

Analysing the water and greenhouse gas effects of soya bean-based biodiesel in five different regions

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Abstract

Bioenergy may have significant lower greenhouse gas (GHG) emission intensities compared to fossil alternatives, but concerns are raised that bioenergy would contribute to additional water scarcity. Therefore, the GHG intensity, water intensity and water-related risks are analysed simultaneously for conventional diesel and soya bean-based biodiesel from Argentina, Brazil, United States (U.S.), Thailand and Iran on a life cycle basis. The water-related risks are estimated with a water scarcity—consumption matrix, which was recently developed. Results show that a significant share (9%–38%) of the GHG emissions in all biodiesel cases is caused by soil N₂O emissions. In addition, the ranges in water consumption intensity for soya bean-based biodiesel are considerably larger than for fossil fuels. However, whether this leads to high water-related risks depends on the local water scarcity. Soya bean-based biodiesel from Argentina has low water-related risks to all nodes of the supply chain due to low local water stress combined with a low direct water consumption intensity (20 L/GJ_{fuel}). In addition, high GHG emission reduction (71%) and a low-specific eutrophication potential (0.04 kg PO₄³⁻/GJ_{fuel}) are achieved. The indirect water consumption intensity is estimated at 120–420 L/GJ for soya bean-based biodiesel, which is significant if the soya beans are rainfed, like in Argentina and Brazil. If irrigation is required, indirect water consumption is dwarfed by irrigation water. Overall, it is concluded that soya bean-based biodiesel can have significant lower GHG emission intensity than fossil diesel, without causing additional water stress in the supply chain if they are produced in water abundant areas and good agricultural practices are used. The used method shows disaggregated water-related risks for the different nodes of the supply chain to acknowledge the regional nature of water scarcity and enables decision makers to identify “hot spots” and take targeted actions.

1 | INTRODUCTION

To avoid dangerous climate change, the parties of the United Nations Framework Convention on Climate Change agreed to keep the global average temperature increase well below 2°C above pre-industrial levels (United Nations, 2015). To achieve this, CO₂ and other greenhouse gas

(GHG) emissions must be reduced drastically. Bioenergy is expected to play a major role in this reduction (International Energy Agency, 2016).

However, concerns are raised that an increase in bioenergy could contribute to additional water scarcity (Delucchi, 2010; Gerbens-Leenes, Hoekstra, & Meer,

2009; Gerbens-Leenes, Lienden, Hoekstra, & van der Meer, 2012; Mekonnen & Hoekstra, 2016; Mekonnen, Gerbens-Leenes, & Hoekstra, 2015). Water scarcity is defined as the imbalance between supply and demand of freshwater in a specified region caused by high demand compared with available supply, under prevailing institutional arrangements (including price) and infrastructural conditions (FAO, 2016a). Currently, about two-thirds of the global population lives in areas that experience water scarcity for at least 1 month a year (Mekonnen & Hoekstra, 2016). In most cases, water scarcity refers to water quantity alone, although insufficient water quality may also impose water scarcity (FAO, 2016a).

Therefore, it is important to understand not only the GHG emissions of a product, but also to assess whether (bioenergy) products impact water scarcity or deteriorate water quality. A methodology was developed to compare different fuels for water consumption, GHG emissions and water pollution (i.e., eutrophication potential) from a life cycle perspective in a previous study (Knoope et al., submitted). Water consumption is defined as freshwater that will not become available for other users because of evaporation, incorporation into products or removal in other ways from freshwater resources during a production activity (Hoekstra, Chapagain, Aldaya, & Mekonnen, 2011). In the methodology, only water consumption of river and groundwater (i.e., blue water) is incorporated, meaning that the consumption of rain (i.e., green) water is excluded.

The risks of water consumption are assessed by using a matrix with one axis as the water consumption intensity and the other as water scarcity (Knoope et al., submitted). The reasoning behind the matrix is that large amounts of water can be consumed in a water abundant area without negative effects. However, small amounts of water consumption could already lead to negative environmental effects and business risks in water scarce areas. The methodology was demonstrated by a case study for biodiesel based on irrigated and rainfed soya bean grown in Nebraska and conventional diesel based on water flooding and refinery in California (Knoope et al., submitted).

