Institute of Technology, Sweden*
[m] *Department of Geosciences and Natural Resource Management, University of Copenhagen, Rolighedsvej 23, DK-1958, Frederiksberg C, Denmark*
[n] *PBL Netherlands Environmental Assessment Agency, Bezuidenhoutseweg 30, 2594 AV, The Hague, the Netherlands*
[o] *Centre for Environmental Policy, Imperial College, Weeks Building, 16-18 Prince's Gardens, London, SW7 1NE, London, United Kingdom*
[p] *Centre for Environment & Sustainability, University of Surrey, Arthur C. Clarke building, Guildford, GU2 7XH, Guildford, United Kingdom*

ARTICLE INFO

Keywords:
Biomass
Co-benefits
Sustainable development goals
Land use change
Environmental impacts
Socio-economic impacts
Energy crops

ABSTRACT

Bioenergy aims to reduce greenhouse gas (GHG) emissions and contribute to meeting global climate change mitigation targets. Nevertheless, several sustainability concerns are associated with bioenergy, especially related to the impacts of using land for dedicated energy crop production. Cultivating energy crops can result in synergies or trade-offs between GHG emission reductions and other sustainability effects depending on context-specific conditions. Using the United Nations Sustainable Development Goals (SDGs) framework, the main synergies and trade-offs associated with land use for dedicated energy crop production were identified. Furthermore, the context-specific conditions (i.e., biomass feedstock, previous land use, climate, soil type and agricultural management) which affect those synergies and trade-offs were also identified. The most recent literature was reviewed and a pairwise comparison between GHG emission reduction (SDG 13) and other SDGs was carried out. A total of 427 observations were classified as either synergy (170), trade-off (176), or no effect (81). Most synergies with environmentally-related SDGs, such as water quality and biodiversity conservation, were observed when perennial crops were produced on arable land, pasture or marginal land in the 'cool temperate moist' climate zone and 'high activity clay' soils. Most trade-offs were related to food security and water availability. Previous land use and feedstock type are more impactful in determining synergies and trade-offs than climatic zone and soil type. This study highlights the importance of considering context-specific conditions in evaluating synergies and trade-offs and their relevance for developing appropriate policies and practices to meet worldwide demand for bioenergy in a sustainable manner.

Abbreviations: Greenhouse gas, GHG; Sustainable Development Goals, SDGs; Intergovernmental Panel on Climate Change, IPCC; Global Bioenergy Partnership, GBEP; Renewable Energy Directive, REDII; Soil Organic Carbon, SOC; Soil & Water Assessment Tool, SWAT; indirect Land Use Change, iLUC; Life Cycle Assessment, LCA; United States of America, USA.

* Corresponding author.
E-mail address: i.c.veraconcha@uu.nl (I. Vera).

https://doi.org/10.1016/j.rser.2022.112409
Received 27 December 2021; Received in revised form 10 March 2022; Accepted 27 March 2022

1. Introduction

Reducing greenhouse gas (GHG) emissions to limit global temperature rise to well below 2 °C above pre-industrial levels is crucial for avoiding serious impacts from climate change [1,2]. Meeting GHG emission reduction targets will require various forms of renewable energy. Bioenergy is expected to play an essential role in future energy supply [2–4] and could exceed 20% of global (gross) final energy consumption by 2050 [5–7]. However, in recent years, the sustainability of large-scale bioenergy deployment has been the subject of fierce debate, with a strong focus on the impacts of using land for dedicated energy crops [8–12].

By reducing GHG emissions, bioenergy can contribute directly to the United Nations Sustainable Development Goals (SDGs) 7 (Affordable and clean energy) and 13 (Climate action) [13]. Although bioenergy aims to reduce emissions, it does not always lead to emission reductions [14]. Furthermore, allocating land to dedicated energy crops can compete with other ecosystem services, such as the provision of food, feed, and fibre [15,16]. In addition, growing dedicated energy crops may compete for land with other climate change mitigation options (e.g., afforestation and solar energy) or the conservation of natural habitats [17–20]. Competition for land will increase hand in hand with the increase in demand for these services [8]. This competition can lead to trade-offs by diminishing biodiversity and water resources or by causing adverse socio-economic impacts (e.g., increasing the risk in food security) [21]. Conversely, relative to arable land, utilizing land for dedicated energy crops can result in synergies with an increase in, among other things, biodiversity, water conservation, soil carbon stocks and employment (SDG 6 - Clean water and sanitation, SDG 8 - Decent work and economic growth and 15 - Life on Land) [22–24].

Whether land use for dedicated energy crops leads to synergies or trade-offs depends on a wide range of context-specific biophysical and socio-economic conditions [25,26]. Not accounting for these conditions can lead to sustainability impacts and counterproductive land use planning. For example, afforestation programs in China with non-native tree species have exacerbated water shortages [27,28]. Similar effects can occur for certain dedicated energy crops [29]. Despite potentially providing GHG mitigation benefits, the production of dedicated energy crops can simultaneously worsen other sustainability aspects when not considering context-specific conditions, e.g., increased food prices driven by land use change [30]. Therefore, identifying the context-specific conditions that maximize synergies and minimize trade-offs between the impacts of using land for dedicated energy can better inform decision-making on sustainable bioenergy systems.

Some studies have quantified synergies and trade-offs between different sustainability aspects of land use for dedicated energy crops [31–34]. Nevertheless, the understanding of this topic is still limited [34]. In addition, a synthesis that highlights the context-specific conditions underpinning the synergies and trade-offs between sustainability effects is missing. This lack of understanding hinders the development of sustainable land use strategies in which context-specific biophysical and socio-economic conditions are explicitly considered to prevent undesirable effects, or opportunities to deliver win-win outcomes are increased. Therefore, a synthesis to highlight the effect of context-specific conditions in shaping sustainability is paramount to developing coherent land use strategies.

Using the United Nations SDGs as a framework, this study synthesizes research on synergies and trade-offs between SDGs associated with land use for dedicated energy crops. This is done by reviewing the literature through a pairwise comparison between GHG emission reduction and other sustainability impacts of land use for dedicated energy crop production. Furthermore, the context-specific conditions under which sustainability synergies or trade-offs are found by examining biomass feedstock type, previous land use, climate, soil type and agricultural management leading to each outcome are assessed. Based on this analysis, strategies that can maximize synergies and minimize trade-offs, providing insights and identifying challenges for policy-making and future research are discussed.

2. Materials and methods

The scope of the study is land use for dedicated energy crops. Hence, bioenergy systems that use, for example, agricultural or forest residues as main feedstock are not considered. The residues definition of the European Commission's Renewable Energy Directive (REDII) to exclude residues studies was applied [35]. Synergies and trade-offs between the effects of land use for dedicated energy crops on SDGs were analyzed. As the objective of many policies promoting bioenergy is climate change mitigation, it was specifically addressed the synergies and trade-offs related to GHG emission savings. Therefore, synergies and trade-offs are analyzed through a pairwise comparison between GHG emission savings and effects in other SDGs. Studies that explicitly define and quantify GHG emission savings, and those that implicitly assume these savings were included. For example, studies that assess the effects on sustainability aspects (e.g., water availability) driven by dedicated energy crop production (biomass potentials) to meet bioenergy demand or climate change targets (implicitly assuming GHG savings).

Given the different definitions of synergies and trade-offs in literature, these terms were explicitly defined in accordance with the definitions provided by the IPCC. Positive connections between mitigation options (in this case, use of land for dedicated energy crop production to reduce GHG emissions) and SDGs are presented as synergies and negative connections as trade-offs [2]. Therefore, a synergy was considered when in addition to mitigating GHG emissions, land use for dedicated energy crops results in a positive effect on another SDG. For example, growing poplar for bioenergy on land previously in use for pasture can mitigate GHG emissions (SDG 13 Climate action) and reduce the risk of soil erosion (SDG 15 life on land) [30]. This positive connection is thus considered a synergy. Conversely, a trade-off occurs when land use for dedicated energy crops results in GHG emission reduction (SDG 13) while adversely affecting another SDG. For example, converting pasture to sugarcane for ethanol production can reduce GHG emissions (SDG 13) but also increase water scarcity (SDG 6 clean water and sanitation) [36]. This negative connection is, therefore, considered a trade-off. A connection was classified as 'no effect' when no positive or negative effects on SDGs besides GHG emission reduction were reported from using the land for growing dedicated energy crops. Unless explicitly specified, on every occasion where synergies and trade-offs are addressed in the following sections, it refers to those between GHG emission reduction (SDG 13) and other SDGs of using land for dedicated energy crop production for bioenergy.

The review was conducted in two stages, (1) synergies and trade-offs were identified, and (2) the context-specific conditions of these connections were characterized. For the first stage, international peer-reviewed journal papers were analyzed, seeking to extract reported synergies and trade-offs. An integrated search string in Scopus (TITLE-ABS-KEY (bioenergy AND land use AND trade-offs OR synergies/co-benefits) AND DOCTYPE (ar), where "ar" refers to articles) was applied. The search words were based on relevant terms that capture the most important literature regarding synergies (or 'co-benefits'), trade-offs and bioenergy. Only studies that include both terms "bioenergy" and "land use" were considered. Only articles published from 2010 onwards were included to focus on the most recent developments and ensure a state-of-the-art review. Review style papers were not considered to avoid double counting. The search was complemented with additional relevant peer-reviewed publications suggested by experts from the International Energy Agency Bioenergy Task 45: Climate and Sustainability Effects of Bioenergy within the broader Bioeconomy. An overview of the studies included in the sample is presented in Table S1 of the supplementary material and in section 3 on the observations of synergies and trade-offs of land use for bioenergy section.

For this first stage, a multi-step approach was followed in which first the sustainability effects presented in each study and their direction (positive or negative) were identified. No threshold was applied on the severity of the sustainability effects; the focus was on the direction of the sustainability effect and not its intensity. Second, these sustainability effects were classified according to the SDGs. This was based on previously defined linkages between sustainability indicators for bioenergy (here taken from the Global Bioenergy Partnership, (GBEP)) and the SDGs [37]. The GBEP has developed a set of indicators for assessing bioenergy sustainability [38]. These indicators are developed for the three pillars of sustainability. Frtischce et al. [37] has developed a framework to link SDGs and GBEP sustainability indicators for bioenergy based on the relevant criteria of each indicator and SDG descriptions. For example, effects on water quality from biomass production were linked with SDG 6 (clean water and sanitation), more specifically with target 6.3 water quality [37]. Thus, effects on water quality were classified within SDG 6. For this first stage of the literature review, sustainability effects were classified on an SDG level, and thus SDG targets and indicators were not specified. Third, based on the SDG classification and the direction of the relation, it was established whether the connection between GHG emission reduction (SDG 13) and other SDGs was a synergy or a trade-off. Fourth, the number of "observed" synergies and trade-offs present in the literature sample were counted. For this study, one "observation" refers to one individual synergy or trade-off found in the literature sample. To illustrate, an identified synergy or trade-off between GHG emission reduction (SDG 13) and life on land (SDG 15) represents one observation.

For the second stage of the review, the scope of the analysis was narrowed to the environmental SDGs and included SDG indicators. The focus was on the environmental SDGs because of the primary relevance of the natural environment for human well-being [39]. Synergies and trade-offs between GHG emission reduction (SDG 13) and SDG 6 (Clean water and sanitation), SDG 15 (Life on land), and other indicators of SDG 13 (Climate action, e.g., albedo effect) are covered. The following context-specific conditions that can determine synergies and trade-offs are considered: previous land use, biophysical characteristics (mainly climate conditions and soil characteristics), management practices and feedstock type. The IPCC climate zone and soil type classes (IPCC 2006) were used to classify the biophysical characteristics of the area of each reviewed study. This was done to harmonize terminology used by different studies to describe biophysical characteristics and ascribe conditions for studies that did not report soil or climate data. The designation 'scale' was used to classify observations in which the geographical scope of the study extended beyond the boundaries of one particular climate zone or soil type. The context-specific conditions for each study were identified in order to link them to the synergies and trade-offs. This allowed determining under which conditions land use for energy crops led to synergies or trade-offs between GHG emission reduction and other SDGs.

