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Land, water and carbon footprints of circular bioenergy production systems

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ABSTRACT

Renewable energy sources can help combat climate change but knowing the land, water and carbon implications of different renewable energy production mixes becomes a key. This paper systematically applies land, water and carbon footprint accounting methods to calculate resource appropriation and CO_2eq GHG emissions of two energy scenarios. The '100% scenario' is meant as a thinking exercise and assumes a complete transition towards bioenergy, mostly as bioelectricity and some first-generation biofuel. The 'SDS-bio scenario' is inspired by IEA's sustainable development scenario and assumes a 9.8% share of bioenergy in the final mix, with a high share of first-generation biofuel. Energy inputs into production are calculated by differentiating inputs into fuel versus electricity and exclude fossil fuels used for non-energy purposes. Results suggest that both scenarios can lead to emission savings, but at a high cost of land and water resources. A 100% shift to bioenergy is not possible from water and land perspectives. The SDS-bio scenario, when using the most efficient feedstocks (sugar beet and sugarcane), would still require 11–14% of the global arable land and a water flow equivalent to 18–25% of the current water footprint of humanity. In comparative terms, using sugar or starchy crops to produce bioenergy results in smaller footprints than using oil-bearing crops. Regardless of the choice of crop, converting the biomass to combined heat and power results in smaller land, water and carbon footprints per unit of energy than when converting to electricity alone or liquid biofuel.

1. Introduction

Global energy demand is rising: total final energy consumption has increased twofold since 1973, reaching 9425 million tonnes of oil equivalent (Mtoe) in 2014 [1]. Electricity consumption has increased 3.9 times during this period, which is faster than consumption of other energy sources (natural gas, oil, coal). The increase in energy demand is driven by population growth, industrialization and urbanization [2]. Per capita energy use in 2014 (1921 kg of oil equivalent) was 35% higher than in 1973 (1418 kg of oil equivalent) [3]. The largest increase in regional energy consumption occurred in the Middle East, 5.1% of the final global energy consumption in 2014 versus 0.7% in 1973 [1].

Most of current human energy requirements are satisfied using fossil fuels, which are harmful to the environment. The most imminent dangers stemming from the energy sector are the emission of greenhouse gases (GHGs), air pollution, and water stress [4]. The emission of GHGs is a global issue and perhaps the most concerning. The energy sector contributes about two thirds of all anthropogenic GHG emissions [4]. According to the Intergovernmental Panel on Climate Change (IPCC), these anthropogenic GHG emissions may have contributed between 0.5 and 1.3 °C increase to the global mean surface warming from 1951 to 2010 [5].

Renewable energy is increasingly viewed as a prominent part of the solutions to mitigate climate change [4,6,7]. Renewable energy is defined as energy from biological, geophysical or solar sources that is naturally replenished faster or at the rate equal to its use [6]. The feasibility and efficiency of different renewable energy depend on the availability, conversion efficiency and utilization rate of required natural resources. The resource appropriation of the major renewable energy sources, i.e., biomass, solar photovoltaics (PV), solar thermal,

Abbreviations: CF, carbon footprint; CH_4, methane; CHP, combined heat and power; CO_2, carbon dioxide gas; CO_2eq, carbon dioxide equivalent; DM, dry mass; EEA, European Environment Agency; EROI, energy return on investment; FAO, Food and Agriculture Organization of the United Nations; GHGs, greenhouse gases; H_2, hydrogen gas; HAC, high activity soil; HHV, higher heating value; HI, harvest index; IEA, International Energy Agency; IPCC, Intergovernmental Panel on Climate Change; LCA, life cycle assessment; LF, land footprint; N_2, nitrogen gas; NBE, net bioelectricity; NBF, net biofuel; NH_3, ammonia; N_2O, nitrous oxide; PV, photovoltaic; RFA, Renewable Fuel Association; SDS, sustainable development scenario; USDA, United States Department of Agriculture; USEPA, United States Environmental Protection Agency; WF, water footprint

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Units

GJ	gigajoule
Gt	gigatonne
GJ ha^{-1}	gigajoule per hectare
GJ $tonne^{-1}$	gigajoule per tonne
kg ha^{-1}	kilogram per hectare
kg L^{-1}	kilogram per litre
km^2 y^{-1}	square kilometre per year
km^3 y^{-1}	cubic kilometre per year
L ha^{-1}	litre per hectare
lb ac^{-1}	pound per acre
m^2 GJ^{-1}	square meter per gigajoule
m^3 $tonne^{-1}$	cubic meter per tonne
MJ ha^{-1}	megajoule per hectare
MJ kg^{-1}	megajoule per kilogram
MJ L^{-1}	megajoule per litre
MJ t^{-1} km^{-1}	megajoule per tonne-kilometre
Mtoe	million tonnes of oil equivalent
MW	megawatt

hydro, wind, ocean, and geothermal [6,8] are far from equal and require foreknowledge of their appropriateness for particular sites or aims.

Globally, a sizable fraction of final energy consumption is already generated from renewable sources such as bioenergy [1] and many countries have formed national plans to transition towards renewable energy generation in the near future. The term bioenergy implies that energy is produced from materials of biological origin without counting materials embedded in geological formations and turned into fossil sources [9]. In 2005, 43 countries had national renewable energy targets, while the number had increased to 164 countries by 2015. Moreover, 59 countries had national renewable transport energy targets in 2015 [10]. The fast transition towards renewable energy urges us to understand the implications of energy decisions on natural resources appropriation and sustainability of natural resources use.

A practical method for quantifying and comparing human pressure on the environment is assessing a “footprint” of a particular product or a human activity. Footprints serve as “indicators of human pressure on the environment” that help to understand environmental changes and impacts resulting from this pressure [11]. The common footprints are the land footprint (LF), water footprint (WF) and carbon footprint (CF). The LF is originally part of the “ecological footprint” that measures land required to satisfy consumption and for assimilating waste discharge of a defined population [12], but commonly only the land requirement to satisfy consumption is referred to as the LF [11,13,14]. The WF measures direct and indirect freshwater appropriation of a product, sector or community and consists of three components: the blue WF (consumption of surface water and groundwater), the green WF (consumption of rainwater) and the grey WF (the water demand to assimilate pollutants) [15]. The CF is defined as total carbon dioxide emissions measured in mass units (kg, tonnes, etc.) that are produced over the life of a product or directly and indirectly produced by an activity [16], but usually includes other GHG emissions in terms of carbon dioxide equivalents as well [11,17].

Generally, studies to this day focus on a single footprint of energy, with very few studies covering two footprints and, to our knowledge, none covering more than two. The three footprints together, the “footprint family”, allows comprehensive monitoring of the various pressures on the environment [18,19] Footprint assessments help evaluate the sustainability of an activity or a product. Sustainability of activities depends on footprint characteristics such as size, timing and location relative to local thresholds or the overall planet's carrying capacity [11].

Many studies have looked specifically at the WF of particular energy types at various scales [20–33] or at the CF of a particular energy [34–36]. Fewer studies focused on assessing a combination of LF and WF of particular energy carriers [37–39] or combination of CF and WF [30,40]. No study has looked at the scale of water and land resources necessary to meet the global energy demand produced from renewable energy sources while estimating associated GHG emissions. This is important, however, given the clear evidence that some forms of renewable energy, notably bioenergy, come along with a large need for land and water [20,27]. To fill this gap, this study systematically assesses the LF, WF and CF of two circular bioenergy production scenarios, assuming different ratios of bioenergy in the final energy mix. Here, circular means that the bioenergy production system is self-sustaining and produces excess energy to compensate the input requirements for production.