Although the previous study demonstrated the methodology and its application, there is a need to test the methodology further. Moreover, there is a need to conduct some proper sensitivity and uncertainty analysis related to indirect water consumption, uncertainty in input data and analyse the effect of using maximum rather than average water scarcity indices. These are done in this article by investigating soya bean-based biodiesel in five different regions and compared to conventional diesel. Soya bean biodiesel is a first-generation biofuel and was chosen because soya bean is grown in different world regions and it is a common feedstock for biodiesel.

2 | MATERIALS AND METHODS

2.1 | Water scarcity index

There are many different indices that measure water scarcity. In this study, the ratio between water withdrawal and water availability is used, a so-called withdrawal-to-availability (WTA) ratio, which is a common index to analyse water scarcity. Water withdrawal is defined as the volume of freshwater extracted from surface or groundwater (FAO, 2016a). A WTA ratio between 0.1–0.2, 0.2–0.4 and above 0.4 is stated to lead to low, moderate and high water stress, respectively (Frischknecht, Steiner, & Jungbluth, 2009; Pfister, Koehler, & Hellweg, 2009; Raskin, Gleick, Kirshen, Pontius, & Strzepek, 1997).¹

Monthly WTA ratios are used in this study based on water withdrawal data (Wada et al., 2011; Wada, Wisser, & Bierkens, 2014) and water availability data (van Beek, Wada, & Bierkens, 2011; Wada et al., 2014) over the period 1970–2010 on a water province level. Water provinces are composed of river basins and administrative boundaries (Veldkamp, Wada, Aerts, & Ward, 2016). In this study, the monthly median WTA is calculated for each water province to exclude years with very high or low water availability. Subsequently, the average of the monthly medians of the relevant period, which relates to the growing season for cultivation or the entire year for industrial processes, is used in further analyses.

2.2 | Integrated approach to assess water-related risks, GHG emissions and eutrophication

In this study, different soya bean-based biodiesel and fossil fuel pathways are compared:

- Specific eutrophication potential calculated with the mid-point method of CML-IA (van Oers, 2015).
- GHG emission intensities calculated with the most recent global warming potentials over a 100-year period as published by the IPCC (Myhre, Shindell, Bréon, Collins, & Fuglestedt, 2013).²³
- Water-related risks, which is a relation between direct water consumption intensity and water scarcity.

¹The terminology of these categories differs slightly between the sources.

²This means a global warming potential of 28 for methane and 265 for N₂O.

³Some GHG intensities were only given in CO₂-equivalent and were not calculated with the latest global warming potentials, like the regional GHG intensities of fertilizers (Kool et al., 2012) and pesticides (Audsley et al., 2009). If this is the case, they are used as it is the best regional data available.

The matrix in Figure 1 is used to assess the water-related risks. Firstly, the direct water consumption intensity for each step in the supply chain is calculated and the corresponding line in the matrix is chosen. Secondly, the WTA for considered the water province determines the relevant column in the risk matrix. The crossing provides the water risk classification.

Also, the other considered environmental impacts, that is, GHG emissions and specific eutrophication potential are translated into indicators. For GHG emissions, the reduction in percentages is calculated compared to the fossil fuel case that leads to the highest GHG emission intensity. GHG reduction potentials of more than 60% receive a (light or dark) green colour, which is the European GHG target for biofuels produced in new installations (European

Commission, 2015). GHG reductions of 20%, 40%, 60% and 80% form the border between red-orange, orange-yellow, yellow-light green and light green-dark green areas, respectively. Note that GHG emissions of indirect land-use change are not incorporated within the EU target and are also not included in the GHG emission intensities stated in this study.

For specific eutrophication potential, it was assumed that 0.5 kg $\text{PO}_4^{3-}/\text{GJ}$ or higher is unacceptable and receives a red colour. In addition, a linear relation is assumed, meaning that 0.125, 0.25 and 0.375 kg $\text{PO}_4^{3-}/\text{GJ}$ become the borders between dark and light green, light green and yellow and yellow and orange, respectively. These thresholds were established based on the specific eutrophication potential of 19 different transportation fuels (Knoope et al., submitted).