3. Observations of synergies and trade-offs of land use for bioenergy

A total of 134 peer-reviewed studies were found through the systematic literature search. However, studies that focused on agricultural residues were excluded [40–42], land use mapping [43–46], stakeholders' perspectives and decision making [47–50], farmland services (e.g., dairy and poultry) [51–53] and review style studies [54–57]. Thus, in total only 59 studies fell within the scope of the study.

The geographical scope of the sample was mainly limited to North America (39%) and Europe (29%). 7% of studies focused on South America and the Caribbean, and 2% focused on Africa. The geographical scope of the rest of the studies included in the review was worldwide (23%). The study area (scale) of each study varied considerably within the sample, from a few hectares (8%) to a global scale (25%). The scale from a few studies was limited to a continent (7%) or country (7%), while the majority applied a regional scale (53%). Nevertheless, the scale of the regional studies varied considerably in extent. For some studies, a small area was defined by a county, while others comprised an entire region like the Southeastern US. Regarding the approach used by these studies, 73% of studies present in the sample were modelling exercises with a wide range of model types such as input-output models, partial equilibrium models, integrated assessment models and hydrological models (e.g., SWAT). In addition, several studies combined the modelling exercise with other particular methods such as ecosystem service assessment (7%) or a life cycle assessment approach (LCA) (2%). Few studies carried out field trials (8%). The rest of the studies were carried out with an LCA approach (2%), ecosystem service assessment (5%) or a descriptive assessment (3%). A large proportion (74%) of the relevant studies were published in the last years (from 2015), highlighting increasing interest in the topic. Table S1 in the supplementary material presents the overview of the studies in the sample.

A total of 427 observations from the 59 retained studies were classified as either synergies (170), trade-offs (176), or no effect (81) (Fig. 1). Most of the observations were found between GHG emission reduction (SDG 13) and SDGs 6 (Clean water and sanitation) with 45 synergies, 72 trade-offs and 32 no effects; and SDG 15 (Life on land) with 74 synergies, 56 trade-offs and 31 no effects. Fewer observations were found with SDG 2 (Zero hunger with 1 synergy, 34 trade-offs and 9 no effects), other indicators of SDG 13 (Climate action; 21 synergies, 4 trade-offs and 2 no effects), SDG 8 (Decent work and economic growth; 6 synergies, 10 trade-offs and 2 no effects) and SDG 3 (Good health and well-being; 18 synergies, 0 trade-offs and 4 no effects). One synergy was observed related to SDG 14 (Life below water).

3.1. Synergies and trade-offs with SGD 15 – Life on land

Compared to other SDGs, more synergies and trade-offs were found in the sample between GHG emission reductions (SDG 13) and life on land (SDG 15) (Fig. 1). SDG 15 aims to protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, halt and reverse land degradation, and halt biodiversity loss. Most synergies are observed with soil quality and biodiversity conservation, while most trade-offs are with the sustainable management of forests. Production of dedicated perennial energy crops can increase soil organic carbon (SOC) levels compared to the previous land uses such as arable land and pasture. In addition, it can also increase sediment retention, and improve the overall quality of soils, thus contributing to restoring degraded land (SDG 15) [30,58–63]. Because perennial crops are not replanted every year, soil disturbance is less frequent than annual crops. Nevertheless, it is also reported that the initial cultivation of dedicated energy crops when non-agricultural land is used can aggravate soil erosion, negatively affect soil quality, and contribute to overall soil degradation [36,64–66].

For some locations and feedstocks, the production of dedicated energy crops was reported to increase species abundances and improve habitat for insects, birds and mammals (SDG 15) [30,59,67–69]. For example, it has been observed that using land for dedicated energy crops can enhance ecosystem conservation and promote pollinator communities, depending on the land use transition [70–72]. Other studies reported a trade-off between growing dedicated energy crops and biodiversity. Specifically, habitat deterioration was reported for lands with high ecological and biodiversity values [73,74]. Negative effects on species abundance were also reported in former natural areas [62,75].

Only trade-offs were reported for producing dedicated energy crops and the sustainable management of forests (SDG 15). Without mitigation measures, land used for dedicated energy crops can lead to competition for land with other land-based objectives, which can imply the loss of forest and other important biodiversity areas [76–79]. The majority of studies that presented these trade-offs followed a global geographical scope with an ex-ante type of assessment, in which forest loss was traced as an indirect effect of land competition under different bioenergy, food demand and socio-economic scenarios [21,80–82]. Therefore, trade-offs

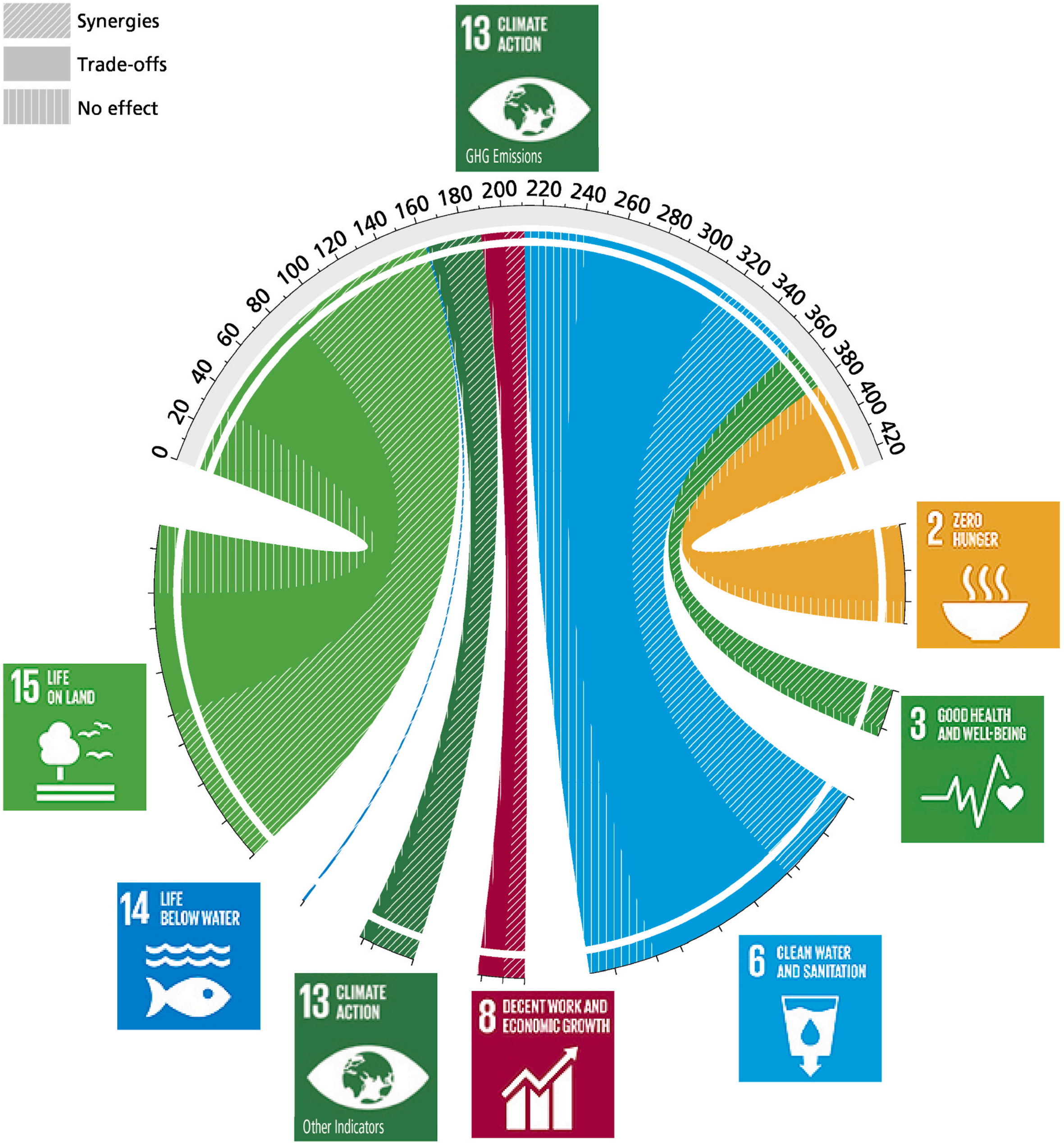


Fig. 1. Synergies and trade-offs between effects of growing dedicated energy crops on GHG emission reductions (SDG 13 Climate action) and other SDGs. The width of each connection refers to the number of observations recorded as synergies, trade-offs and no effect found in the literature.

with sustainable management of forests depended upon additional dynamics such as the development of future food demand [34].

3.2. Synergies and trade-offs with SGD 13 – Water and sanitation

Fewer synergies and trade-offs were reported between the effects of land used for dedicated energy crops on GHG emission reductions (SDG 13) and clean water and sanitation (SDG 6). Most trade-offs were related to a region (mainly a watershed or a basin), hydrological cycle changes, or the effect of irrigation water withdrawals on water availability. Using land for dedicated energy crops can result in changes in run-off or streamflow, disturbances of evapotranspiration balances, and reductions in water storage [65,73,83–85]. To illustrate, using land for dedicated energy crops such as eucalyptus or oil palm is shown to reduce the streamflow of a watershed as a consequence of higher evapotranspiration rates compared to the previous land uses [86,87]. Reducing GHG emissions and meeting bioenergy targets by the end of the century can substantially increase water withdrawals, intensify the pressure on water resources, and exacerbate water stress [88–92]. In many regions, the cultivation of dedicated energy crops does not require irrigation. However, in some water-scarce regions, yields would be reduced if no irrigation is applied. Consequently, more land would be required to achieve the same bioenergy production. This can indirectly affect forests (SDG 15) and decrease food-related agricultural production (SDG 2) [34,91,93].

Most synergies between using land for dedicated energy crops and clean water and sanitation (SDG 6) are related to water quality. Generally, an overabundance of nutrients (mainly phosphorous and nitrogen) in water bodies can deteriorate water quality and affect aquatic life. However, it is shown that the production of some dedicated energy crops on agricultural landscapes can help to reduce these impacts by intercepting nutrient run-off to water bodies and benefit downstream ecosystems [94,95]. Therefore, these are synergies with water quality (SDG 6) and life below water (SDG 14). Lower fertilization and pesticides rates characterize the production of some dedicated energy crops so that the introduction of these crops into agricultural landscapes with previously high fertilization inputs can improve water quality and reduce salinization of water bodies [30,60,62,70,96].

3.3. Synergies and trade-offs with SDG 2 – Zero hunger

There are considerably more trade-offs than synergies between land use impacts for dedicated energy crops on GHG emission reduction (SDG 13) and zero hunger (SDG 2). Literature has highlighted that food security risks increase when land dedicated to food production is limited by dedicated grown energy crops [21,57,75,78,83,97–99]. Land competition can negatively affect agricultural production and food supply, and lead to increases in food prices [30,76]. Furthermore, it can potentially drive the conversion of natural land to managed systems and affect other SDGs such as SDG 15 [74]. Meeting global bioenergy demand while simultaneously assuring sufficient land for agricultural production for a continuously growing and changing food demand is a challenge [21,79,83]. However, shifting from 1st to 2nd generation crops for bioenergy (i.e. annual crops to lignocellulosic energy crops) can reduce food security risks and can even provide synergies with SDG 2 (Fig. 1). For example, in the Brandenburg region (Germany), the regional biogas and GHG emissions reduction target can be achieved using miscanthus on marginal land instead of corn on arable land. Due to the comparatively higher yields, less area is required. This results in the release of land previously occupied by corn cultivation for biogas to additional agricultural production [59].