2. Methods

2.1. Fuel composition of two bioenergy production scenarios

Two bioenergy production scenarios are considered (Table 1). The 100% scenario is a complete shift to bioenergy. The SDS-bio scenario is adapted from the sustainable development scenario (SDS) of the International Energy Agency (IEA), with a 9.77% bioenergy share in the final consumed energy mix [41].

2.1.1. 100% scenario

In this scenario, the share of heat in the total is assumed the same as the current global heat consumption, while the share of biofuel is taken equal to current fuel consumption in aviation, maritime and road freight transports combined. All the remaining energy consumption is assumed bioelectricity. The large share of bioelectricity is assumed because: (a) electricity consumption has increased the most since 1973 [1]; (b) demand is expected to further increase by 70% towards 2035 [42]; and (c) its production is more water efficient than the production of biofuels [22]. The global bioenergy production equals the world's final consumption less non-energy uses [43]. Aviation energy demand is determined by adding final consumption of aviation gasoline and jet kerosene for 2014 [44]. Maritime and road freight energy demand are assumed as 5% and 18% of the total final oil products consumption, respectively, which correspond to the actual shares in 2015 [45]. Total final oil products consumption and total final heat consumption in 2014 are obtained from IEA [43].

2.1.2. SDS-bio scenario

For this scenario the production quantity and ratios of bioelectricity, biofuel and heat are determined using IEA's SDS scenario for 2040 [41]. In IEA's SDS scenario, bioenergy will provide 9.77% of the total final consumption or 41.6 EJ in 2040, an assumption that is based on the rationale and data described in detail by IEA [41]. Here, the shares of bioelectricity, fuel and heat from IEA's SDS scenario for 2040 are back calculated to align with the 2014 consumption in two steps. First, total

Table 1
Shares of biofuel, heat and bioelectricity in the two scenarios.

	Electricity	Fuel	Heat	Total
	100% scenario			
Exajoules	316.1	47.1	11.4	374.6
% composition	84.4	12.6	3.1	100
	SDS-bio scenario			
Exajoules	6.1	16.0	15.9	38.0
% composition	1.6	4.1	4.1	9.8

bioenergy consumption in 2014 is assumed the same as in 2040–9.77%. Second, the ratios of biofuel, bioelectricity and heat presented in the original SDS scenario are multiplied by their respective values for 2014. Specifically, in IEA's SDS scenario, 8.5% of power is generated using bioenergy [41], thus 8.5% of total final consumed electricity in 2014 is assumed bioelectricity. Similarly, 14.5% of total final consumed energy in the transport sector in 2040 is in the form of biofuels [41], thus 14.5% of total final consumed energy in the transport sector in 2014 is assumed biofuels. The difference between the total bioenergy and consumed bioelectricity plus biofuels in 2014 is assumed heat from bioenergy. The 2014 total energy consumption is obtained from the IEA [43].

2.2. Energy calculations

Bioelectricity or combined heat and power (CHP) are generated using the entire feedstock biomass while only the economic yield fraction of the crop (the part of the crop that contains most of the sugar, starch or oil) can be converted to liquid biofuels. In both scenarios, we consider five alternative crops as feedstock for bioenergy, namely sugar beet, sugarcane, maize, soybean and rapeseed, which are selected for four reasons. First, sugar beet, sugarcane and maize are selected because they are the most utilized feedstock for bioethanol production [46–49] and second, they have the smallest WF per unit of bioelectricity production [20]. Third, although the biodiesel can be produced from a range of oilseeds [50,51] as the number of known oil-bearing crops exceeds 350 [52], rapeseed and soybean are the most commonly utilized crops for biodiesel production and fourth, their WFs are smaller compared to biodiesel from other crops [20].

2.2.1. Bioelectricity and heat

The energy embedded in crop biomass is converted to bioelectricity and heat through combustion in the CHP plant or only to bioelectricity in the power plant. In both cases, the heat energy content of crop biomass is calculated and converted to bioelectricity, or bioelectricity and heat, using conversion ratios presented below. The heat energy content of crop biomass is calculated by combining the higher heating value (HHV) of major plant ingredients, similar to the method employed by Gerbens-Leenes et al. [20,21]:

$$E(c) = \left(HI(c) \times DM_y(c) \times \sum_{i=1}^{5} C_i \times A_{y,i}\right) + \left((1 - HI)(c) \times DM_r(c) \times \sum_{i=1}^{5} C_i \times A_{r,i}\right) \quad (1)$$

where E(c) is the heat energy of crop c in GJ tonne^{-1}, HI(c) the harvest index of c, DM the fraction of dry mass, A the content of ingredient *i* in the DM (g/100 g) (see Appendix Table A.10), *C* the HHV value of ingredient *i* in GJ tonne^{-1} (Table A.11), *y* the economic yield fraction, and *r* the rest fraction.

Power plants achieve higher conversion efficiency of biomass to bioelectricity compared to CHP plants [53]. For the bioelectricity-only route, we use the highest reported operational conversion efficiency of 43% [54] achieved by combusting biomass in a power plant (Table 2). For the CHP route, the conversion efficiencies are assumed as 22% bioelectricity and 63% heat, corresponding to the average EU values in large CHP plants (> 20 MW) operating on bio feedstock [53].

2.2.2. Bioethanol

Bioethanol is produced from the sugar or starch in the economic yield fraction of crops. The bioethanol yield is calculated by the method described in Gerbens-Leenes et al. [20], assuming bioethanol's HHV of 29.7 GJ tonne^{-1}:

$$E_{bioethanol}(c) = DM_y(c) \times f_{carbohydrate}(c) \times f_{bioethanol} \times HHV_{bioethanol} \quad (2)$$

where $E_{bioethanol}(c)$ is the bioethanol output of crop c in GJ tonne^{-1}, $f_{carbohydrate}(c)$ the fraction of carbohydrates in the DM of the economic yield (g/100 g) and $f_{bioethanol}$ the bioethanol yield per unit of carbohydrate that, consistent with [20], is assumed 0.51 g/g for sugar (in the case of sugar beet and sugarcane) and 0.53 g/g for starch (for maize).

2.2.3. Biodiesel

Biodiesel is produced from fat in the economic yield fraction of plants. The biodiesel yield is calculated following [20], assuming biodiesel's HHV of 37.7 GJ tonne^{-1}:

$$E_{biodiesel}(c) = DM_y(c) \times f_{fat}(c) \times f_{biodiesel} \times HHV_{biodiesel} \quad (3)$$

where $E_{biodiesel}(c)$ is the biodiesel output of crop c in GJ tonne^{-1}, $f_{fat}(c)$ the fraction of fats in the DM of the economic yield (g/100 g) and $f_{biodiesel}$ the amount of biodiesel yield per unit of fat that, consistent with [20], is assumed 1 g/g of fat.

Global average crop yields (hectogram ha^{-1}) for 2014 are obtained from the FAO [55]. Gross biofuel output for crop c, calculated in steps 2 and 3 is converted to GJ ha^{-1} using the global average crop yields. Gross bioelectricity and heat output for crop c, calculated in step 1 is converted to GJ ha^{-1} by first converting the global average crop yields to the global average biomass yields. The biomass yields are calculated by dividing the economic yields by the crop specific HI (Table A.10). Next, the gross bioelectricity and heat outputs per unit weight of crop c biomass are multiplied by the global average biomass yield.

2.3. Energy balance calculations

Energy is required to produce energy. The amount and quality of energy input per unit of output can vary considerably, affected by factors such as the type of energy output, production scale, transport distances of required inputs and intermediate products, efficiency of production technology. Moreover, different feedstock crops have different cultivation requirements and biofuel production is very different from bioelectricity or combined heat-bioelectricity production.