WTA	No	Low	Moderate		High		Very high		Extreme		Examples ^a
Direct water consumption (L/GJ _{final_product})	<0.1	0.1–0.2	0.2–0.3	0.3–0.4	0.4–0.5	0.5–0.6	0.6–0.7	0.7–0.8	0.8–0.9	>0.9	
10,000–100,000											Irrigated agriculture for biofuels or hydropower
1,000–10,000											
100–1,000											Cellulosic ethanol production, or Coal power plant with cooling tower
10–100											
1–10											Dry cooling for gas power plants, or Refinery E.U.
<1											
Examples ^b	Congo	Japan, Mali	Peru, Italy, Moldova		Thailand, South Africa		Tunisia, Senegal		Yemen, Saudi Arabia		

^a The examples are based on (Henderson, 2016; Macknick et al., 2015; Schornagel et al., 2012; Spence, 2015)

^b The examples are related to the annual weighted average WTA based on the surface area of water provinces within a country (van Beek et al., 2011; Wada et al., 2011; Wada et al., 2014). Note that there can be significant differences within countries and between season

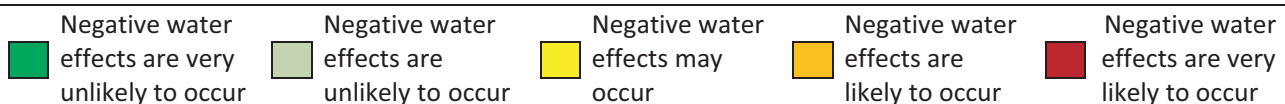


FIGURE 1 Decision matrix to estimate the water-related risks (Knoope et al., submitted)

The scores for the various indicators are incorporated in a radar diagram, to assess trade-offs and synergies between the different indicators. Moreover, multiple alternatives can be pictured and compared in one radar diagram to support decision makers in choosing the right alternative.

2.3 | Indirect water consumption

The production of required input products for soya bean, biofuel or fossil fuel production, such as electricity, fertilizers and chemicals, also emits GHG emissions and require water. The GHG emissions of these input products are included. However, the indirect water consumption was not included in our previous analysis (Knoope et al., submitted), because it was simply unknown where the input products are produced. In this study, the indirect water consumption intensity is estimated for soya bean-based biodiesel by using the EcoInvent database (Frischknecht et al., 2005; Wernet et al., 2016). This means that not only the water consumed during, for instance, fertilizer production is incorporated, but also the water consumed by producing the inputs (e.g., energy and chemicals) for fertilizer production. The indirect water consumption is treated separately from the direct water consumption, as the locations of water use may differ.

2.4 | System boundaries

Soya bean cultivation, transportation, crushing, transesterification and combustion are included in the system boundaries for soya bean-based diesel. For the fossil fuel cases, oil production, transportation, refinery and combustion are incorporated into the analysis. For both fuels, this is the entire life cycle except for the distribution process from the terminals to the retail stations. The reason for this is that produced biodiesel is primarily domestically used in some countries (e.g., United States), while it is partly exported in others (e.g., Argentina). To compare the fuels on an equal scope, the analysis excludes the distribution process. This omission of (overseas) transport of the end-product normally only has a small contribution to the overall GHG intensity (Edwards, Larivé, Rickeard, & Weindorf, 2014), and no direct water is used during transport.

For all cases, transportation of the required inputs to the production and processing facilities is excluded, mainly due to data unavailability.