3.4. Synergies and trade-offs with SDG 8 – Decent work and economic growth

Most of the trade-offs between using land for dedicated energy crops for GHG emission reduction and decent work and economic growth (SDG 8) were related to farmers' revenue. Studies reported negative effects on farmers' revenue when they shifted from 1st to 2nd generation crops as bioenergy feedstock. In most cases, the shift reduced GHG emissions and decreased revenue for farmers [65,70,72,100]. Unfavorable economic conditions, such as low biomass prices and high logistical costs, resulted in lower revenues for dedicated energy crops than food crops [65]. For example, in Illinois (USA), corn for bioethanol is more competitive in term of farmers' revenue than switchgrass under current market conditions and policy incentives [72]. However, in other locations (e.g., East Tennessee), it has been shown that under certain conditions 2nd generation bioenergy crops can provide additional sources of income [95]. For example, farmers can benefit from additional income from harvesting switchgrass at times of the year when there is no other agricultural work available [101]. Still, bioenergy production costs are too high to compete with (conventional) energy costs in several world regions (Wu et al., 2019). This disincentivizes farmers to use the land for dedicated energy crops. However, subsidies can promote increasing land use for dedicated energy crops for bioenergy and positively affect income and revenues (SDG 8) [102]. Furthermore, in some cases, wood pellet production from short-rotation coppice (SRC) is cost-competitive for heat and electricity, such as reported for Mexico [103]. Several synergies are also reported between GHG emission reduction and job creation (SDG 8). Using land for dedicated energy crops for bioenergy can create jobs for local communities [59,73,101].

3.5. Synergies and trade-offs with other indicators from SDG 13 – Climate action and SDG 3 – Good health and well-being

Utilizing land for dedicated energy crops shows synergies with climate change adaptation indicators of SDG 13. It has been reported that using land for such purposes can help to mitigate floods, especially when integrating perennials in flood-prone areas in agricultural landscapes [60,104]. This effect is not only crucial for the adaptation to climate-related hazards and natural disasters (SDG 13), which can become more frequent in the upcoming years, but it also contributes to avoiding the high costs of other potential flood mitigation efforts [58]. In addition, integrating perennial crops into arable areas can provide cooling effects through albedo changes and improved air quality [32,83,101].

For good health and well-being (SDG 3), mostly synergies were reported with dedicated energy crop production. Most of these synergies are related to ecosystem cultural services. For example, in Denmark, managing land to grow poplar or oak for bioenergy positively affected recreation and aesthetics services, whereas miscanthus reported neither a positive nor negative effect [105]. Synergies were also reported for other recreational services and wildlife habitats. For example, in Illinois, dedicating land to grow switchgrass instead of corn for bioenergy production was reported to enhance water-based recreation, wildlife viewing and pheasant hunting [72].

4. Context-specific conditions that shape synergies and trade-offs

Previous land use, feedstock type, soil and climate zone influence the synergies and trade-offs between GHG emissions reduction (SDG 13) and other environmentally-related SDGs. The analysis of these context-specific conditions and how they affect synergies and trade-offs show that previous land use and feedstock type appear to have more influence than other context-specific conditions.

4.1. Previous land use

Previous land use is an important biophysical attribute that defines trade-offs and synergies. The analysis showed more synergies than trade-offs between environmentally-related SDGs (6, 13, 14 and 15) (Fig. 2) when agricultural land was used for the production of dedicated energy crops. However, this did not hold true when potential effects of indirect land use change on other SDGs were considered (SDG 2, 3, and 8). Dedicating arable land to the production of dedicated energy crops can result in GHG emission reductions (SDG 13) and simultaneously improve water quality (SDG 6.3); help to strengthen resilience and adaptive capacity to climate-related hazards and natural disasters (SDG 13.1); increase biodiversity (SDG 15.1); and improve soil quality (SGD 15.3). The synergies that are reported for a land use transition from arable land to dedicated energy crops are linked to the feedstock change from annual food crops (e.g., corn and soybean) to perennial energy crops (e.g., perennial grasses and SRC) (Fig. 3). Conversely, when arable land is dedicated to growing perennial energy crops, it generally results in trade-offs with water-use efficiency (SDG 6.4).

Converting arable land to producing dedicated perennial energy crops has been reported to have synergies with several SDG indicators (Fig. 2). For example, it was reported that growing perennials on land previously in use for (intensively) managed corn and soy bean decreased nutrient loading at the watershed/basin level (SDG 6.3) and helped to prevent downstream hypoxia episodes, thus benefitting aquatic life (14.1) [94]. Synergies with biodiversity conservation were reported for several locations (e.g., the USA, Germany and the Netherlands) [30,59,69,70,72]. For example, allocating less-profitable areas of arable land to switchgrass has been shown to increase bird species richness [106]. It was also reported that perennial crops provided better habitat conditions compared to annual crops in arable land, which increased the abundance of species such as birds, mammals, and pollinators (e.g., Dauber et al., 2015). In the Netherlands, the introduction of miscanthus in intensively managed arable areas positively affected biodiversity [64]. Another synergy relates to improving soil quality by accumulating organic matter in deeper soil layers, providing better conditions to increase sediment retention and decreasing soil erosion (SDG 15.3) (e.g.

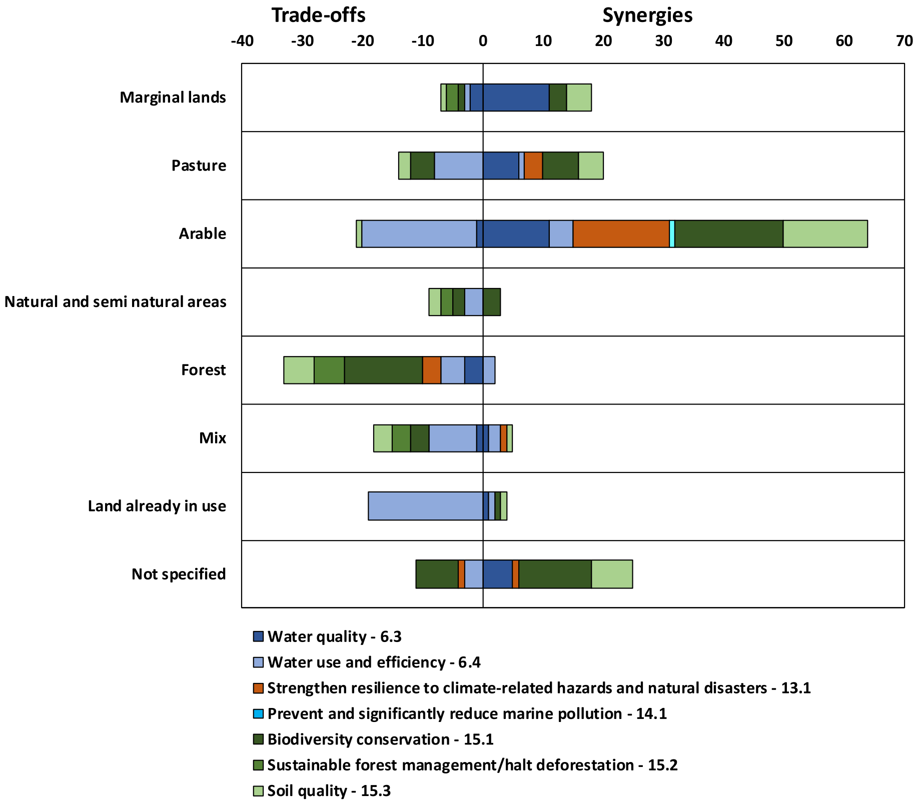


Fig. 2. Number of observations recorded as synergies and trade-offs between the effects of using land for dedicated energy crops on GHG emission reductions (SDG 13 Climate action) and other environment-related SDG targets classified according to the type of previous land use. A description of the land use categories can be found in Table S2 of the supplementary material.

Ref. [62]). Integrating deep-rooted perennial crops as buffers into agricultural landscapes can help to increase resilience to more extreme climate conditions [104] and to provide mitigation benefits on flood events [58] (SDG 13.1). Conversely, Introducing dedicated energy crops (e.g., eucalyptus) can lead to changes in the hydrological system of a region and affect water availability by increasing water use for irrigation compared to previously arable land (e.g., Heidari et al., 2021).

Synergies with water quality (SDG 6.3) from land previously in use as pastures (including intensively managed) generally involved a feedstock change to perennial crops as they require lower fertilization rates than annual crops such as corn. Applying fewer inputs can result in less nutrient run-off and overall water quality improvement [64,72,105]. However, meeting global bioenergy targets with dedicated energy crops produced in areas previously used as pasture (and forest) could double agricultural water withdrawal, increase pressure on water resources and lead to ecosystem degradation (Bonsch et al., 2016). In addition, it can also reduce the soil water storage capacity and reduce water streamflow [73]. For example, the production of oil palm in tabasco on pastures increased evapotranspiration considerably and reduced the water shed stream flow (Heidari et al., 2020). Nevertheless, for some locations, it is suggested that the production of poplar in pasture areas can have minimal hydrological effects [90]. When sugarcane was produced on land previously in use for pastures, it provided a slightly worst cover against the impacts of rain, thereby increasing soil loss to a limited extent [36].

Allocating natural or semi-natural areas, including forests, to the production of dedicated energy crops generally led to trade-offs affecting different targets related to life on land (SDG 15), especially target 15.1 biodiversity conservation and 15.2 sustainable use of forest (end deforestation and restore degraded forests) [76,80,107]. Meeting future global bioenergy demand while preserving natural and semi-natural areas and avoiding effects in other ecosystem services can be a significant challenge [108]. In addition, conversion from natural vegetation to dedicated energy crops can reduce carbon stocks in biomass and soil and can therefore result in negative effects on GHG emissions (SDG 13) [21]. Nevertheless, restoring natural landscapes, such as natural grasslands or forests, can provide a valuable source of biomass for bioenergy and (depending on the species grown) could enhance biodiversity conservation by providing species habitats. However, land restoration is undertaken to enhance conservation values and will not necessarily maximize biomass production (Van Meerbeek et al., 2016). In the USA, converting grassland to arable land (corn/soybean rotation for bioenergy purposes) decreased bird communities (Blank et al., 2016). It has also been shown that compared to grasslands, introducing switchgrass affects the hydrological cycle by reducing transpiration and increasing evaporation [109].

Although there are fewer observations compared to other land use transitions, using marginal land for dedicated energy crops provided more synergies than trade-offs (Fig. 2). These synergies were mainly observed between GHG emission reduction (SDG 13) and water quality (SDG 6.3), and to a lesser extent with soil quality (15.3). For example, allocating marginal lands previously used for cropland to dedicated energy crop production reduced nutrient loading to water bodies [96]. In addition, growing perennial crops such as miscanthus and poplar on marginal lands reduced sediment loss and the overall risk of soil erosion [84]. For land already in use for the production of dedicated energy crops, trade-offs are mainly with water-use efficiency (SDG 6.4). In South America and the Caribbean, many countries will have to introduce irrigation schemes to mitigate climate change-induced yield losses in sugar crop plantations to meet bioethanol demand and avoid significant expansion. These irrigation schemes can have impacts on local water resources (Zhong et al., 2021).