The net to gross energy conversions and relevant methods and data sources are described in the Appendix (Supplementary materials). The net energy production is converted to the gross energy production using a circular feedback loop. The feedback loop differentiates input energy into bioelectricity versus biofuels. Moreover, the feedback loop treats the CHP route differently from the power-only route to account for different conversion efficiencies.

2.4. Footprint calculations

2.4.1. Land footprint

In each scenario, the total LF is calculated by summing land requirement for gross biofuel and gross bioelectricity production for a given crop c. The land requirement for gross biofuel production using a crop c is calculated as the sum of the gross biofuel requirements across the CHP and power-only routes for crop c (Table A.9) divided by the gross biofuel output per hectare for crop c (Table 5). In contrast, the land requirement for gross bioelectricity production is calculated by dividing gross CHP production and gross bioelectricity production for a given crop c (Table A.9) by their respective gross bioelectricity output

Table 2
Biomass to bioelectricity and combined heat and bioelectricity conversion efficiencies used in this work. Biomass to CHP conversion efficiency is obtained from Ref. [53] and biomass to bioelectricity efficiency from Ref. [54].

	Power plant	CHP plant
Bioelectricity	43%	22%
Heat	–	63%
Losses	57%	15%

Table 3
Assumptions for "current" soil organic carbon conditions in mineral soils.

Crop	Climate and soil for reference carbon stock value	Land-use factor	Management factor	Carbon input values
Sugar beet	cold temperate moist, HAC[a] - Regosols	long term cultivation	reduced tillage	low
Sugarcane	tropical moist, HAC - Vertisols	long term cultivation	reduced tillage	low
Maize	warm temp, moist HAC - Chernozem	long term cultivation	reduced tillage	low
Soybean	cold temperate moist, HAC - Phaeozems	long term cultivation	reduced tillage	medium
Rapeseed	cold temperate dry, HAC - Luvisol	long term cultivation	reduced tillage	low

[a] HAC refers to high activity clay.

Table 4
Biofuel density conversion values.

Biofuel	Value	Unit	Source
Bioethanol	0.7887	kg L^{-1}	RFA [63]
Biodiesel	0.8424	kg L^{-1}	Alptekin and Canakci [64]

per hectare (Table 5), and then adding them. That is because unlike the biofuel production, the bioelectricity production efficiency depends on the process and is different for the CHP route versus the power-only route.

2.4.2. Water footprint

Global average green, blue and grey WF of crops per unit of weight is obtained from Mekonnen and Hoekstra [56] (Table A.12) and converted to WF per hectare using the average crop yields per hectare for 2014 from FAO [55]. The average WF per hectare is then multiplied by the total land requirement for crop c in each of the two scenarios to obtain the total WF for a particular scenario.

2.4.3. Carbon footprint

Total bioenergy-related CFs of the two scenarios are calculated as the sum of CO_2eq emissions associated with: (1) nitrogen fertilizer production; (2) soil management; and (3) biomass and biofuel combustion as described below. All the GHG emissions are calculated according to IPCC's tier 1 method and the CH_4 and N_2O emissions from combustion are converted to CO_2eq using their 100 year global warming potentials of 28 and 265, respectively [5].

GHG emissions from fertilizer production (Fig. 1) refer to the cumulative emissions from producing nitrogen fertilizer - ammonium nitrate - that is obtained by neutralizing nitric acid with gaseous ammonia [57]. Ammonium nitrate can be used directly or combined with limestone, dolomite or calcium carbonate to produce other nitrogen fertilizers, i.e., urea ammonium nitrate, magnesium ammonium nitrate, ammonium sulphate nitrate and calcium ammonium nitrate, making it the most used fertilizer product in the Western Europe [57].

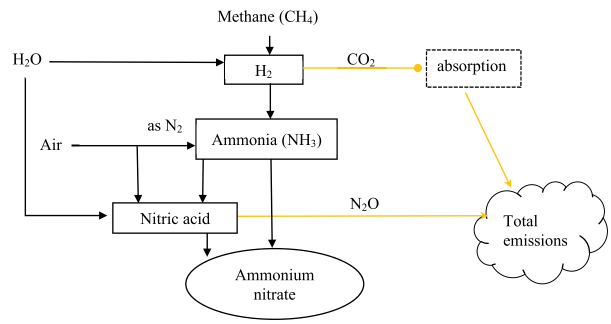


Fig. 1. Simplified representation of the GHG emissions from nitrogen fertilizer production.

Nitric acid and ammonia production are significant contributors to global GHG emissions [58]. Ammonia is produced by synthesizing hydrogen gas (H_2) with nitrogen gas (N_2) [57]. While the atmosphere is a good source of N_2, hydrogen production involves fossil fuels as feedstock. Hydrogen in ammonia production obtained through steam reforming accounts for 77% of the global capacity [57]. In this work, methane is assumed as the hydrogen feedstock.

The default values used to calculate CO_2 emissions from ammonia production correspond to production processes in a modern European plant employing the conventional reforming of a natural gas [58]. One adjustment is made for consistency with the previous assumptions, that is the total energy requirement per tonne of ammonia output excludes methane used as feedstock for hydrogen production [57]. The default N_2O emission factor from nitric acid production corresponds to a production process in a high-pressure plant [58]. The ratio of ammonia in ammonium nitrate fertilizer production and the ratio of nitric acid in fertilizer production are taken from Fossum [59]. The nitrogen fertilizer application requirements for specific crops are listed in the Appendix

Table 5
Energy outputs in GJ $tonne^{-1}$ specified per crop.

Crop	Accounting	Electricity[b]	CHP[b]		Bioethanol[c]	Biodiesel[c]
			Electricity	Heat		
Sugar beet	Gross	1.6	0.8	2.4	2.6	–
	Net[a]	1.4	0.8	2.2	2.3	–
Sugarcane	Gross	2.3	1.2	3.4	2.3	–
	Net	2.1	1.1	3.2	2.1	–
Maize	Gross	7.3	3.7	10.6	10.0	–
	Net	6.5	3.5	10.1	5.2	–
Soybean	Gross	4.3	2.2	6.3	–	6.2
	Net	3.7	2.1	5.9	–	2.6
Rapeseed	Gross	3.0	1.6	4.4	–	11.7
	Net	2.1	1.3	3.7	–	6.6

[a] Net is gross minus input energy per tonne.
[b] Feedstock is 1 tonne of biomass.
[c] Feedstock is 1 tonne of economic yield fraction.

(Table A.3).

GHG emissions from managing soils refer to direct and indirect N_2O emissions [58]. The direct emissions are linked to nitrogen inputs to managed soils and include: N_2O-N emissions linked to the amount of synthetic nitrogen fertilizer applied for a specific crop, the annual amount of nitrogen in crop residues, and the amount of nitrogen in mineral soils that is mineralized based on soil carbon loss from organic matter caused by changes in land management and use. Crop-specific assumptions on soil organic carbon condition are summarized in Table 3. Utilized crop-specific soil characteristics are taken from the World Reference Base for Soil Resources [60]. The default IPCC factors are used to estimate N added to soils from crop residue, with two exceptions. First, the crop dry matter ratio is adopted from Gerbens-Leenes et al. [20,21] (Table A.10). Second, crop yields are adjusted to account for seed requirements (i.e. economic yield minus seed requirements). For nitrogen additions, a default N_2O-N emission factor from IPCC [58] is used in this work.

The indirect emissions cover N_2O-N emissions from: the atmospheric deposition of nitrogen that is volatilised from managed soils and from leaching/runoff. Atmospheric deposition of volatilised nitrogen is linked to the synthetic fertilizer application for a specific crop multiplied by the fraction that is volatilised and the default emission factor [58]. Similarly, emissions from leaching are linked to the synthetic fertilizer application for a specific crop, but extend to also cover nitrogen added annually to soils from crop residue, and annual nitrogen mineralized in mineral soils multiplied by the fraction of all added nitrogen that is lost to leaching and the default emission factor from leaching [58].