2.5 | Data collection

For soya bean-based diesel, mainly regional-specific life cycle assessment (LCA) studies were used as data source. Also, the transportation distances between the various production locations are based on regional case studies

(Argonne, 2016; Castanheira, Grisoli, Coelho, Anderi da Silva, & Freire, 2015; Panichelli, Dauriat, & Gnansounou, 2008; Patthanaisaranukool, 2017; Rajaeifar, Ghobadian, Safa, & Heidari, 2014). If multiple transportation modes and distances were given, the most likely transportation mode and corresponding distance are selected based on the percentages given in the source or based on external information. In some cases, the exact water province was unclear or data about locations was completely missing (Thailand and Iran); expert judgements were used based on existing or likely locations and the distances between them.⁴

N₂O is emitted during soya bean cultivation due to decomposition of biomass residues, leakage of N fertilizer (inorganic and manure) and volatilization. In this study, these emissions are estimated with the “Global crop and site specific Nitrous Oxide emission Calculator” (GNOC) tool (Köble, 2014). GNOC follows the IPCC tier 1 methodology, but the belowground nitrogen content for soya beans is increased from 0.008 to 0.087 kg N/kg dry mass belowground biomass (Edwards et al., 2012; Köble, 2014).

Most LCA studies for soya bean-based biodiesel did not include water data for the industrial processes. Therefore, general literature ranges, which are not location specific, are used for most industrial processes.

For the fossil fuel cases, water and GHG intensities are based on scientific articles and reports, related to specific production technologies and regions. The specific eutrophication potential of diesel is (directly) based on EcoInvent (Wernet et al., 2016), and no distinction is made between different production technologies and regions.

Also, the eutrophication potentials of the various biodiesel cases are modelled with the life cycle analysis software SimaPro by using the EcoInvent database (Wernet et al., 2016).

The GHG intensities for electricity and fertilizers are region-specific and are based on BIOGRACE (2015) and Kool, Marinussen, and Blonk (2012), respectively. The GHG emission intensities of lime (Kool et al., 2012), pesticides (Audsley, Stacey, Parsons, & Williams, 2009), chemical inputs (e.g., hexane, methanol; Frischknecht et al., 2005; Wernet et al., 2016), transportation and other energy inputs (e.g., natural gas, coal) (Argonne, 2016) are not region-specific, mainly because of data unavailability.

2.6 | Data quality and uncertainty

Some of the used LCA studies of soya bean-based biodiesel already include uncertainty ranges (based on min. and

⁴See the Supporting Information Appendix S1 for more information on regional WTA, data sources and assumptions.

max. values or two standard deviations) for the input data, while others do not. If no uncertainty ranges are mentioned, a standard uncertainty range of 30%–50% is used, depending on the quality of the data. In general, 30% is used when the input data are based on survey results for the region under consideration and 50% is used when either standard literature values or survey results from other regions are used as approximation. To avoid unrealistically high uncertainty ranges, by combining minimal inputs with maximal outputs, the yield and conversion efficiencies are kept constant. Furthermore, GHG intensities of the inputs are not varied in this study. For water intensities, literature ranges are used.

For the soil N₂O emissions, the higher belowground nitrogen content is used for the average and maximum cases. The lower bound N₂O emissions are estimated by using the standard IPCC value, which is believed to underestimate the belowground nitrogen content (Edwards et al., 2012).

The analysed fossil fuel cases represent a lower and upper bound scenario for water-related risks. Further uncertainties for the fossil fuel cases are not analysed in this study.

2.7 | Sensitivity analysis

2.7.1 | Monthly water scarcity

As a base case, water scarcity is incorporated by using the average WTA of the monthly medians of the relevant period (i.e., growing season or whole year) for a given water province. However, an average WTA may hide water issues which may occur during periods of low water availability, especially in monsoonal areas (Boulay et al., 2015; Hoekstra, Mekonnen, Chapagain, Mathews, & Richter, 2012). Therefore, an analysis is conducted by using the highest monthly median WTA, rather than the average WTA (of the relevant period), for all steps in the supply chain.

2.7.2 | Water consumption vs. water withdrawal

Some technologies withdraw large volumes of freshwater and discharge it after use back in the river. These technologies have a low water consumption intensity and would get a relatively good water scarcity risk classification category. To ensure that the water-related risks are not underestimated, a sensitivity analysis is conducted by using water withdrawal rather than water consumption intensities to estimate the risk classification in Figure 1.