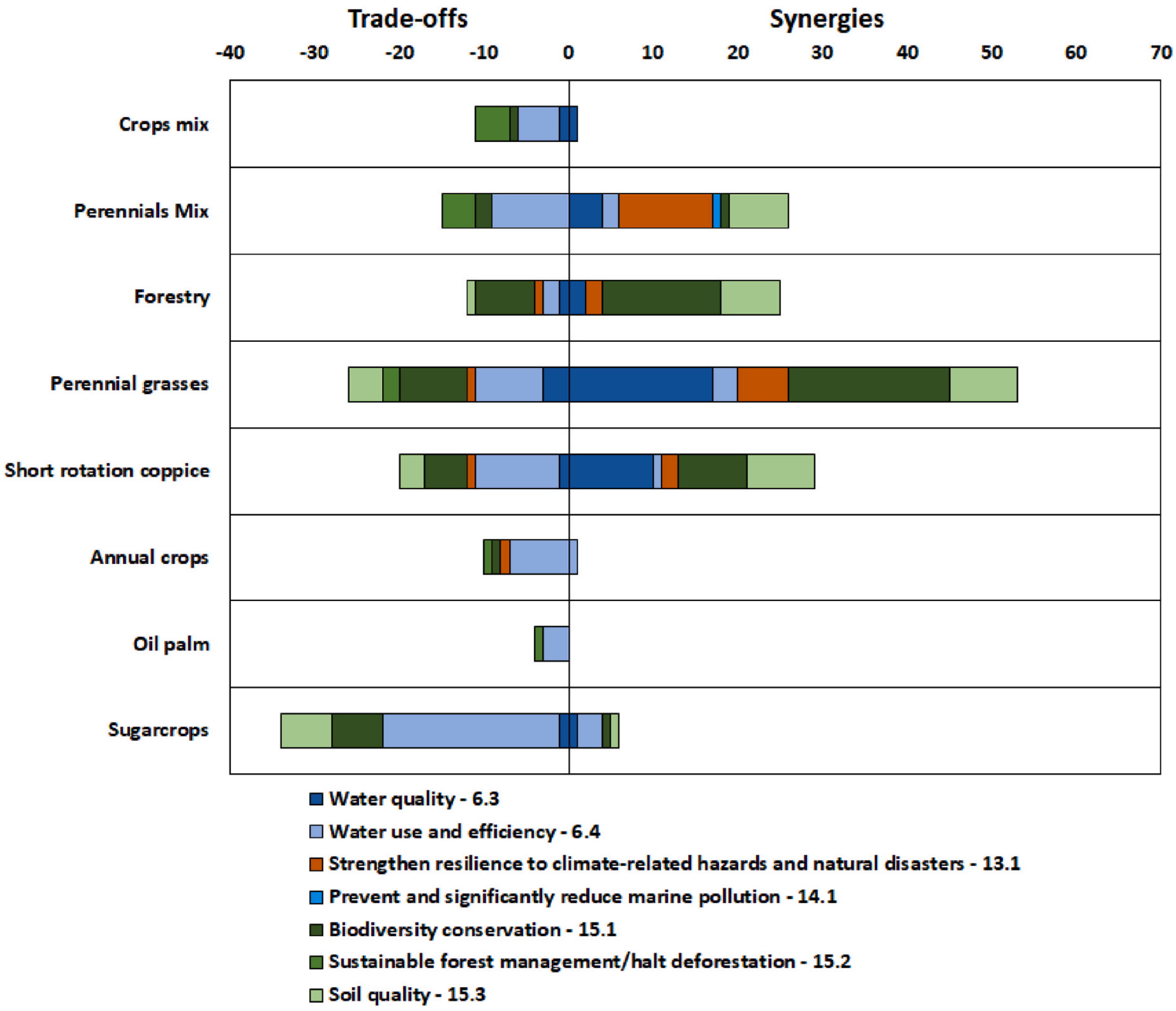


Fig. 3. Number of observations recorded as synergies or trade-offs between GHG emission reductions (SDG 13 Climate action) and other environment-related SDG targets for using land for dedicated energy crops, classified according to feedstock type. A description of the feedstock types can be found in Table S3 of the supplementary material.

4.2. Feedstock type

Based on the studies in the sample, utilizing perennial crops and forestry feedstock provides more synergies than trade-offs, compared to annual crops (Fig. 3). Most of the synergies for perennial crops were related to water quality (SDG 6.3), strengthening resilience and adaptive capacity to climate-related hazards and natural disasters (13.1), and biodiversity conservation (15.1), while the majority of trade-offs are with water use and water-use efficiency (SDG 6.4). Generally, perennial crops require fewer inputs such as fertilizers and pesticides. Therefore, for several locations, nitrogen and phosphorus losses to water consistently decreased when perennials were planted, resulting in an overall water quality improvement [101]. However, the reduction of nutrient losses is relative to the type of previous land use. In most of these cases, land previously in use for the cultivation of annual crops with high inputs was used for dedicated energy crop production [30,70,72,96]. The positive effect of perennial crops on biodiversity, and on resilience and adaptive capacity to climate-related hazards and natural disasters also depends on the previous land use. For example, including perennial crops in agricultural areas with annual crops can mitigate impacts from floods [60,104] and enhance biodiversity [68]. Furthermore, this feedstock transition can also lead to regional cooling via changes in albedo [110]. Conversely, the production of perennials to meet global bioenergy demand can considerably affect biodiversity if carried out in natural areas [74]. Still, perennial crops provide better habitat for species than annual crops [101].

Although most observations with water use and water use efficiency (SDG 6.4) for perennial crops are trade-offs associated with the inclusion of irrigation schemes for high yields and hydrological changes, there are also synergies. Perennial crops are characterized by higher water-use efficiency than annual crops, and can capture more water, i.e., increase interception of lateral flow. For example, under the same conditions, miscanthus is reported to have a higher water-use efficiency than corn [109]. In addition, deep-rooted perennials can have a reduced need for irrigation. However, watershed models show that replacing annual with perennial crops consistently reduces stream flow because of increased evapotranspiration [84,86]. Nevertheless, these effects can also vary across seasons. To illustrate, the production of poplar has minimal effects on annual stream flows. However, evapotranspiration from poplar substantially exceeds that of the previous land use during summer months, decreasing seasonal streamflow considerably [90]. Synergies are also found with soil quality (SDG 15.3) as perennials can accumulate more SOC than annual crops leading to an overall improvement in soil fertility.

For forestry feedstocks such as oak and spruce, mostly synergies have been shown between GHG emissions reduction and biodiversity conservation (SDG 15.1). In Denmark, it is reported that under local biophysical conditions, forestry feedstock types provide better habitat for species and thus a higher conservation potential relative to perennial grasses and SRC [105]. Similar outcomes are reported for other locations when poplar is managed under a short rotation forestry scheme [61]. Forestry feedstocks are also shown to increase soil quality (SDG 15.3) and provide pollination services (SDG 15.1) [105]. They are also reported to have less impact on local water availability than other feedstocks such as miscanthus. These positive effects also depend upon the previous land use, such as arable land or grassland.

For sugar crops, oil palm and annual crops, mostly trade-offs are reported. These feedstock types were reported to negatively affect water availability (SDG 6.4), biodiversity (SDG 15.1) and soil quality (15.3). However, these trade-offs also depend considerably on the local biophysical conditions and previous land use. For example, in Brazil, water availability can be diminished if sugarcane is produced in areas where precipitation conditions are not adequate for plant development and irrigation is required [88]. A similar outcome is reported for annual crops (e.g., maize, wheat and sorghum) at a regional and global scale where developing irrigation schemes in water-scarce areas can affect water availability [92,93]. Local water availability could also be affected in several countries in South America and the Caribbean, where climate change-induced precipitation changes could result in irrigation being required for sugar crops [89]. Producing sugar crops can affect biodiversity and soil quality, e.g., reducing species abundance and increasing soil erosion risk [36,64]. Nevertheless, this effect og sugar crops production relies strongly on the previous land use. In some cases, sugarcane production shows synergies as it increases species abundance and reduces the risk of soil erosion, mainly when carried out on previously arable land under annual crop regimes. Oil palm production has also been shown to have a negative effect on sustainable forest management, and it is suggested that developing oil palm in the Congo Basin can negatively affect the country's sustainable forest management (SDG 15.3) [76].

4.3. *Biophysical conditions*

For dedicated energy crops grown in a 'cool temperate moist' climate more synergies than trade-offs were reported between GHG emission reduction and other SDGs (see Fig. SM1 in the supplementary material). Under these climate conditions, more synergies were reported between GHG emission reduction (SDG 13) and water quality (SDG 6.3), strengthening resilience to climate-related hazards and natural disasters (SDG 13.1), biodiversity conversation (SDG 15.1) and soil quality (SDG 15.3). In contrast, more trade-offs were reported with water use and efficiency (SDG 6.4). Most synergies reported for a 'cool temperate moist' climate were also characterized by 'high activity clay' soils (see Fig. SM2 in the supplementary material). In addition, most synergies were related to the production of perennial crops accompanied by a transition away from arable land, which generally produced more synergies than trade-offs. For example, the production of poplar on land previously in use as arable land in Mulde, Germany, which has a 'cool temperate moist' climate and has 'high activity clay' soils, resulted in positive effects on water quality (SDG 6.3), biodiversity conservation (SDG 15.1) and soil quality (SDG 15.3) [30]. Similar outcomes are reported for other locations with comparable biophysical characteristics. For example, the production of miscanthus in Ireland and switchgrass in Wisconsin (USA) on land previously in use for arable cropping with a 'cool temperate moist' climate and 'high activity clay' soils, positively affected biodiversity [67,68].

Also, more synergies than trade-offs were reported for the 'warm temperate moist' climate, especially related to water quality (SDG 6.3) and soil quality (15.3). Most of these synergies are classified under either 'high activity clay' soils or 'low activity clay' soils. For 'low activity clay' soils, more synergies than trade-offs were reported (see Fig. SM2 in the supplementary material). These synergies were also related to the production of perennial crops on land previously in use as pasture or cropland [72,95]. However, under this combination of biophysical characteristics, switchgrass production also reported trade-offs by reducing water storage (SDG 6.4), negatively affecting biodiversity (SDG 15.1) and hampering soil quality (SDG 15.3) [73]. Nevertheless, these trade-offs were also traced to a change in a combination of land use categories to produce dedicated energy crops, i.e., savannah, grasslands, pasture and barren land (see category Mix in Fig. 2). It was also reported that allocating land to the production of dedicated energy crops under 'warm temperate moist' and 'low activity clay soil' negatively affected the sustainable use and managament of forest via indirect land use change (SDG 15.2) [111].

Other climate zones and soil types were not well represented in the literature. However, studies in the 'tropical' (moist and wet) climate zone reported more trade-offs than synergies between GHG emission reduction and other SDGs, especially with water use and efficiency (SDG 6.4). For example, oil palm production in Mexico reduced watershed streamflow due to an increase in evapotranspiration rates [87]. In addition, in the same climate zone, it was shown that the production of oil palm can affect the sustainable use of forests and biodiversity (SDG 15.1 and 15.2) [76]. Water availability trade-offs were also reported for sugarcane production under a 'tropical moist' climate zone and 'low activity clay' soil [36]. The production of eucalyptus was also shown to lead to streamflow reduction and affect water quantity (SDG 6.4) under a 'tropical moist' climate zone and 'high activity clay' soils [86].

The large majority of synergies and trade-offs were reported under the 'scale' classification for climate zone and soil type (studies in which the geographical scope extended beyond the boundaries of one particular climate zone or soil type). Most of the studies classified under 'scale' had a global, national or regional focus. Most of the trade-offs were related to water use and efficiency (SDG 6.4) and, to a lesser extent, to biodiversity conservation (15.1). Regardless of the feedstock type and previous land use, it was generally shown that deploying large-scale bioenergy systems to meet global and national bioenergy demand can lead to unsustainable water withdrawals in the form of irrigation [89,92,112]. These trade-offs were generally reported through the nexus between land and water and its effects on biodiversity conservation (SDG 15.1) [74,79] and the sustainable use of forest (SDG 15.2) [21,81,113].

5. Discussion

5.1. *Key findings*

This study compiled state-of-the-art knowledge on synergies and trade-offs between GHG emission reduction from utilizing land for dedicated energy crops production (SDG 13) and other SDGs. Context-specific conditions under which sustainability synergies or trade-offs occur, particularly for environmentally-related SDGs were identified. The findings suggest that using land for dedicated energy crops results overall in almost an equivalent number of synergies and trade-offs between SDG 13 and other SDGs, just a few more trade-offs were reported. Note that more synergies were found for SDGs 3, 13, 14 and 15, and more trade-offs for SDGs 2, 6 and 8. Dedicated energy crops can compete for land with food production and therefore (directly or indirectly) affect food supply and food price [114]. In addition, the pressure on food markets can intensify when annual crops such as corn are allocated to bioenergy [115]. However, this effect is not exclusively negative: increased food prices can harm consumers, especially low-income households, but can simultaneously benefit farmers through higher profits [116]. Still, the degree to which an increase in food prices is directly driven by using land to produce dedicated energy crops is difficult to determine, as food prices depend on interactions among many variables [117].