Emissions from combustion of biomass in stationary plants for bioelectricity production are calculated differently than emissions from combustion of biofuel in mobile sources. In this study, emissions from biomass and biofuel combustion include CH_4 and N_2O emissions only because consistent with the IPCC assumptions the CO_2 emissions are assumed zero [58]. Default emission factors for combustion of solid biomass in stationary sources are obtained from the IPCC [58]. Emissions factors for combustion of biofuels in mobile sources depend on many factors, such as the type of transport, technology, etc. [58]. In this study, emission factors for biodiesel and bioethanol combustion refer to emissions from medium and heavy duty trucks obtained from USEPA [61]. The emissions are converted from gram mile^{-1} to kg ha^{-1} based on the following assumptions and data: 5.8 miles gallon^{-1} average fuel efficiency of class-8 trucks traveling at a speed of 55 mph [62], biofuel density from Table 4, HHVs of bioethanol and biodiesel of 29.7 and 37.7 GJ tonne^{-1} respectively, biofuel energy yield per unit of land from Table 6, and conversion of miles to km and US gallons to litres.

3. Results and discussion

3.1. Energy outputs per unit of weight and per unit of area

Energy outputs per tonne of feedstock do not differ between scenarios. Maize-based production yields most energy as bioelectricity, CHP, and bioethanol per unit weight (Table 5). In contrast, sugar beet as a feedstock gives least bioelectricity or CHP, while sugarcane gives least bioethanol per unit weight. Rapeseed as a feedstock yields more biodiesel energy per unit of weight than soybean.

Table 6 shows the energy output per hectare. Sugarcane is the most efficient feedstock for producing net bioethanol, bioelectricity and CHP per unit area while sugar beet comes second. Maize gives the least bioethanol per unit area, four times less than either sugar beet or sugarcane in net terms. The rapeseed-based production system generates the least bioelectricity and CHP output per unit area. The soybean-based production system generates the least biodiesel per unit area.

CHP generation yields the most total energy per unit of land and unit of weight (with the exception of rapeseed). Sugarcane, maize and soybean can produce more net energy as bioelectricity than biofuel per unit of land. Net bioelectricity output of a soybean-based production system yields over three times more energy than net biodiesel output per unit of land. Similarly, net bioelectricity output of a maize-based production system yields over twice more energy than net bioethanol output per unit of land. In contrast, sugar beet and rapeseed can produce more energy as biofuel than bioelectricity per unit of land.

3.2. Energy return on investment for different crops and carriers

The computed ratios of energy output per unit of energy input, referred to in literature as the Energy Return on Investment (EROI) [65], do not differ between the two scenarios. With the exception of the case of sugar beet, EROI is highest for CHP output followed by the bioelectricity output (Tables 7 and 8). For CHP and bioelectricity outputs, the sugarcane-based production system has the highest EROI, while the rapeseed-based production system has the lowest EROI. The EROI of using maize feedstock for CHP and bioelectricity output is also high, only slightly lower than the EROI of the sugarcane-based production system.

The EROI values for biofuels are lower than for bioelectricity (except for the sugar beet feedstock) and for CHP (Table 8). The EROIs of biofuels produced from sugar beet, sugarcane, maize, soybean and rapeseed feedstock are higher in this study than in most previous literature. Biofuels from sugarcane has the highest overall EROI, followed by bioethanol from sugar beet. Biodiesel from soybean has the lowest EROI.

Table 6
Energy outputs in GJ ha^{-1} specified per crop.

Crop	Accounting	Electricity[b]	CHP[b]		Bioethanol[c]	Biodiesel[c]
			Electricity	Heat		
Sugar beet	Gross	147.2	75.3	215.7	157.3	–
	Net[a]	126.2	69.9	200.1	139.6	–
Sugarcane	Gross	261.2	133.6	382.7	157.3	–
	Net	239.8	128.1	366.8	142.0	–
Maize	Gross	90.5	46.3	132.6	56.1	–
	Net	80.7	43.8	125.4	29.1	–
Soybean	Gross	27.8	14.2	40.7	–	15.8
	Net	23.9	13.2	37.8	–	6.5
Rapeseed	Gross	19.3	9.9	28.3	–	23.8
	Net	13.3	8.3	23.8	–	13.3

[a] Net is gross minus bioelectricity and biofuel inputs per hectare.
[b] Feedstock is the total biomass.
[c] Feedstock is the economic yield fraction.

Table 7
Calculated EROI for bioelectricity and CHP production from different crops.

	Sugar beet	Sugarcane	Maize	Soybean	Rapeseed
Bioelectricity	7.0	12.2	9.2	7.1	3.2
CHP	13.9	24.1	18.2	14.0	6.3

Table 8
EROI values of biofuel production utilizing different feedstock (without co-products if specified) from the current study versus literature.

Source	Bioethanol			Biodiesel	
	Sugar beet	Sugarcane	Maize	Soybean	Rapeseed
de Oliveira et al. [66]		3.7	1.1		
Pimentel and Patzek[a] [67]			0.8	0.8	
Hill et al. [68]			1.3	1.9	
Smith et al. [69]				1.7	2.2[e]
Von Blottnitz and Curran[b] [70]	2.0	7.9	1.3		
Boddey et al. [71]		8.8			
Pimentel et al.[a] [72]			0.7	0.6	
Yee et al. [73]					1.4
Pereira and Ortega [74]		8.2			
Chen and Chen [75]					0.9
Fore et al.[a] [76]				1.3	1.2[e]
Nogueira [77]				3.3	
Kraatz et al.[c] [78]			1.6		
de Castro et al.[d] [79]		5.0	1.3		1.5
Brondani et al. [80]				1.0	
van Duren et al. [81]					< 2.2
Donke et al. [82]		11.5	6.9		
Current study	8.9	10.3	2.1	1.7	2.3

[a] Not originally reported but calculated by dividing energy outputs by the inputs.
[b] Results from a review.
[c] Not originally reported but calculated by dividing the HHV of ethanol by the energy inputs, excluding energy invested for drying the co-product.
[d] Estimate, not the actual calculation.
[e] Reported for canola that is treated same as rapeseed.

Within the dynamic loop, the share of output circulated to sustain production varies between energy scenarios, between biofuel and bioelectricity, and between crops (Fig. 2). In the 100% scenario, 32–41% of gross biofuel output is used as input for bioelectricity production, the precise fraction depending on the feedstock, while in the SDS-bio scenario that fraction is 4–13% percent. Regardless of the scenario, oil-bearing crops consume a larger share of the output to sustain production.

Table 9
The LF per unit of net energy ($m^2 GJ^{-1}$).

Crops	Bioelectricity	CHP	Bioethanol	Biodiesel
Sugar beet	79	37	72	–
Sugarcane	42	20	70	–
Maize	124	59	344	–
Soybean	418	196	–	1544
Rapeseed	754	311	–	750

3.3. LF of the bioenergy production scenarios

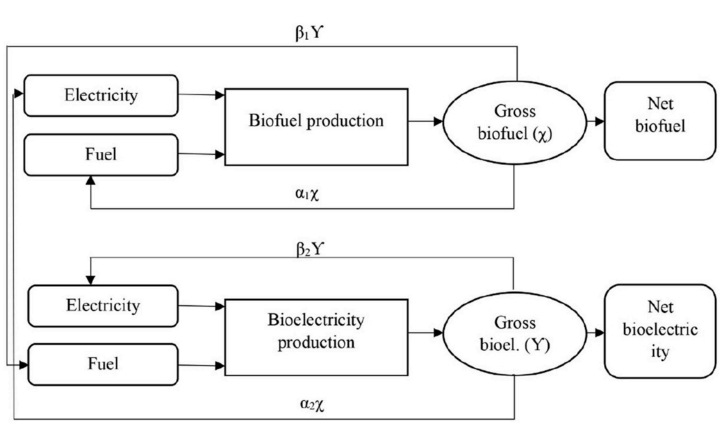
The LF per GJ of bioenergy varies between feedstocks and is different for biofuel, bioelectricity and CHP. For sugarcane, maize and soybean, the LF of producing a GJ of biofuel is larger than the LF per GJ of bioelectricity or CHP output (Table 9). The LF of a GJ of biodiesel output using soybean feedstock, for example, is over three times larger than the LF of producing a GJ of bioelectricity and seven time larger than the LF of producing a GJ of CHP. Only in case of sugar beet and rapeseed the LF of producing a GJ of biofuel is smaller than producing a GJ of bioelectricity, albeit slightly.