2.7.3 | Different allocation methods

As a base case, allocation is conducted on an energy basis in this study. A sensitivity analysis is conducted with

economic and mass allocation. In Table 1, energy densities and market prices are given for the (co-)products for which allocation is relevant.

3 | CASE STUDY

3.1 | Soya bean-based diesel

The analysed soya bean cultivation regions are Nebraska in the United States, Mato Grosso in Brazil, Córdoba in Argentina, Chiang Mai in Thailand and Golestan in Iran. The first three regions are chosen because they represent one of the most important soya bean production regions in the world. Together these countries are responsible for almost 80% of the global soya bean production (FAO, 2016b). Thailand and Iran are chosen as they represent extreme cases. However, these countries represent <0.1% of the global soya bean production (FAO, 2016b). An overview of the locations, transportation modes and distances for every case are given in Figure 2. In the online Supporting Information Appendix S1, maps are provided for each case to show the locations in a spatial explicit way.

In Table 2, the input values for soya bean cultivation are listed with their uncertainty range for the different cases. For agricultural practices, it is assumed that freshwater withdrawal equals consumption due to evapotranspiration. This water is assumed not to be available for reuse within the modelled system boundaries. In addition, distribution losses from water pipes etc. are assumed to be negligible. The freshwater consumption stated in Table 2 refers to irrigation water and, in case of rainfed soya bean production, the volume of freshwater required to apply pesticides. In Table 3, the freshwater, energy and chemical input data as well as the conversion efficiencies for soya bean crushing, oil extraction and transesterification are given.

3.2 | Fossil fuel cases

Fossil fuels can be produced with various production methods (e.g., oil sands, primary, secondary oil production),

TABLE 1 Energy densities and market prices for the relevant (co-)products

	Energy (MJ/kg) ^a	Market prices (\$/tonne)
Soy-oil	36.6 ^b	718 ^d
Soy-meal	16.3 ^b	349 ^d
Glycerine	15.2 ^b	100 ^b
Biodiesel	33.5 ^c	1,078 ^b

^aLower heating values are used. ^bBased on (Castanheira et al., 2015). ^cBased on (Argonne, 2016). ^dThese prices refer to the (preliminary) market prices for the season 2016–2017 (Ash & Matias, 2017).