In general, the findings show that trade-offs between SDG 13 and clean water and sanitation (SDG 6) are mostly related to water use and efficiency (SDG 6.4). In contrast, most synergies are related to water quality (SDG 6.3). Water demand for dedicated energy crops can increase water withdrawal through irrigation and increase water scarcity. However, carefully choosing locations to produce dedicated energy crops for bioenergy and choosing feedstocks adapted to local conditions can minimize pressures on water availability [20]. Synergies and trade-offs with SDG 15 are both consistently reported. Depending on context-specific conditions, it is shown that producing dedicated energy crops can positively or negatively affect biodiversity (SDG 15.1). Also, using arable land to grow dedicated energy crops can improve soil quality (15.3). Generally, perennials provide better protection to soil erosion and increase soil quality [118]. However, dedicating land to produce dedicated energy crops can also negatively affect sustainable forest management (15.2) without concrete mitigation measures. Utilizing land for dedicated energy crops without economic incentives results in trade-offs with farmers' revenues and income (SDG 8) but also in synergies with good health and well-being (SDG 3).

A combination of context-specific conditions influences synergies and trade-offs. Most synergies were observed when perennial crops were produced on marginal land, previous arable land or pasture under a 'cool temperate moist' climate zone and 'high activity clay' soils. However, synergies arising from the production of perennials on land previously in use as cropland were also reported for other climate zones such as 'cool temperate dry' and 'warm temperate moist'. Other feedstock types such as sugarcane also present synergies across different climatic zones and soil types. However, these synergies are limited to specific land use transitions. In addition, it is also shown that regardless of the feedstock type, allocating natural or semi-natural areas, including forests, to the production of dedicated energy crops generally leads to trade-offs. Therefore, these findings suggest that previous land use and feedstock type appear to be more relevant in modulating synergies and trade-offs than climatic zones and soil types.

5.2. Strategies and challenges to reduce trade-offs

This literature review showed that using abandoned arable land or marginal lands to produce perennial crops as bioenergy feedstock is an option that may maximize synergies and minimize trade-offs between GHG emission reduction and SDGs. On marginal land, perennial crop production is less likely to compete with other land-based services (e.g., food security SDG 2) and to generate displacement effects [119]. In addition, it is recognized that utilizing marginal lands for perennial crop production can have advantageous effects on biodiversity and contribute to land restoration [16]. For example, utilizing marginal lands to produce perennials can enhance biodiversity (SDG 15) by avoiding directly or indirectly the conversion of natural ecosystems for bioenergy production [120]. Furthermore, compared to annual crops, perennial crops can sequester more carbon in biomass and soil, improve soil quality, and reduce soil erosion (SDG 15.3) [121,122]. However, the total (current and future) marginal land area that can be dedicated to producing dedicated energy crops is highly uncertain [16]. In addition, the performance (e.g., yield) of perennials on marginal lands also remains uncertain [10]. So far, only a limited number of trials have been carried out with perennial feedstocks on marginal lands and these perennial crops are also not commonly planted by farmers [123,124]. In addition, feedstock production costs in marginal conditions are relatively high [125]. These conditions, including market uncertainties and lack of knowledge, affect the farmer's willingness to adopt perennial crop production systems in general. Nevertheless, there are new practices, techniques and technologies such as precision farming, reduced tillage and soil sampling that could improve the cultivation of perennial crops on marginal lands, achieve higher yields and reduce costs. For example, carefully selecting well-adapted perennial crop species to local biophysical conditions, considering the crop's chemical and physical characteristics for specific end-uses applying a life cycle perspective [126]. This selection process can avoid additional pre-processing steps before the conversion process and provide more competitive production costs. Yields can be enhanced by identifying the morphological or physiological traits that allow plants to thrive in marginal conditions and enhance these traits in perennial crops through new breeding technologies [127]. Shifting from rhizome-based to seed-based or stem-based establishment practices has shown to reduce perennial grasses production costs [128]. The implementation of perennial crop production systems should focus on reducing or overcoming negative farmer income and revenue (SDG 8) and promoting the sustainability benefits of other SDGs.

To overcome barriers of changing to perennial bioenergy production systems, changes in the rewarding systems, policies and practices are needed. Introducing perennial crop systems should include long-term contracts with fixed prices and tax credits [129] to help guarantee farmers' income. In addition, policy can focus on internalizing the value of positive externalities. For example, by creating schemes to reward farmers for sequestering carbon, restoring ecosystems, enhancing biodiversity, increasing soil quality and improving water quality. Smart feedstock choices within perennials can minimize adverse effects on water availability while considering location-specific biophysical characteristics, thus resulting in more water-efficient biomass production systems. Irrigation schemes could be applied to obtain higher yields and reduce overall costs. However, irrigation schemes for bioenergy systems are controversial and should be avoided in water-stressed regions. Biomass production costs, dominated by stable costs related to land rent, are largely fixed per unit of land, and thus, overall production costs can decrease with higher yields [123].

5.3. Uncertainties of the study

The results of this review should be interpreted with care. The number of observations is limited to the sample size of relevant studies (59 relevant studies were included). Studies that failed to meet the search string or were not suggested by the board of experts were excluded. For example, the sample did not include studies that assessed the impacts of biomass production under different indicators that did not include the terms "synergy" or "trade-off". In addition, a focus was given to reporting and linking the number of synergies and trade-offs between GHG emission reduction (SDG 13) and other SDGs found in the literature. Although this allowed us to quantify how often a synergy or trade-off is studied, it falls short of indicating the strength of the connection. For example, more synergies related to biodiversity conversation were generally encountered for perennial grasses than for SRC (SDG 15.1). However, in some cases, growing SRC could be more beneficial for biodiversity than growing perennial grasses. For example, Sántha and Bentsen (2020) suggest that managing land for poplar rather than miscanthus production has a stronger positive effect on biodiversity. The magnitude of synergies and trade-offs depends on the context and therefore needs to be considered when designing bioenergy systems.

The analysis intended to serve as a basis to expand the current knowledge on synergies and trade-offs between SDG 13 and other SDGs. Most of the observations presented in the study are based on modeling assessments limited to the "Global North". In addition, a large part of the observations' study areas extended extensively beyond the boundaries of one particular climate zone or soil type. Therefore, other geographical regions, climate and soil types are under-represented. More observations from the "Global South", different climate zones and soil types are required to better understand synergies, trade-offs and potential trends in sustainability effects of using land for dedicated energy crop production. In addition, there are still relatively few trials to study the actual effects of growing novel feedstocks such as perennials for bioenergy systems on SDGs [130]. Furthermore, synergies and trade-offs between SDGs are also directly related to the scale of bioenergy implementation [16]. For example, regarding biodiversity, possible synergies are mainly reported on the field level, while the negative effects are reported across field, region, continent or global scales (Immerzeel et al., 2014). Thus, the effect of synergies and trade-offs also depends upon scale.

The scope of this review is limited to analyzing context-specific conditions through direct observations reported primarily around environmentally-related SDGs. However, bioenergy-induced synergies and trade-offs with socio-economic SDGs, such as SDG2 'zero hunger', also depend on context-specific conditions [25] and were not considered. The study provides a first impression of the relevance of context-specific conditions and how they affect synergies and trade-offs. Other analytical approaches such as regression analysis could be more suitable to identify the hierarchical relevance of context-specific conditions in determining specific positive or negative effects [131]. In addition, the included studies specifically mentioned or assumed that growing dedicated energy crops leads to GHG emissions reduction (progressing SDG 13) and thus, bioenergy crop production provides synergies when it leads to positive effects for another SDG. Nevertheless, land use transitions can also result in additional GHG emissions by disturbing carbon stocks in biomass and soils [132].

Determining actual synergies related to GHG emissions reductions from bioenergy requires a full supply chain perspective within the entire energy system as GHG performance of bioenergy value chains depends on supply chain designs, logistics, and end uses, and not just land management [126,133,134]. Similar positive and negative pairwise correlations between SDGs can also occur at later stages of the supply chain. For example, synergies exist between GHG emissions reduction and job creation (SDG 8) in the bioenergy sector (e.g., processing and transporting biomass) [135]. Furthermore, significant indirect effects across connected systems, induced by market perturbations, may require a broader consequential life cycle perspective to be captured [136].

Although synergies and trade-offs between GHG emissions (SDG 13) and other environmental SDGs were assessed through a pairwise comparison, effects on SDGs are shown to be interconnected. For example, utilizing arable land for dedicated energy crops can displace food production, expanding agricultural activities into natural areas [88]. This process of indirect land use change (iLUC) can simultaneously affect biodiversity (SDG 15) and global food prices (SDG 2) [74]. In contrast, interconnected effects can also result in synergies. For example, it can result in monetary benefits (SDG 8) from nitrate (SDG 6) and sediment retention (SDG 15), and increase the recreational and aesthetic value of the landscape [72,105]. Sediment retention can also contribute to reducing the adverse effects of floods (SDG 13) and the costs of flood mitigation projects (SDG 8 and SDG 13) [58,104]. Understanding these interconnected effects can expand the knowledge on synergies and trade-offs towards more sustainable land systems and be addressed in future research as well as to include other land-based feedstock types such as residues.

Although management practices are an important part of the context that determines whether synergies or trade-offs will occur, it was not possible to identify the effects of management practices in this study. The variety of management practices connected to feedstock types, scopes, geographical and temporal scales prohibited us from discerning clear patterns. However, synergies with water quality are shown for perennial crops partially as a result of fewer inputs (e.g., fertilizers) than annual crops [70,72,96,137]. Therefore, from a management practice perspective, the low requirements of perennial crops for chemical inputs are a characteristic that can potentially lead to more synergies with various SDGs than other feedstock types.

The differences in scope and approach with similar studies result in a challenge for comparison purposes. For example, this study focused on synergies and trade-offs between GHG emissions reduction (SDG 13) from using land for dedicated energy crops and six other SDGs that were found in the literature sample. However, bioenergy is a potential option to achieve "Affordable and clean energy" (SDG 7). In addition, more interlinkages between SDGs such as "Responsible consumption and production" (SDG 12) could be established under a different scope. To illustrate, producing dedicated energy crops can synergize with SDG 12 as it provides a more responsible way of producing and consuming energy than fossil fuels. For example, Nerini et al. (2018) [138] identified that 16 SDGs are related to achieving affordable and clean energy. However, Nerini et al. (2018) [138] assessed the whole energy sector and not specifically dedicated energy crop production. Studies with other biomass types have also found that developing bioenergy systems can indirectly result in synergies with societal related SDGs such as "No poverty" (SDG 1), "Quality education" (SDG 4) "Gender inequality" (SDG 5) and "Reduced inequalities" (SDG 10) [13,139]. Also, as shown in this study, Blair et al. (2021) reported that bioenergy systems have several synergies and trade-offs with SDG 6 and 15. It has also been reported that sustainable soil management is intrinsically related to 11 SDGs [140]. As allocating land for bioenergy crops can improve soil quality, it can also be related to additional SDGs like the ones shown in Lal et al. (2021).

5.4. *Conclusions*

This literature review synthesizes the current understanding of the synergies and trade-offs between the impacts of land use for dedicated energy crops to reduce GHG emissions (SDG 13) and other SDGs, and identifies the context-specific conditions that determine these relationships. Overall, an almost equal number of synergies and trade-offs were found between GHG emission reduction and SDGs 2 (Zero hunger), 3 (Good health and well-being), 6 (Clean water and sanitation), 8 (Decent work and economic growth), 13 (Climate action-other indicators), 14 (Life below water) and 15 (Life on land). However, more synergies were found related to SDGs 3, 13, 14 and 15, while more trade-offs were found related to SDGs 2, 6 and 8. Most synergies related to environmental SDGs were observed when perennial crops (SRC and perennial grasses) were produced on arable, pasture or marginal land in a 'cool temperate moist' climate zone and 'high activity clay' soils. Utilizing marginal land to produce perennial crops is a key strategy as it can avoid trade-offs with other land-based services such as food, feed, and fiber production (SDG 2). To minimize trade-offs, the findings suggest that it is of paramount importance to consider context-specific conditions, with priority given in the order of first land use transitions and second feedstock types, while both parameters need to be considered in line with local biophysical conditions to contribute to multiple SDGs. The magnitude of synergies and trade-offs between GHG emission reduction and other SDGs must be accounted for in decision making and from a supply chain perspective approach. Otherwise, it can lead to suboptimal implementation strategies and negative effects. This study highlights the importance of considering context-specific conditions to analyze synergies and trade-offs, informing appropriate policies and practices to meet worldwide demand for bioenergy, especially in regions with strongly competing needs for land for various land-based ecosystem services.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2022.112409.