In the 100% scenario, the LF of energy production is larger than the global land area currently utilized in arable agriculture (14.2 million km^2 in 2014) [83] regardless of choice of feedstock. Meeting global energy consumption with bioenergy using sugarcane feedstock is the least land intensive, requiring 18.3 million km^2 or 129% of the current global arable land, while using sugar beet feedstock requires 28.3 million km^2 or 200% of the global arable land (Fig. 3). The LF of maize-based bioenergy production in the 100% scenario is 53.7 million km^2 or 379% of the global arable land, whereas using soybean would require 1337% and rapeseed 1970% of the global arable land. In the 100% scenario, bioelectricity generation accounts for more than two thirds of the LF regardless of the feedstock choice.

In the SDS-bio scenario, the LF varies widely between feedstock crops as well. Using sugarcane would require the least land, namely 11.4% of the current global arable land, using sugar beet would take 14.2%, maize 37.9%, soybean 149% and rapeseed 157.6%. In the SDS-bio scenario, biofuel generation is responsible for a larger LF compared to bioelectricity generation in all cases except in a rapeseed-based production system.

3.4. WF of the bioenergy production scenarios

The WF per GJ of biofuel is larger than the WF per GJ of bioelectricity or CHP when sugarcane, maize or soybean is used as feedstock (Table 10). The least amount of water is needed to produce a GJ as CHP output using sugar beet or sugarcane feedstock. In contrast, producing a GJ of biodiesel from soybean requires the most amount of water, that is



Crop	Production	100% scenario α (%)	100% scenario β (%)	SDS-bio α (%)	SDS-bio β (%)
Sugar beet	Biofuel	7.5	38.1	9.1	4.3
	Bioelectricity	1.1	3.7	6.5	3.5
Sugarcane	Biofuel	7.7	40.8	8.6	4.3
	Bioelectricity	0.3	1.2	1.9	1.2
Maize	Biofuel	5.2	31.7	10.1	6.8
	Bioelectricity	5.5	6.9	41.0	5.8
Soybean	Biofuel	4.8	37.5	18.9	11.6
	Bioelectricity	6.7	9.6	46.9	2.2
Rapeseed	Biofuel	5.4	40.6	15.3	13.4
	Bioelectricity	9.1	22.3	49.9	14.1

Fig. 2. Schematic representation of the dynamic feedback loop and percentages of gross biofuel and bioelectricity outputs used as inputs.

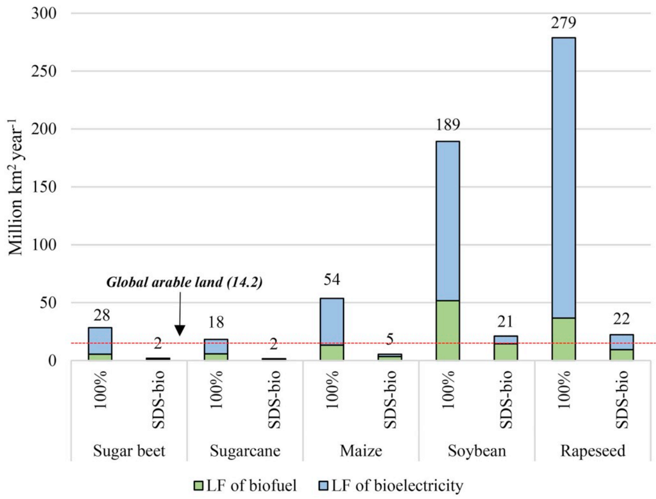


Fig. 3. LFs of the two global bioenergy production scenarios based on different feedstock specified by type of energy (biofuel or bioelectricity).

Table 10
The WF per unit of net energy ($m^3\ GJ^{-1}$).

Crops	Bioelectricity	CHP	Bioethanol	Biodiesel
Sugar beet	63	29	57	–
Sugarcane	59	29	100	–
Maize	85	40	235	–
Soybean	227	106	–	838
Rapeseed	348	144	–	346

14 times more than required to produce a GJ of bioethanol using sugar beet.

In the 100% scenario, using any feedstock, the water requirement would be so large that it would even exceed the current WF of humanity of 9087 $km^3\ y^{-1}$ [84]. Meeting the global energy consumption using sugar beet feedstock would have the smallest WF, i.e. 22,600 $km^3\ y^{-1}$ (with a blue WF component of 4400 $km^3\ y^{-1}$). In this best-case, water use in the world would increase by a factor 3.5. Using rapeseed, the WF would be 128,600 $km^3\ y^{-1}$ (blue WF of 13,100 $km^3\ y^{-1}$) (Fig. 4), thus multiplying current water use in the world by a factor 15. In relative terms, the WFs of sugar/starch-bearing feedstock are smaller and comparable whereas the WF of the oil-bearing feedstock are larger and mutually comparable.

In the SDS-bio scenario, the WF of the bioenergy produced using sugar/starch-bearing feedstock is smaller than the current WF of humanity but larger in case of oil-bearing feedstock systems (Figs. 4 and 5). Using any of the five feedstocks will require WF larger than the current global WF of all industries. The global WF of industries, which includes the WF of energy production, is currently estimated at 400 $km^3\ y^{-1}$ [84]. The blue WF of the current energy production varies between studies due to methodological differences from 48 $km^3\ y^{-1}$ for global power and primary energy production [85] to 217 $km^3\ y^{-1}$ for power and heat production alone [27]. In this study, the most water-efficient production system, based on sugar beet, has a WF of 1600 $km^3\ y^{-1}$ (with a blue WF of 310 $km^3\ y^{-1}$), the next most water-efficient production system, based on sugarcane, has a WF of 2290 $km^3\ y^{-1}$ (with a blue WF of 620 $km^3\ y^{-1}$), and the least water-efficient production, based on soybean, has a WF of 11,450 $km^3\ y^{-1}$ (with a blue WF of 370 $km^3\ y^{-1}$).

Green WF makes up the largest share of the total WF in both scenarios, in the range of 62%–95%, regardless of the choice of feedstock. The contribution of blue and grey WF varies between crops. While the blue WF is larger than the grey WF in case of sugar beet, sugarcane and soybean, the grey WF is larger than blue WF in case of maize and rapeseed. The share of blue WF in a total WF ranges from 3.3% in the soybean-based system to 27% in the sugarcane-based system.

3.5. CF of the bioenergy production scenarios

The CF per unit of biofuel energy from sugarcane, maize and soybean is larger than the CF per unit of bioelectricity or CHP derived energy (Table 11). Sugar beet and rapeseed feedstock are the exceptions, where the CF per unit of biofuel energy is smaller than the CF per unit of bioelectricity. The rapeseed-based production system has the largest CF per unit of bioelectricity and CHP derived energy, while the soybean-based production system has the largest CF per unit of biofuel energy.