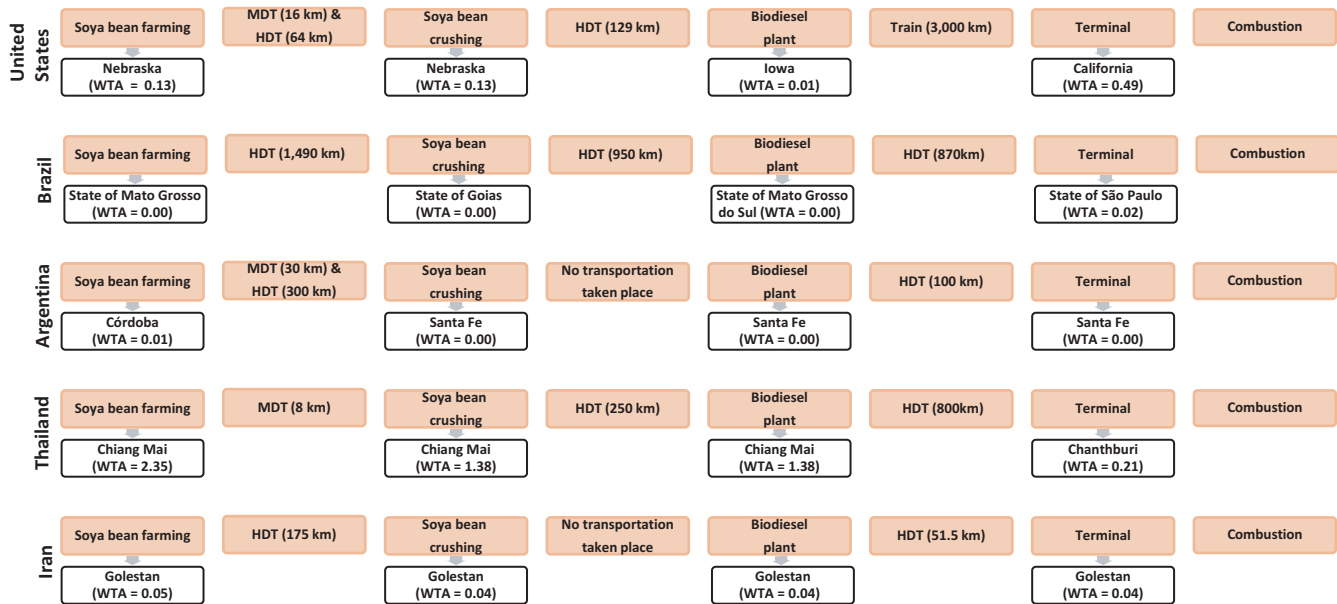


FIGURE 2 Overview of the different cases to show the locations and the associated withdrawal-to-availability (WTA) ratio where the processes take place, the transportation modes and distances. The regional WTA refers to the average of the monthly medians in the relevant period (i.e., growth season or whole year). MDT and HDT refer to medium and heavy-duty truck, respectively

which have different GHG and water intensities. Typical region-specific GHG intensities for fossil diesel are available (Air Resources Board, 2016; Edwards, Hass, et al., 2014), but not for water. To give an indication of the water-related risks of fossil diesel, a low bound scenario and high bound scenario are calculated.

The low bound scenario consists of offshore oil production in the North Sea and refining in water abundant Scotland. A negligible amount of freshwater is used during offshore oil production (Williams & Simmons, 2013). For the refinery, the average freshwater withdrawal intensity (24 L/GJ crude oil) and consumption intensity (7.5 L/GJ crude oil) of European refineries are used (Spence, 2015). It is assumed that 1.1 GJ_{crude} is needed for every GJ_{fuel} (Edwards, Larivé, et al., 2014).

Two sources estimated the carbon intensity of oil produced in the European Union. Firstly, a weighted carbon intensity of 4.91 gCO₂-eq/MJ_{crude} is given for different offshore oil fields in Denmark, United Kingdom and Norway (Malins et al., 2014). Secondly, a carbon intensity of European oil production of 2.03 gCO₂-eq/MJ_{crude} is given by the International Oil and Gas Producers Association (Edwards, Larivé, et al., 2014). This intensity is not specific for North Sea oil, but most European oil is produced on the North Sea (JRC, 2015) and can therefore be used as approximation. An average of these two is used for the carbon intensity of oil production in the North Sea. The GHG intensity of the other processes in the supply chain is estimated by Edwards, Larivé, et al. (2014), that is, transportation (1.0 gCO₂-eq/MJ_{diesel}), transformation (8.6 gCO₂-eq/MJ_{diesel}) and

combustion of diesel (73.2 gCO₂-eq/MJ_{diesel}). The GHG emissions for distribution (1.1 gCO₂-eq/MJ_{diesel}) are not included, which is consistent with our system boundaries.

The high bound scenario is based on onshore oil production by secondary production methods (i.e., water flooding) and entirely located in California, which is a water scarce area. The GHG and water intensities of this case were already established in previous work (Knoope et al., submitted). However, the GHG emissions caused by distribution are excluded (0.6 kgCO₂-eq/GJ) to be consistent with the system boundaries of this study.

4 | RESULTS

4.1 | GHG intensities

In Figure 3, the average, minimum GHG emission intensity and maximum GHG emission intensity for soya bean-based biodiesel are presented for the different cases and compared to the fossil fuel cases. In all biodiesel cases, a significant share of the GHG emissions is caused by soil N₂O emissions, ranging from 9% for the minimum case in Brazil to 38% for the maximum case in Iran. In addition, agricultural inputs are a large contributor, but there is significant variation between the regions, ranging from 11% in the min. U.S. case to 51% in the min. Iran case. This is mainly caused by the amount and type of fertilizer and pesticides applied, and the energy required for, for example, irrigation.