References

[1] Masson-Delmotte V, Zhai P, Priani A, Connors SL, Péan C, Berger S, IPCC. Climate change 2021: the physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change. 2021. 2021.

[2] Masson-Delmotte TWV, Zhai P, Pörtner HO, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia W, Péan C, Pidcock R. IPCC, 2018: summary for policymakers. In: Global warming of 1.5 C. An IPCC Special Report on the impacts of global warming of 1.5 C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global, World Meteorol. Organ. Geneva, Tech. Rep.; 2018.

[3] IEA. World energy outlook 2020. 2020. www.iea.org/weo.

[4] Rogelj J, Shindell D, Jiang K, Fifita S, Forster P, Ginzburg V, Handa C, Kheshgi H, Kobayashi S, Kriegler E. Mitigation pathways compatible with 1.5 C in the context of sustainable development. 2018.

[5] IRENA, Global renewables outlook. Energy transformation 2050, ISBN 978-92-9260-238-3. Abu Dhabi https://doi.org/.

[6] Daioglou V, Doelman JC, Wicke B, Faaij A, van Vuuren DP. Integrated assessment of biomass supply and demand in climate change mitigation scenarios. Global Environ Change 2019;54:88–101. https://doi.org/10.1016/J.GLOENVCHA.2018.11.012.

[7] Schleussner C-F, Rogelj J, Schaeffer M, Lissner T, Licker R, Fischer EM, Knutti R, Levermann A, Frieler K, Hare W. Science and policy characteristics of the Paris Agreement temperature goal. Nat Clim Change 2016;6:827–35.

[8] Muscat A, de Olde EM, de Boer IJM, Ripoll-Bosch R. The battle for biomass: a systematic review of food-feed-fuel competition. Global Food Secur 2020;25:100330.

[9] Gaba S. Review of the impacts on biodiversity of land-use changes induced by non-food biomass production. In: Sustain. Agric. Rev., vol. 30. Springer; 2018. p. 195–212.

[10] Whitaker J, Field JL, Bernacchi CJ, Cerri CEP, Ceulemans R, Davies CA, DeLucia EH, Donnison IS, McCalmont JP, Paustian K. Consensus, uncertainties and challenges for perennial bioenergy crops and land use. GCB Bioenergy 2018;10:150–64.

[11] Heck V, Gerten D, Lucht W, Popp A. Biomass-based negative emissions difficult to reconcile with planetary boundaries. Nat Clim Change 2018;8:151–5.

[12] Smith P, Adams J, Beerling DJ, Beringer T, Calvin KV, Fuss S, Griscom B, Hagemann N, Kammann C, Kraxner F. Land-management options for greenhouse gas removal and their impacts on ecosystem services and the sustainable development goals. Annu Rev Environ Resour 2019;44:255–86.

[13] Blair MJ, Gagnon B, Klain A, Kulišić B. Contribution of biomass supply chains for bioenergy to sustainable development goals. Land 2021;10:181.

[14] Harper AB, Powell T, Cox PM, House J, Huntingford C, Lenton TM, Sitch S, Burke E, Chadburn SE, Collins WJ. Land-use emissions play a critical role in land-based mitigation for Paris climate targets. Nat Commun 2018;9:1–13.

[15] Brandão M, i Canals LM, Clift R. Food, feed, fuel, timber or carbon sink? towards sustainable land use: a consequential life cycle approach. Springer Nature; 2021.

[16] Shukla PR, Skea J, Calvo Buendia E, Masson-Delmotte V, Pörtner HO, Roberts DC, Zhai P, Slade R, Connors S, Van Diemen R, IPCC. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. 2019. 2019.

[17] Kalt G, Mayer A, Theurl MC, Lauk C, Erb K-H, Haberl H. Natural climate solutions versus bioenergy: can carbon benefits of natural succession compete with bioenergy from short rotation coppice? GCB Bioenergy 2019;11:1283–97. https://doi.org/10.1111/gcbb.12626.

[18] Leirpoll ME, Næss JS, Cavalett O, Dorber M, Hu X, Cherubini F. Optimal combination of bioenergy and solar photovoltaic for renewable energy production on abandoned cropland. Renew Energy 2021;168:45–56.

[19] Strassburg BBN, Iribarrem A, Beyer HL, Cordeiro CL, Crouzeilles R, Jakovac CC, Junqueira AB, Lacerda E, Latawiec AE, Balmford A. Global priority areas for ecosystem restoration. Nature 2020;586:724–9.

[20] Næss JS, Cavalett O, Cherubini F. The land–energy–water nexus of global bioenergy potentials from abandoned cropland. Nat Sustain 2021;4:525–36.

[21] Yamagata Y, Hanasaki N, Ito A, Kinoshita T, Murakami D, Zhou Q. Estimating water–food–ecosystem trade-offs for the global negative emission scenario (IPCC-RCP2.6). Sustain Sci 2018;13:301–13. https://doi.org/10.1007/s11625-017-0522-5.

[22] Harris ZM, Spake R, Taylor G. Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions. Biomass Bioenergy 2015;82:27–39.

[23] Donnison C, Holland RA, Harris ZM, Eigenbrod F, Taylor G. Land-use change from food to energy: meta-analysis unravels effects of bioenergy on biodiversity and amenity. BioRxiv; 2021.

[24] Robertson GP, Hamilton SK, Barham BL, Dale BE, Izaurralde RC, Jackson RD, Landis DA, Swinton SM, Thelen KD, Tiedje JM. Cellulosic biofuel contributions to a sustainable energy future: choices and outcomes. Science 2017;(80-):356. https://doi.org/10.1126/science.aal2324.

[25] van der Hilst F. Location, location, location. Nat Energy 2018;3:164–5. https://doi.org/10.1038/s41560-018-0094-3.

[26] Efroymson RA, Dale VH, Kline KL, McBride AC, Bielicki JM, Smith RL, Parish ES, Schweizer PE, Shaw DM. Environmental indicators of biofuel sustainability: what about context? Environ Manag 2013;51:291–306. https://doi.org/10.1007/s00267-012-9907-5.

[27] Wang J, Zhao W, Jia L, Hu X, Cherubini F. Soil desiccation trends after afforestation in the Loess Plateau of China. J Soils Sediments 2021;21:1165–76.

[28] Feng X, Fu B, Piao S, Wang S, Ciais P, Zeng Z, Lü Y, Zeng Y, Li Y, Jiang X. Revegetation in China's Loess Plateau is approaching sustainable water resource limits. Nat Clim Change 2016;6:1019–22.

[29] Wu M, Zhang Z, Chiu Y. Life-cycle water quantity and water quality implications of biofuels. Curr Sustain Energy Rep 2014;1:3–10.

[30] Schulze J, Frank K, Priess JA, Meyer MA. Assessing regional-scale impacts of short rotation coppices on ecosystem services by modeling land-use decisions. PLoS One 2016;11. https://doi.org/10.1371/journal.pone.0153862.

[31] Immerzeel DJ, Verweij PA, Van Der Hilst F, Faaij APC. Biodiversity impacts of bioenergy crop production: a state-of-the-art review. Gcb Bioenergy 2014;6:183–209.

[32] Hanes RJ, Gopalakrishnan V, Bakshi BR. Synergies and trade-offs in renewable energy landscapes: balancing energy production with economics and ecosystem services. Appl Energy 2017;199:25–44.

[33] Santangeli A, Di Minin E, Toivonen T, Pogson M, Hastings A, Smith P, Moilanen A. Synergies and trade-offs between renewable energy expansion and biodiversity conservation–a cross-national multifactor analysis. Gcb Bioenergy 2016;8:1191–200.

[34] Humpenöder F, Popp A, Bodirsky BL, Weindl I, Biewald A, Lotze-Campen H, Dietrich JP, Klein D, Kreidenweis U, Müller C, Rolinski S, Stevanovic M. Large-scale bioenergy production: how to resolve sustainability trade-offs? Environ Res Lett 2018;13. https://doi.org/10.1088/1748-9326/aa9e3b.

[35] European Commission. Directive (EU) 2018/2001 of the European parliament and of the council of 11 December 2018 on the promotion of the use of energy from renewable sources. Off J Eur Union 2018:128. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN.

[36] Vera I, Wicke B, van der Hilst F. Spatial variation in environmental impacts of sugarcane expansion in Brazil. Land 2020;9:397.

[37] Fritsche UR, Eppler U, Fehrenbach H, Giegrich J. Linkages between the sustainable development goals (SDGs) and the GBEP sustainability indicators for bioenergy (GSI), int. Inst. Sustain. Anal. Strateg. Berlin: Ger.; 2018.

[38] GBEP S. The global bioenergy partnership sustainability indicators for bioenergy. 2011.

[39] Díaz S, Demissew S, Carabias J, Joly C, Lonsdale M, Ash N, Larigauderie A, Adhikari JR, Arico S, Báldi A. The IPBES Conceptual Framework—connecting nature and people. Curr Opin Environ Sustain 2015;14:1–16.

[40] Lee M, Lin Y-L, Chiueh P-T, Den W. Environmental and energy assessment of biomass residues to biochar as fuel: a brief review with recommendations for future bioenergy systems. J Clean Prod 2020;251. https://doi.org/10.1016/j.jclepro.2019.119714.

[41] Monteleone M, Garofalo P, Cammerino ARB, Libutti A. Cereal straw management: a trade-off between energy and agronomic fate. Ital J Agron 2015;10:59–66. https://doi.org/10.4081/ija.2015.655.

[42] Younis A, Trujillo Y, Benders R, Faaij A. Regionalized cost supply potential of bioenergy crops and residues in Colombia: a hybrid statistical balance and land suitability allocation scenario analysis. Biomass Bioenergy 2021;150:106096.

[43] Alcantara C, Kuemmerle T, Baumann M, Bragina EV, Griffiths P, Hostert P, Knorn J, Müller D, Prishchepov AV, Schierhorn F, Sieber A, Radeloff VC. Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data. Environ Res Lett 2013;8. https://doi.org/10.1088/1748-9326/8/3/035035.

[44] Löw F, Prishchepov AV, Waldner F, Dubovyk O, Akramkhanov A, Biradar C, Lamers JPA. Mapping cropland abandonment in the aral sea basin with MODIS time series. Rem Sens 2018;10. https://doi.org/10.3390/rs10020159.

[45] Estel S, Kuemmerle T, Levers C, Baumann M, Hostert P. Mapping cropland-use intensity across Europe using MODIS NDVI time series. Environ Res Lett 2016;11. https://doi.org/10.1088/1748-9326/11/2/024015.

[46] Stefanski J, Kuemmerle T, Chaskovskyy O, Griffiths P, Havryluk V, Knorn J, Korol N, Sieber A, Waske B. Mapping land management regimes in western Ukraine using optical and SAR data. Rem Sens 2014;6:5279–305. https://doi.org/10.3390/rs6065279.

[47] Leibensperger C, Yang P, Zhao Q, Wei S, Cai X. The synergy between stakeholders for cellulosic biofuel development: perspectives, opportunities, and barriers. Renew Sustain Energy Rev 2021;137. https://doi.org/10.1016/j.rser.2020.110613.

[48] Brunner A, Currie WS, Miller S. Cellulosic ethanol production: landscape scale net carbon strongly affected by forest decision making. Biomass Bioenergy 2015;83:32–41. https://doi.org/10.1016/j.biombioe.2015.08.002.

[49] Rouleau M, Zupko R. Agent-Based Modeling for bioenergy sustainability assessment. Landsc Urban Plann 2019;188:54–63. https://doi.org/10.1016/j.landurbplan.2019.04.019.

[50] Truax B, Gagnon D, Lambert F, Fortier J. Multiple-use zoning model for private forest owners in agricultural landscapes: a case study. Forests 2015;6:3614–64. https://doi.org/10.3390/f6103614.

[51] Battini F, Agostini A, Boulamanti AK, Giuntoli J, Amaducci S. Mitigating the environmental impacts of milk production via anaerobic digestion of manure: case study of a dairy farm in the Po Valley. Sci Total Environ 2014;481:196–208. https://doi.org/10.1016/j.scitotenv.2014.02.038.