In the 100% scenario, the CF of energy production from all feedstocks except rapeseed is smaller than the actual 32.4 Gt of CO_2eq [86] emitted in 2014 from fuel combustion. The sugarcane-based production system has the smallest CF, 4.4 Gt of GHGs per annum, while, at the other extreme, the rapeseed-based production system has a CF of 34.4 Gt of CO_2eq emissions (Fig. 6), that exceeds current emissions level by 6%. The CF values are 7.8 Gt for sugar beet, 13.7 Gt for maize, and 17.7 Gt for soybean-based production systems. The CF of bioelectricity generation is responsible for a much larger CF than the biofuel generation.

In the 100% scenario, the circular bioenergy production system leads to emission savings in all but rapeseed based feedstock systems (Table 12). The largest savings occur when sugarcane is used as feedstock (86.5%). In contrast, using rapeseed as feedstock leads to 6.2% higher emissions compared to the current emission from fuel combustion.

Resource trade-offs in the 100% scenario are presented in Fig. 7 and Fig. 8. Emission savings in the 100% scenario come at the expense of large LFs and WFs. Using rapeseed will emit higher emissions than current emissions while requiring large land and water footprints. For each of the five considered feedstocks, the LF will exceed the global arable land (Fig. 7). The WF will exceed the current total WF of humanity irrespective the choice of feedstock (Fig. 8).

In the SDS-bio scenario, the CF of bioenergy ranges from 0.35 Gt of CO_2eq in the case of sugarcane as feedstock to 2.70 Gt in the case of rapeseed. The share of biofuel-related CF is larger than the bioelectricity-related CF in all production systems except for the rapeseed-based production systems.

Emission savings in the SDS-bio scenario compared to the actual emissions are all positive (Table 12). The emission savings range from 8.7% for when sugarcane is used as feedstock to 8.1% for sugar beet, 5.7% for maize, 4.0% for soybean and 1.4% for rapeseed.

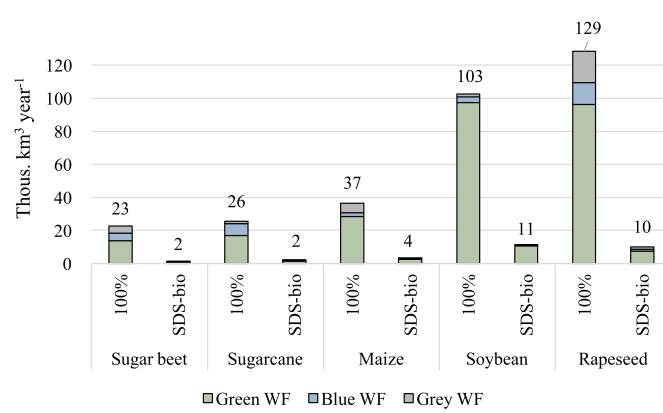


Fig. 4. WF of two global bioenergy production scenarios based on different feedstock and specified by WF component (green, blue, grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

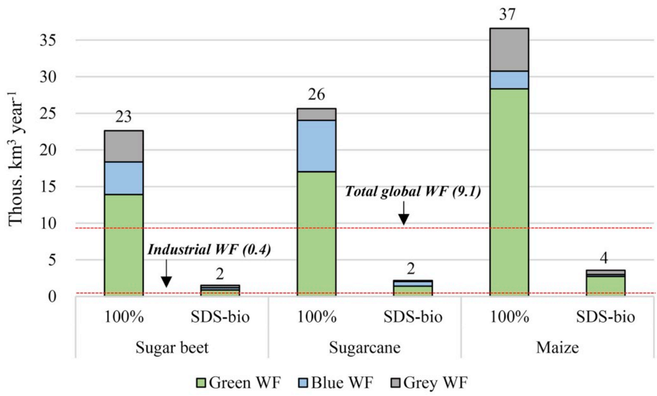


Fig. 5. WF of two global bioenergy production scenarios based on three most water efficient feedstock and specified by WF component (green, blue, grey). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 11
The CF per unit of net energy (kg CO_2eq GJ^{-1}).

Crops	Bioelectricity	CHP	Bioethanol	Biodiesel
Sugar beet	22	10	19	–
Sugarcane	11	5	14	–
Maize	32	15	82	–
Soybean	40	19	–	130
Rapeseed	94	39	–	87

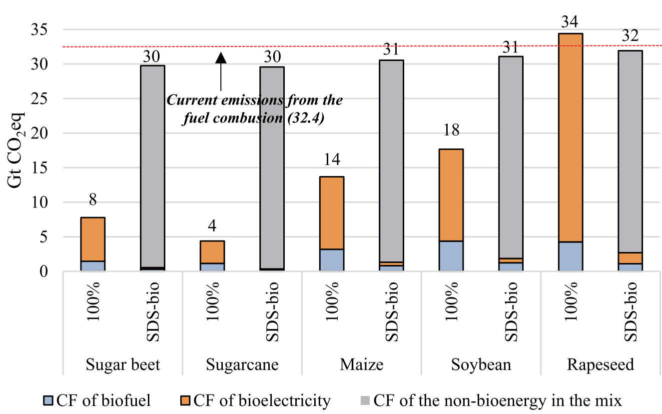


Fig. 6. CF of two global bioenergy production scenarios based on different feedstock and specified by energy type.

Table 12
Emissions savings in two bioenergy scenarios for alternative feedstock.

Feedstock	100% scenario	SDS-bio scenario
Sugar beet	76.0%	8.1%
Sugarcane	86.5%	8.7%
Maize	57.8%	5.7%
Soybean	45.4%	4.0%
Rapeseed	−6.2%	1.4%

In both scenarios, emissions from soil management are responsible for the largest share of GHG emissions (Table 13). More specifically, direct emissions from soil management make up over half of total emissions for producing bioelectricity and biofuels, except in a sugarcane-based production system. Combustion of biomass in stationary sources leads to higher GHG emissions than combustion of biofuel in mobile sources.

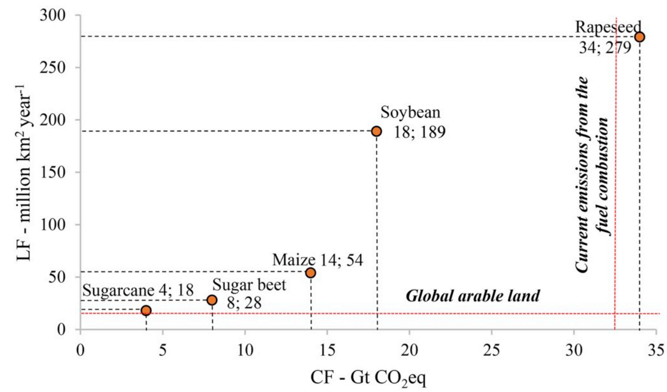


Fig. 7. The LF versus CF of bioenergy production in the 100% scenario for alternative feedstock.

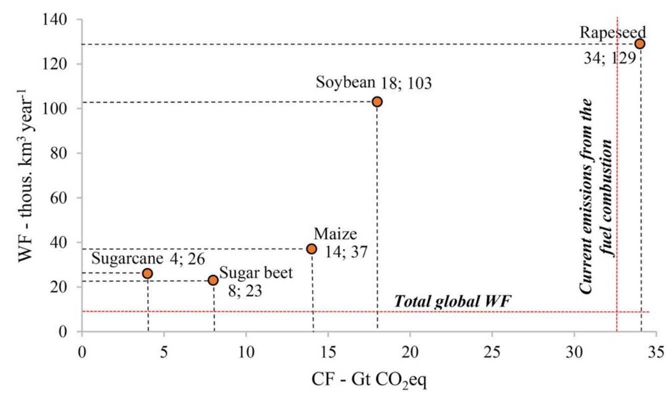


Fig. 8. The WF versus CF of bioenergy production in the 100% scenario for alternative feedstock.