Transportation is in most cases only a minor contributor, except for Brazil where it contributes for 27%-60% to the

TABLE 2 Input values and yield for soya bean farming for the different cases analysed in this study

	Unit	United States–Nebraska	Brazil–Mato Grosso	Argentina–Córdoba	Thailand–Chiang Mai	Iran–Golestan
Diesel	L/ha	33.3 ^a (23.3–43.3)	31.0 ⁱ (19.3–48.6)	39.7 ^m (24.9–81.4)	125 ^p (89.6–161)	104 ^t (46–161)
Gasoline	L/ha	12.8 ^a (9.0–16.6)			2.9 ^p (1.9–3.8)	
Propane (LP gas)	L/ha	2.0 ^a (1.4–2.6)				
Electricity	MJ/ha	61.6 ^a (43.1–80.0)	82.8 ⁱ (10.9–376)			4,809 ^t (3,181–6,438)
Natural gas	MJ/ha	151 ^a (106–196)				
Lime	kg/ha	464 ^a (325–603)	420 ⁱ (127–884)			
Seeds	kg/ha	68.9 ^a (48.2–89.6)	49 ⁱ (32.6–83.5)	73.7 ^m (51.2–101)		68.8 ^t (48.2–89.4)
Fertilizers						
Nitrogen	kg N/ha	6.1 ^b (0–14.6)	6.7 ^j (1.6–12.6)	0.39 ^m (0–0.61)	20.5 ^p (11.6–29.4)	95.0 ^{t,u} (28.5–161)
Phosphate	kg P ₂ O ₅ /ha	29.1 ^b (0–56.0)	81.3 ^j (50.3–145)	18.3 ⁿ (12.8–23.7)	22.6 ^p (11.2–34.0)	50.4 ^{t,u} (15.1–85.8)
Potash	kg K ₂ O/ha	5.6 ^b (0–40.4)	87.3 ^j (49.0–134)		19.3 ^p (2.8–35.8)	9.18 ^{t,u} (2.75–15.6)
Sulphur	kg S/ha	2.1 ^b (0–10.1)				3.30 ^{t,u} (0.99–5.61)
Manure	kg/ha					5,348 ^{t,u} (1,602–9,094)
Herbicides						
Glyphosate	kg/ha	1.7 ^{b,c,d} (0–6.7)		2.34 ⁿ (1.6–3.0)	2.6 ^{p,q} (2.3–2.9)	
2,4-D	kg/ha	0.13 ^{b,c,d} (0–1.17)		0.24 ⁿ (0.17–0.31)		
Other	kg/ha	0.06 ^{b,c,d} (0–0.53)	4.55 ^{j,k} (0.17–9.84)		6.9 ^{p,q} (4.9–8.9)	2.65 ^{t,u} (0.74–4.56)
Insecticides	kg/ha	0 ^{b,e}	1.81 ^j (0.09–6.63)			2.68 ^{t,u} (0.74–4.62)
Cypermethrin	kg/ha				2.3 ^{p,q} (1.7–2.9)	
Fungicides	kg/ha	0.009 ^f (0–0.18)	1.15 ^j (0.07–2.94)			
Pesticides	kg/ha			0.68 ⁿ (0.48–0.89)		
Freshwater consumption and withdrawal	m ³ /ha	1,900 ^g (0–2,743)	0.09 ^l (0.0–0.23)	0.04 ^l (0.03–0.05)	1,994 ^r (1,824–2,198)	3,303 ^t (938–5,668)
Yield	kg/ha	3,703 ^h	3,201 ^j	3,040 ^o	1,715 ^p	3,233 ^u
Growing season		June–October ⁱ	November–April ⁱ	November–May ^j	January–April ^s	July–November ^v

TABLE 2 (Continued)

^aFrom Pradhan et al. (2011), who estimated the energy balance based on survey and statistical data for the United States. No uncertainty range is mentioned in Pradhan et al. (2011), and therefore, a standard uncertainty range of 30% was assumed (see text).