[52] Rivas Casado M, Mead A, Burgess PJ, Howard DC, Butler SJ. Predicting the impacts of bioenergy production on farmland birds. Sci Total Environ 2014. https://doi.org/10.1016/j.scitotenv.2013.12.080. 476–477 7–19.

[53] Verloop J, Hilhorst GJ, Pronk AA, Šebek LB, van Keulen H, Janssen BH, Van Ittersum MK. Organic matter dynamics in an intensive dairy production system on a Dutch Spodosol. Geoderma 2015;237:159–67. https://doi.org/10.1016/j.geoderma.2014.09.003.

[54] Cherubin MR, Carvalho JLN, Cerri CEP, Nogueira LAH, Souza GM, Cantarella H. Land use and management effects on sustainable sugarcane-derived bioenergy. Land 2021;10:1–24. https://doi.org/10.3390/land10010072.

[55] Kalu A, Vrzel J, Kolb S, Karl J, Marzahn P, Pfaffenberger F, Ludwig R. Considering the environmental impacts of bioenergy technologies to support German energy transition. Energies 2021;14. https://doi.org/10.3390/en14061534.

[56] Roe S, Streck C, Obersteiner M, Frank S, Griscom B, Drouet L, Fricko O, Gusti M, Harris N, Hasegawa T, Stehfest E, Lawrence D. Contribution of the land sector to a 1.5 °C world. Nat Clim Change 2019;9:817–28. https://doi.org/10.1038/s41558-019-0591-9.

[57] Tapia JFD, Samsatli S, Doliente SS, Martinez-Hernandez E, Ab Karim WABW, Lim KL, Shafri HZM, Shaharum NSNB. Design of biomass value chains that are

synergistic with the food–energy–water nexus: strategies and opportunities. Food Bioprod Process 2019;116:170–85. https://doi.org/10.1016/j.fbp.2019.05.006.

[58] Donnison C, Holland RA, Hastings A, Armstrong L-M, Eigenbrod F, Taylor G. Bioenergy with Carbon Capture and Storage (BECCS): finding the win–wins for energy, negative emissions and ecosystem services—size matters. GCB Bioenergy 2020;12:586–604. https://doi.org/10.1111/gcbb.12695.

[59] Tavakoli-Hashjini E, Piorr A, Müller K, Vicente-Vicente JL. Potential bioenergy production from miscanthus x giganteus in brandenburg: producing bioenergy and fostering other ecosystem services while ensuring food self-sufficiency in the Berlin-Brandenburg region. Sustain Times 2020;12. https://doi.org/10.3390/su12187731.

[60] Englund O, Börjesson P, Berndes G, Scarlat N, Dallemand J-F, Grizzetti B, Dimitriou I, Mola-Yudego B, Fahl F. Beneficial land use change: strategic expansion of new biomass plantations can reduce environmental impacts from EU agriculture. Global Environ Change 2020;60. https://doi.org/10.1016/j.gloenvcha.2019.101990.

[61] Milner S, Holland RA, Lovett A, Sunnenberg G, Hastings A, Smith P, Wang S, Taylor G. Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. GCB Bioenergy 2016;8:317–33. https://doi.org/10.1111/gcbb.12263.

[62] Meyer MA, Chand T, Priess JA. Comparing bioenergy production sites in the southeastern US regarding ecosystem service supply and demand. PLoS One 2015;10. https://doi.org/10.1371/journal.pone.0116336.

[63] Harris ZM, Alberti G, Viger M, Jenkins JR, Rowe R, McNamara NP, Taylor G. Land-use change to bioenergy: grassland to short rotation coppice willow has an improved carbon balance. Gcb Bioenergy 2017;9:469–84.

[64] van der Hilst F, Lesschen JP, van Dam JMC, Riksen M, Verweij PA, Sanders JPM, Faaij APC. Spatial variation of environmental impacts of regional biomass chains. Renew Sustain Energy Rev 2012;16:2053–69. https://doi.org/10.1016/J.RSER.2012.01.027.

[65] Nepal S, Tran LT. Renew Energy 2019;142:272–83. https://doi.org/10.1016/j.renene.2019.04.110.

[66] Wu W, Hasegawa T, Ohashi H, Hanasaki N, Liu J, Matsui T, Fujimori S, Masui T, Takahashi K. Global advanced bioenergy potential under environmental protection policies and societal transformation measures. GCB Bioenergy 2019; 11:1041–55. https://doi.org/10.1111/gcbb.12614.

[67] Dauber J, Cass S, Gabriel D, Harte K, Åström S, O'Rourke E, Stout JC. Yield-biodiversity trade-off in patchy fields of Miscanthus × giganteus. GCB Bioenergy 2015;7:455–67. https://doi.org/10.1111/gcbb.12167.

[68] Blank PJ, Williams CL, Sample DW, Meehan TD, Turner MG. Alternative scenarios of bioenergy crop production in an agricultural landscape and implications for bird communities. Ecol Appl 2016;26:42–54. https://doi.org/10.1890/14-1490.1/suppinfo.

[69] Helms JA, Ijelu SE, Wills BD, Landis DA, Haddad NM. Ant biodiversity and ecosystem services in bioenergy landscapes. Agric Ecosyst Environ 2020;290. https://doi.org/10.1016/j.agee.2019.106780.

[70] Meehan TD, Gratton C, Diehl E, Hunt ND, Mooney DF, Ventura SJ, Barham BL, Jackson RD. Ecosystem-service tradeoffs associated with switching from annual to perennial energy crops in riparian zones of the US Midwest. PLoS One 2013;8:e80093.

[71] Van Meerbeek K, Ottoy S, de Andrés García M, Muys B, Hermy M. The bioenergy potential of Natura 2000 – a synergy between climate change mitigation and biodiversity protection. Front Ecol Environ 2016;14:473–8. https://doi.org/10.1002/fee.1425.

[72] Mishra SK, Negri MC, Kozak J, Cacho JF, Quinn J, Secchi S, Ssegane H. Valuation of ecosystem services in alternative bioenergy landscape scenarios. GCB Bioenergy 2019;11:748–62. https://doi.org/10.1111/gcbb.12602.

[73] Dolan KA, Stoy PC, Poulter B. Land management and climate change determine second-generation bioenergy potential of the US Northern Great Plains. GCB Bioenergy 2020;12:491–509. https://doi.org/10.1111/gcbb.12686.

[74] Prudhomme R, Palma AD, Dumas P, Gonzalez R, Leadley P, Levrel H, Purvis A, Brunelle T. Combining mitigation strategies to increase co-benefits for biodiversity and food security. Environ Res Lett 2020;15. https://doi.org/10.1088/1748-9326/abb10a.

[75] Behrman KD, Juenger TE, Kiniry JR, Keitt TH. Spatial land use trade-offs for maintenance of biodiversity, biofuel, and agriculture. Landsc Ecol 2015;30:1987–99. https://doi.org/10.1007/s10980-015-0225-1.

[76] Mosnier A, Havlík P, Obersteiner M, Aoki K, Schmid E, Fritz S, McCallum I, Leduc S. Modeling impact of development trajectories and a global agreement on reducing emissions from deforestation on Congo basin forests by 2030. Environ Resour Econ 2014;57:505–25. https://doi.org/10.1007/s10640-012-9618-7.

[77] Lautenbach S, Volk M, Strauch M, Whittaker G, Seppelt R. Optimization-based trade-off analysis of biodiesel crop production for managing an agricultural catchment. Environ Model Software 2013;48:98–112. https://doi.org/10.1016/j.envsoft.2013.06.006.

[78] Costanza JK, Abt RC, McKerrow AJ, Collazo JA. Bioenergy production and forest landscape change in the southeastern United States. GCB Bioenergy 2017;9:924–39. https://doi.org/10.1111/gcbb.12386.

[79] Erb K-H, Haberl H, Plutzar C. Dependency of global primary bioenergy crop potentials in 2050 on food systems, yields, biodiversity conservation and political stability. Energy Pol 2012;47:260–9. https://doi.org/10.1016/j.enpol.2012.04.066.

[80] Calvin K, Wise M, Kyle P, Patel P, Clarke L, Edmonds J. Trade-offs of different land and bioenergy policies on the path to achieving climate targets. Clim Change 2014;123:691–704. https://doi.org/10.1007/s10584-013-0897-y.

[81] Kraxner F, Nordström E-M, Havlík P, Gusti M, Mosnier A, Frank S, Valin H, Fritz S, Fuss S, Kindermann G, Máthé L, Obersteiner M. Global bioenergy scenarios - future forest development, land-use implications, and trade-offs. Biomass Bioenergy 2013;57:86–96. https://doi.org/10.1016/j.biombioe.2013.02.003.

[82] Doelman JC, Stehfest E, Tabeau A, van Meijl H, Lassaletta L, Gernaat DEHJ, Neumann-Hermans K, Harmsen M, Daioglou V, Biemans H, van der Sluis S, van Vuuren DP. Exploring SSP land-use dynamics using the IMAGE model: regional and gridded scenarios of land-use change and land-based climate change mitigation. Global Environ Change 2018;48:119–35. https://doi.org/10.1016/j.gloenvcha.2017.11.014.

[83] Krause A, Pughl TAM, Bayer AD, Doelman JC, Humpenöder F, Anthoni P, Olin S, Bodirsky BL, Popp A, Stehfest E, Stehfest E, Arneth A. Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators. Biogeosciences 2017;14:4829–50. https://doi.org/10.5194/bg-14-4829-2017.

[84] Guo T, Cibin R, Chaubey I, Gitau M, Arnold JG, Srinivasan R, Kiniry JR, Engel BA. Evaluation of bioenergy crop growth and the impacts of bioenergy crops on streamflow, tile drain flow and nutrient losses in an extensively tile-drained watershed using SWAT. Sci Total Environ 2018;613:724–35.

[85] Jager HI, Baskaran LM, Schweizer PE, Turhollow AF, Brandt CC, Srinivasan R. Forecasting changes in water quality in rivers associated with growing biofuels in the Arkansas-White-Red river drainage, USA. Gcb Bioenergy 2015;7:774–84.

[86] Heidari A, Watkins D, Mayer A, Propato T, Verón S, de Abelleyra D. Spatially variable hydrologic impact and biomass production tradeoffs associated with Eucalyptus (E. grandis) cultivation for biofuel production in Entre Rios, Argentina. GCB Bioenergy 2021;13:823–37. https://doi.org/10.1111/gcbb.12815.

[87] Heidari A, Mayer A, Watkins D, Castillo MM. Hydrologic impacts and trade-offs associated with developing oil palm for bioenergy in Tabasco, Mexico. J Hydrol Reg Stud 2020;31. https://doi.org/10.1016/j.ejrh.2020.100722.

[88] Munoz Castillo R, Feng K, Sun L, Guilhoto J, Pfister S, Miralles-Wilhelm F, Hubacek K. The land-water nexus of biofuel production in Brazil: analysis of synergies and trade-offs using a multiregional input-output model. J Clean Prod 2019;214:52–61. https://doi.org/10.1016/j.jclepro.2018.12.264.

[89] Zhong H, Feng K, Sun L, Tian Z, Fischer G, Cheng L, Castillo RM. Water-land tradeoffs to meet future demands for sugar crops in Latin America and the Caribbean: a bio-physical and socio-economic nexus perspective. Resour Conserv Recycl 2021;169:105510.

[90] Heidari A, Mayer A, Watkins D. Hydrologic impacts and trade-offs associated with forest-based bioenergy development practices in a snow-dominated watershed, Wisconsin, USA. J Hydrol 2019;574:421–9. https://doi.org/10.1016/j.jhydrol.2019.04.067.

[91] Bonsch M, Humpenöder F, Popp A, Bodirsky B, Dietrich JP, Rolinski S, Biewald A, Lotze-Campen H, Weindl I, Gerten D, Gerten D, Stevanovic M. Trade-offs between land and water requirements for large-scale bioenergy production. GCB Bioenergy 2016;8:11–24. https://doi.org/10.1111/gcbb.12226.