3.6. Resource hungry bioenergy: a forbidden fruit?

Meeting the global energy demand using first-generation bioenergy is not feasible. Limited water and land availability prevents a large-scale application of first-generation bioenergy. The dilemma of water for food and feed versus water for energy has received a lot of attention [39,72,87–89], and this study's results show that first-generation bioenergy is incredibly thirsty.

The fact that WFs per unit of bioenergy are much larger than for fossil energy has been shown extensively [21,90]. Recent studies looked at the water footprints of generating electricity and heat from a range of sources and found that the WF of bioenergy (using firewood as the feedstock) are degrees of magnitude larger than WFs of electricity and heat generated from other renewables such as wind, solar PV, geothermal [27] and also the fossil sources such as coal, oil, natural gas, and nuclear [30]. The gross WF per unit of biofuels calculated in this study are similar to those reported by Gerbens-Leenes et al. [23].

Although fewer studies looked at the LF of bioenergy, there is a

Table 13
Contribution of different stages to the total CF (kg CO_2eq ha^{-1}).

	Fertilizer prod.	Soil management		Combustion		Total	
	Nitrogen	Direct	Indirect	Bioel.	Biofuel	Bioel.	Biofuel
Sugar beet	257	1479	383	650	534	2769	2653
Sugarcane	102	1080	263	1154	534	2599	1979
Maize	348	1456	395	400	191	2600	2391
Soybean	11	679	155	123	1	967	845
Rapeseed	216	735	207	85	2	1244	1160

concern that bioenergy can lead to undesired land use changes and transformations [89,91–94]. This study demonstrates that the LF of first-generation bioenergy is as prohibitive as the WF. The land requirement in the 100% scenario will exceed cropland area currently available. Especially in the case of rainfed agriculture, land becomes a key factor determining the impact of biofuels [42]. Moreover, continuous use of land for monoculture cultivation can have negative impact on the regional hydrologic cycle [95], aggravating any existing water issues.

The LFs per unit of bioenergy calculated in this study are similar to the results of previous studies. Rulli et al. [39] reported a weighted mean of 90 m^2 of land required per GJ of bioethanol that is close to the LF per unit of net bioethanol from sugar beet (72 $m^2 GJ^{-1}$) and sugarcane (70 $m^2 GJ^{-1}$) calculated in this study. Gerbens-Leenes et al. [38] reported the LF of algae-based biofuel in the range of 20–200 $m^2 GJ^{-1}$ that is also similar to the LF of bioethanol production calculated in this study.

Next-generation biofuels may help reduce the WF [42] but can lead to a range of complications as well. Mathioudakis et al. [96] calculated WFs of second-generation bioenergy from crop residues and reports that bioethanol from sugar beet pulp requires only 6.3 $m^3 GJ^{-1}$ and from sugarcane bagasse 18.3 $m^3 GJ^{-1}$. Gerbens-Leenes et al. [38] calculated WFs of third-generation biofuels from microalgae and reports that the net WF ranges from 8 to 193 $m^3 GJ^{-1}$. These results suggest that the WF of next-generation bioenergy can be reduced several times compared to the WF of the first-generation bioenergy. However, there are factors that prevent large-scale application of next-generation bioenergy. The most evident factors are: agricultural residues already serve important functions [93] (e.g. preventing erosion, maintaining soil structure and mineral composition, animal feed), the processes are costly [94], energy yields are lower compared to first-generation [97], and resultant biofuels are of inferior quality (in case of pyrolysis oil from agricultural residue) [98]. In addition, the use of trees for energy purposes may be inefficient and can accelerate climate change [99]. Also the WF of wood-based bioethanol at 97 $m^3 GJ^{-1}$ [100] exceeds the WF of first-generation bioethanol from sugar beet and is similar to that of bioethanol from sugarcane. The advanced biofuels are being produced on a commercial scale only after 2013 [94] and their commercial production is still negligible [39,42,93]. Investments on advanced biofuels in 2015 were an order of magnitude smaller than investment levels on conventional (first-generation) biofuels in 2006 or 2007 [101]. So it is likely that first-generation biofuels will dominate until 2030s [102,103].

3.7. Biofuel or bioelectricity?

The choice of crops should be aligned with the type of energy demand as the efficiency of converting crops to bioelectricity versus biofuel varies. Specifically, the LF, WF and CF of producing biofuel from sugar beet and rapeseed are smaller than the respective footprints of producing bioelectricity. In contrast, the LF, WF and CF of producing bioelectricity from sugarcane, maize and soybean are smaller than the respective footprints of producing biofuels. For all crops, the smallest LF, WF and CF per unit of net bioenergy is through the CHP generation.

In terms of the smallest footprints per unit of bioelectricity and biofuels, sugarcane and sugar beet are the winners among the considered feedstock crops. From the LF and CF perspectives, sugarcane is the most efficient feedstock to produce CHP, bioelectricity or bioethanol. From the WF perspective, sugarcane is the most efficient feedstock to produce bioelectricity but sugar beet is the most efficient feedstock to produce bioethanol. In contrast, soybean and rapeseed are the least efficient feedstock from the LF, WF and CF perspectives, meaning that biodiesel production is much less efficient than bioethanol production.

3.8. Bioenergy – can lead to emission savings

Findings of this paper suggest that bioenergy can lead to significant emission savings. In the 100% scenario the GHG emissions can be reduced compared to the actual emissions in all cases except using rapeseed feedstock. The level of GHG emission reductions varies caused by many causal factors such as the supply chain efficiency, feedstock, and land use change linked emissions [93,104,105]. Depending on the choice of causal factors the GHG emission potential of bioenergy have been reported both positive and negative compared to that of fossil fuels [89,106,107].

In the SDS-bio scenario the GHG emission savings also largely depend on the choice of feedstock. The emissions in this case can be reduced compared to the actual emissions regardless of the choice of feedstock.

3.9. Bioenergy – emission savings versus water and land costs

From the climate perspective, the GHG reductions calculated in this study are significant but at the large cost of land and water. In the 100% scenario, the emission reduction potential of all but rapeseed based system can help maintain the emissions under or within the desired range of 18–25 Gt CO_2eq per annum [11]. However, these significant emission reductions would require more water than current total global water use and more land than the current global arable land area. This is impossible given the already high levels of current land and water scarcity. An energy scenario at the expense of a steep increase in land and water use as identified in this study cannot be a sustainable solution to reducing GHG emissions.

The emission savings in the SDS-bio scenario also come at a high cost in terms of increased land and water use. The water requirements of the SDS-bio scenario will exceed the current industrial WF by at least several folds and result in an increase of the current WF of humanity by at least 17.6% (in case of a sugar beet based system). The LF in the SDS-bio scenario will require at least 11.4% of the arable land (in case of a sugarcane based system).

3.10. EROI – an inappropriate metric?

A key finding from this work is that an EROI factor is not an appropriate metric to identify energy production efficiencies when different energy output types are considered. EROI captures the ratio of final energy to initial energy, whereby a smaller initial energy input compared to the output generates a large EROI. Rapeseed for example has an EROI of 3.2 in case of bioelectricity production and an EROI of 2.3 in case of biodiesel production. This is because the input energy for bioelectricity production is almost two times smaller than the input energy for biodiesel production. However, despite a higher EROI for the bioelectricity production route, the bioelectricity yield (13.3 $GJ ha^{-1}$) is similar to the biodiesel yield (13.3 $GJ ha^{-1}$) in net accounting terms.