[92] Pacetti T, Lombardi L, Federici G. Water-energy Nexus: a case of biogas production from energy crops evaluated by Water Footprint and Life Cycle Assessment (LCA) methods. J Clean Prod 2015;101:278–91. https://doi.org/10.1016/j.jclepro.2015.03.084.

[93] Pfister S, Bayer P, Koehler A, Hellweg S. Projected water consumption in future global agriculture: scenarios and related impacts. Sci Total Environ 2011;409:4206–16. https://doi.org/10.1016/j.scitotenv.2011.07.019.

[94] Jager HI, Efroymson RA. Can upstream biofuel production increase the flow of downstream ecosystem goods and services? Biomass Bioenergy 2018;114:125–31.

[95] Parish ES, Hilliard MR, Baskaran LM, Dale VH, Griffiths NA, Mulholland PJ, Sorokine A, Thomas NA, Downing ME, Middleton RS. Multimetric spatial optimization of switchgrass plantings across a watershed. Biofuels Bioprod Biorefining 2012;6:58–72.

[96] Ha M, Wu M, Tomer MD, Gassman PW, Isenhart TM, Arnold JG, White MJ, Parish ES, Comer KS, Belden B. Biomass production with conservation practices for two Iowa watersheds. JAWRA J Am Water Resour Assoc 2020;56:1030–44.

[97] Ben Fradj N, Jayet PA, Aghajanzadeh-Darzi P. Competition between food, feed, and (bio)fuel: a supply-side model based assessment at the European scale. Land Use Pol 2016;52:195–205. https://doi.org/10.1016/j.landusepol.2015.12.027.

[98] Stoy PC, Ahmed S, Jarchow M, Rashford B, Swanson D, Albeke S, Bromley G, Brookshire ENJ, Dixon MD, Haggerty J, Straub C, Poulter B. Opportunities and trade-offs among BECCS and the food, water, energy, biodiversity, and social systems nexus at regional scales. Bioscience 2018;68:100–11. https://doi.org/10.1093/biosci/bix145.

[99] Dooley K, Christoff P, Nicholas KA. Co-producing climate policy and negative emissions: trade-offs for sustainable land-use. Glob Sustain 2018;1. https://doi.org/10.1017/sus.2018.6.

[100] Ballarin A, Vecchiato D, Tempesta T, Marangon F, Troiano S. Biomass energy production in agriculture: a weighted goal programming analysis. Energy Pol 2011;39:1123–31. https://doi.org/10.1016/j.enpol.2010.11.035.

[101] Parish ES, Dale VH, English BC, Jackson SW, Tyler DD. Assessing multimetric aspects of sustainability: application to a bioenergy crop production system in East Tennessee. Ecosphere 2016;7:e01206.

[102] Stürmer B, Schmidt J, Schmid E, Sinabell F. Implications of agricultural bioenergy crop production in a land constrained economy - the example of Austria. Land Use Pol 2013;30:570–81. https://doi.org/10.1016/j.landusepol.2012.04.020.

[103] García CA, Riegelhaupt E, Ghilardi A, Skutsch M, Islas J, Manzini F, Masera O. Sustainable bioenergy options for Mexico: GHG mitigation and costs. Renew Sustain Energy Rev 2015;43:545–52.

[104] Jager HI, Parish ES, Langholtz MH, King AW. Perennials in Flood-prone areas of agricultural landscapes: a climate adaptation strategy. Bioscience 2020;70:278.

[105] Sántha E, Bentsen NS. Ecosystem service benefits and trade-offs-selecting tree species in Denmark for bioenergy production. Forests 2020;11. https://doi.org/10.3390/f11030277.

[106] Kreig JAF, Parish E, Jager HI. Growing grasses in unprofitable areas of US Midwest croplands could increase species richness. Biol Conserv 2021;261: 109289.

[107] Kraxner F, Nordström E-M, Havlík P, Gusti M, Mosnier A, Frank S, Valin H, Fritz S, Fuss S, Kindermann G. Global bioenergy scenarios–Future forest development, land-use implications, and trade-offs. Biomass Bioenergy 2013;57: 86–96.

[108] Krause A, Pughl TAM, Bayer AD, Doelman JC, Humpenöder F, Anthoni P, Olin S, Bodirsky BL, Popp A, Stehfest E, Stehfest E, Arneth A. Global consequences of afforestation and bioenergy cultivation on ecosystem service indicators. Biogeosciences 2017;14:4829–50. https://doi.org/10.5194/bg-14-4829-2017.

[109] VanLoocke A, Twine TE, Zeri M, Bernacchi CJ. A regional comparison of water use efficiency for miscanthus, switchgrass and maize. Agric For Meteorol 2012; 164:82–95. https://doi.org/10.1016/j.agrformet.2012.05.016.

[110] Miller JN, VanLoocke A, Gomez-Casanovas N, Bernacchi CJ. Candidate perennial bioenergy grasses have a higher albedo than annual row crops. GCB Bioenergy 2016;8:818–25. https://doi.org/10.1111/gcbb.12291.

[111] Costanza JK, Abt RC, McKerrow AJ, Collazo JA. Bioenergy production and forest landscape change in the southeastern United States. GCB Bioenergy 2017;9: 924–39. https://doi.org/10.1111/gcbb.12386.

[112] Pfister S, Bayer P, Koehler A, Hellweg S. Environmental impacts of water use in global crop production: hotspots and trade-offs with land use. Environ Sci Technol 2011;45:5761–8. https://doi.org/10.1021/es1041755.

[113] Popp A, Dietrich JP, Lotze-Campen H, Klein D, Bauer N, Krause M, Beringer T, Gerten D, Edenhofer O. The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. Environ Res Lett 2011;6. https://doi.org/10.1088/1748-9326/6/3/034017.

[114] Reid WV, Ali MK, Field CB. The future of bioenergy. Global Change Biol 2020;26: 274–86.

[115] Rosegrant MW, Msangi S. Consensus and contention in the food-versus-fuel debate. Annu Rev Environ Resour 2014;39:271–94.

[116] Brinkman M, Levin-Koopman J, Wicke B, Shutes L, Kuiper M, Faaij A, van der Hilst F. The distribution of food security impacts of biofuels, a Ghana case study. Biomass Bioenergy 2020;141:105695.

[117] Kline KL, Msangi S, Dale VH, Woods J, Souza GM, Osseweijer P, Clancy JS, Hilbert JA, Johnson FX, McDonnell PC. Reconciling food security and bioenergy: priorities for action. Gcb Bioenergy 2017;9:557–76.

[118] Cosentino SL, Copani V, Scalici G, Scordia D, Testa G. Soil erosion mitigation by perennial species under Mediterranean environment. BioEnergy Res 2015;8: 1538–47.

[119] Von Cossel M, Lewandowski I, Elbersen B, Staritsky I, Van Eupen M, Iqbal Y, Mantel S, Scordia D, Testa G, Cosentino SL. Marginal agricultural land low-input systems for biomass production. Energies 2019;12:3123.

[120] Núñez-Regueiro MM, Siddiqui SF, Fletcher Jr RJ. Effects of bioenergy on biodiversity arising from land-use change and crop type. Conserv Biol 2021;35: 77–87.

[121] Creutzig F, Ravindranath NH, Berndes G, Bolwig S, Bright R, Cherubini F, Chum H, Corbera E, Delucchi M, Faaij A, Fargione J, Haberl H, Heath G, Lucon O, Plevin R, Popp A, Robledo-Abad C, Rose S, Smith P, Stromman A, Suh S, Masera O. Bioenergy and climate change mitigation: an assessment. GCB Bioenergy 2015;7:916–44. https://doi.org/10.1111/gcbb.12205.

[122] Richter GM, Agostini F, Redmile-Gordon M, White R, Goulding KWT. Sequestration of C in soils under Miscanthus can be marginal and is affected by genotype-specific root distribution. Agric Ecosyst Environ 2015;200:169–77. https://doi.org/10.1016/J.AGEE.2014.11.011.

[123] Germer S, Aleksopoulou E. Innovative lignocellulosic cropping systems in europe: combining knowledge from several EU-projects. In: 27th Eur. Conf. Exhib. 27-30 May 2019; 2019. Lisbon, Port.

[124] Jiang W, Zipp KY, Jacobson M. Economic assessment of landowners' willingness to supply energy crops on marginal lands in the northeastern of the United States. Biomass Bioenergy ;113:22–30.

[125] Soldatos P. Economic aspects of bioenergy production from perennial grasses in marginal lands of South Europe. BioEnergy Res 2015;8:1562–73.

[126] Vera I, Hoefnagels R, Junginger M, van der Hilst F. Supply potential of lignocellulosic energy crops grown on marginal land and greenhouse gas footprint of advanced biofuels—a spatially explicit assessment under the sustainability criteria of the Renewable Energy Directive Recast. GCB Bioenergy 2021;13: 1425–47.

[127] Jones MB, Finnan J, Hodkinson TR. Morphological and physiological traits for higher biomass production in perennial rhizomatous grasses grown on marginal land. Gcb Bioenergy 2015;7:375–85.

[128] Clifton-Brown J, Hastings A, Mos M, McCalmont JP, Ashman C, Awty-Carroll D, Cerazy J, Chiang Y, Cosentino S, Cracroft-Eley W. Progress in upscaling Miscanthus biomass production for the European bio-economy with seed-based hybrids. Gcb Bioenergy 2017;9:6–17.

[129] Pulighe G, Bonati G, Colangeli M, Morese MM, Traverso L, Lupia F, Khawaja C, Janssen R, Fava F. Ongoing and emerging issues for sustainable bioenergy production on marginal lands in the Mediterranean regions. Renew Sustain Energy Rev 2019;103:58–70. https://doi.org/10.1016/J.RSER.2018.12.043.

[130] Cosentino SL, Scordia D, Testa G, Monti A, Alexopoulou E, Christou M. The importance of perennial grasses as a feedstock for bioenergy and bioproducts. In: Perenn. Grasses Bioenergy Bioprod. Elsevier; 2018. p. 1–33.

[131] Buchholz T, Hurteau MD, Gunn J, Saah D. A global meta-analysis of forest bioenergy greenhouse gas emission accounting studies. Gcb Bioenergy 2016;8: 281–9.

[132] IPCC. IPCC guidelines for national greenhouse gas inventories. 2006. https://www.ipcc-nggip.iges.or.jp/public/2006gl/. 2006.

[133] De Meyer A, Cattrysse D, Rasinmäki J, Van Orshoven J. Methods to optimise the design and management of biomass-for-bioenergy supply chains: a review. Renew Sustain Energy Rev 2014;31:657–70.

[134] Cervi WR, Lamparelli RAC, Seabra JEA, Junginger M, de Jong S, van der Hilst F. Spatial modeling of techno-economic potential of biojet fuel production in Brazil. GCB Bioenergy 2020;12:136–57.

[135] Stafford WHL, Von Maltitz GP, Watson HK. Reducing the costs of landscape restoration by using invasive alien plant biomass for bioenergy. WIREs Energy Environ 2018;7:e272. https://doi.org/10.1002/wene.272.

[136] Vázquez-Rowe I, Marvuglia A, Rege S, Benetto E. Applying consequential LCA to support energy policy: land use change effects of bioenergy production. Sci Total Environ 2014;472:78–89.

[137] Meyer MA, Chand T, Priess JA. Comparing bioenergy production sites in the southeastern US regarding ecosystem service supply and demand. PLoS One 2015; 10. https://doi.org/10.1371/journal.pone.0116336.

[138] Nerini FF, Tomei J, To LS, Bisaga I, Parikh P, Black M, Borrion A, Spataru C, Broto VC, Anandarajah G. Mapping synergies and trade-offs between energy and the sustainable development goals. Nat Energy 2018;3:10–5.

[139] Harahap F. Bioenergy Sustainable development in Indonesia and its relation with SDGs goal. In: IOP Conf. Ser. Earth Environ. Sci. IOP Publishing; 2021. p. 12036.

[140] Lal R, Bouma J, Brevik E, Dawson L, Field DJ, Glaser B, Hatano R, Hartemink A, Kosaki T, Lascelles B. Soils and sustainable development goals of the United Nations (New York, USA): an IUSS perspective. Geoderma Reg.; 2021, e00398.