EROI is a useful measure when the energy inputs are similar, but can lead to misinterpretation when different production processes, hence inputs are expected. Producing a similar energy type from different feedstocks entails comparatively similar energy inputs, which is different for the case of producing different energy types from the same or different feedstock. In the latter case, the processes are different and energy inputs for different processes may differ greatly. The EROI measure then cannot reveal the net energy gain for different fuel production routes and can instead lead to misinterpretation of results. An EROI metric should be used with caution when different energy output types are involved.

3.11. Uncertainties and sensitivities

To understand the effects of input data on the results, we assessed the sensitivity to four different input parameters: crop yield, transport

Table 14
Changes in study results due to changing input parameters in the SDS-bio scenario.

Parameter		Sugar beet	Sugarcane	Maize	Soybean	Rapeseed
Yield (+20%)	LF	−17.5%	−17.4%	−19.0%	−23.0%	−25.7%
	WF	−17.5%	−17%	−19.0%	−22.6%	−25.6%
	CF	−11.9%	−9.7%	−15.8%	−20.1%	−24%
Transport 100 km	LF	+6.9%	+9.2%	+4%	+7.5%	+5.8%
	WF	+6.9%	+9.2%	+4%	+7.5%	+5.8%
	CF	+6.8%	+8.5%	+3.9%	+7.4%	+5.8%
Electricity efficiency 27%	LF	+3.5%	+1.2%	+17.4%	+17.2%	+38.9%
	WF	+3.5%	+1.2%	+17.4%	+17.2%	+38.9%
	CF	+3.6%	+1.5%	+18.2%	+18.5%	+39.8%
Fertilizer use (−10%)	LF	−0.4%	−0.2%	−1.1%	−0.6%	−3%
	WF	−0.4%	−0.2%	−1.1%	−0.6%	−3%
	CF	−3.8%	−1.9%	−6.1%	−1%	−9.3%

Table 15
Percent changes in study results due to changing the input parameters in the 100% scenario.

Parameter		Sugar beet	Sugarcane	Maize	Soybean	Rapeseed
Yield (+20%)	LF	−17.4%	−17.3%	−18.6%	−19.6%	−22.7%
	WF	−17.4%	−16.9%	−18.5%	−19.2%	−22.6%
	CF	−11.7%	−8.7%	−14.8%	−15.8%	−20.5%
Transport 100 km	LF	+9.4%	+17.0%	+5.9%	+11.7%	+6.4%
	WF	+9.4%	+17.0%	+5.9%	+11.7%	+6.4%
	CF	+9.1%	+14.0%	+5.6%	+10.8%	+6.2%
Electricity efficiency 27%	LF	+50.5%	+40.5%	+54.0%	+56.6%	+93.1%
	WF	+50.5%	+40.5%	+54.0%	+56.6%	+93.1%
	CF	+51.0%	+43.8%	+55.1%	+58.4%	+93.8%
Fertilizer use (−10%)	LF	−0.4%	−0.2%	−1.0%	−0.6%	−2.2%
	WF	−0.4%	−0.2%	−1.0%	−0.6%	−2.2%
	CF	−3.7%	−1.7%	−5.9%	−0.9%	−8.3%

distance, biomass to electricity conversion efficiency and fertilizer use. Specifically, crop yields can vary between countries, so we tested the effect of a 20% yield increase. Regarding the transport distance, this study assumed 50 km for both crop delivery and fuel delivery. However, the IEA [108] has assumed as much as 100 km for the biomass transport distance, which we used for the sensitivity analysis. Similarly, the highest biomass to electricity conversion efficiency of 43% was assumed in this study, while an average efficiency is 27% [54], which we used for the sensitivity analysis. Lastly, the fertilizer input was decreased by 10% to understand its effect on the study results.

Tables 14 and 15 present the effects of changing the input parameters on the study results for the SDS-bio and the 100% scenarios, respectively. In both cases, increasing yield can reduce land, water and carbon footprints regardless of feedstock. Decreasing biomass to electricity conversion efficiency leads to the largest increase in land, water and carbon footprints in the 100% scenario regardless of feedstock. In the SDS-bio scenario, the changes due to decreasing conversion efficiency lead to larger footprints in systems based on maize, soybean and rapeseed. In both scenarios, reducing fertilizer input leads to larger CF reduction compared to the LF and WF reductions. Increasing the transport distance increases all footprints but the magnitude of increases varies both between scenarios and feedstocks.

Another factor that may contribute to the environmental footprints is the WF of processing of biofuels (crushing, milling and refining) that is, however, small, requiring less than 1 $m^3 GJ^{-1}$ [109] or none at all when the water from the crop itself is used [98]. In addition, emissions from mobile sources may be under- or overestimated in this study because all mobile emissions are calculated using emission data for trucks due to lack of data on emissions from maritime or aviation transport that are using biofuels. Nevertheless, emission savings calculated in this study are very large. Under- or overestimation of emissions from maritime and aviation sources would likely have a small effect on the overall results and conclusions.

3.12. Practical implications of this study

This paper demonstrates that the GHG emission savings of using bioenergy may come at a cost of significant use of land and water resources for crop cultivation or in some cases (i.e. rapeseed in a 100% scenario) lead to higher emissions than the current emissions. While for the GHG emissions, the location of emissions may ultimately be irrelevant, for land and water uses, local resource availability and timing of uses does matter [15]. This suggest, that addressing climate change can have adverse local implications and, reversely, that resource availability constrains the applicability of bioenergy.

Future research may consider focusing on individual crops at country level or for particular energy scenarios at the regional level to derive accurate estimates based on resource availability for sustainable first-generation bioenergy production. Knowledge on the process steps and resource availability at smaller scales may improve results and reveal how much bioenergy can be produced, the actual GHG emission savings from that bioenergy and their resource utilization rate. Conducting such a study in countries that already produce or plan to produce first-generation bioenergy can help governments make conscious decisions. Some policy recommendations stemming from this work are thus to avoid using first-generation biofuels altogether or set quantitative limits proportional to the amount of first-generation bioenergy that can be considered sustainable based on the resource availability of a consuming country. A revised directive of the EU "on the promotion of the use of energy from renewable sources" [110] also acknowledges that the real contribution of "food-based biofuels" to the carbon reduction goal is uncertain and should be limited. However, it falls short of banning import of bioenergy.

4. Conclusion

This paper evaluated the land, water and carbon footprints of gross and net bioenergy generation. Two bioenergy production scenarios with different shares of bioenergy output and with different energy carrier composition were considered. The energy output was differentiated into net versus gross using a dynamic internal feedback loop that distinguishes the quality of input energy in the production systems. The results reflect a systematic attempt to reveal inherent trade-offs between land, water and carbon in the production of bioenergy from five selected feedstock crops and lead to four major conclusions. First, large scale first-generation bioenergy production should be avoided as their water and land requirements are too extensive. Second, CHP generation requires the least water and land resources regardless of the crop. Third, bioelectricity production is most efficient using sugarcane from LF, WF and CF perspectives while biofuel production is most efficient using sugar beet from the WF perspective and sugarcane from the LF and CF perspectives. Fourth, water and land requirements of bioethanol are much smaller than for biodiesel.

Large-scale first-generation bioenergy production is not feasible and should be avoided as the natural resource requirements are too large. Replacing even 9.8% of the final energy demand with bioenergy in the SDS-bio scenario requires several times more water than the current industrial WF or at least 17.6% of the current global water use, and at least 11.4% of the current global arable land. If bioenergy is still aimed for, to some degree, CHP generation can yield most bioenergy per unit of land and water, although mostly in the form of heat.

Among the five feedstock crops, sugar beet and sugarcane require the least water and land resources per unit of bioelectricity and biofuel energy output while also emitting the least amount of GHGs. In general, biodiesel production is less efficient than bioethanol production regardless of the choice of feedstock crops.

Declarations of interest

None.

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Appendix A. Supplementary data

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