^bThese values are based on USDA (2012) and already incorporate that not all soybean fields apply fertilizer and pesticides. For example, 52%, 42%, 21% and 14% of the soya bean hectares are treated with phosphate, nitrogen, sulphur and potash fertilizer in Nebraska, respectively.

^cDifferent types of glyphosate and 2,4-D are applied in Nebraska, according to (USDA, 2012). These different types are added and are assumed to have the same GHG intensity. Besides glyphosate and 2,4-D, some other herbicides are used by some soybean producers. None of these herbicides is applied by more than 20% of the soya bean producers and are therefore grouped in one category.

^dNo minimum and maximum are stated. However, not all fields are treated with herbicides meaning that the minimum would be zero. The average application rates of the different types of herbicides (Glyphosate, 2,4-D or others) are added to estimate the maximum application rate. On the one hand, this would underestimate the amount of pesticide applied, because it is unlikely that there are no outliers in the application rate. On the other hand, it is unlikely that a farm would apply all multiple types of herbicides simultaneously.

^eNo or only a very limited number of soybean operators apply insecticide and is therefore assumed to be zero (USDA, 2012).

^fOnly a total amount of fungicide is mentioned for Nebraska to withheld avoiding disclosing data of individual operations (USDA, 2012). This total amount is divided by the total hectares of soya bean field in Nebraska (USDA, 2014) to estimate the fungicide application on a per hectare basis. Furthermore, no minimum and maximum demands are stated. However, fungicides are only applied on 5% of the fields, meaning that the minimum amount of fungicide would be zero. As maximum, the total application rate of fungicide is divided by the number of hectares treated with fungicide, as there is no better data available. This approach ignores that there are outliers.

^gIn Nebraska, 69% of the soybean fields are irrigated with on average 2,743 m³/ha water (USDA, 2014). This leads to an average freshwater input of 1,900 m³/ha. No minimum and maximum irrigation water demands are stated. However, 31% of the fields are rainfed, meaning the freshwater demand would be (close to) zero. As maximum, the average water demand if irrigation is taken place is used, as there is no better data.

^hBased on USDA (2014).

ⁱThe growing season is based on the AMIS calendar (AMIS, 2012), which indicates suitable months for planting and harvesting of soya bean in different countries (AMIS, 2012). The median month of the suitable planting and harvesting period is used.

^jRaucci et al. (2015) give averages, minimums and maximums for the seasons 2007/2008, 2008/2009 and 2009/2010. The mean of the average, minimum and maximum of the three seasons is used for calculating the overall average, minimum and maximum, respectively.

^kNo distinction is made between different herbicides (Raucci et al., 2015).^lSoya bean irrigation is not a common practice in Mato Grosso (Raucci et al., 2015) or Argentina (Panichelli et al., 2008). Therefore, only freshwater is assumed to be used for applying pesticides, estimated at 0.012 L water per kg active ingredient of pesticides (Lampert et al., 2015).

^mPanichelli et al. (2008) make a distinction for the diesel, N fertilizer and seed inputs required for conventional (80%) and reduced tillage (20%) of first (64%) or second crop soya bean (36%). Reduced tillages became more popular in Argentina over time and, currently, is with about 85% the main cultivation practice (Hilbert & Galligani, 2014). The shares of conventional and reduced tillage are adapted to reflect the higher share of reduced tillage. No more up-to-date data were found about the division between first and second crop soya bean and is therefore assumed to remain stable within each tillage category. The minimum (and maximum) shares are related to -30% (or +30%) of the minimum (or maximum) of either conventional or reduced tillage, depending which figure is the lowest (or highest).

ⁿBased on Panichelli et al. (2008), no uncertainty range is mentioned and an uncertainty of $\pm 30\%$ is assumed (see text).

^oThis is the average provincial yield of Córdoba in the year 2014/2015 (Cuniberti, Herrero, Mir, Berra, & Macagno, 2015). The yield of Panichelli et al. (2008) was stated to be 2,591 kg/ha and was based on the average of the seasons 2000/2001 until 2004/2005. This seems to be outdated. The yields for Brazil (2,544 kg/ha) and United States (2,641 kg/ha) stated in Panichelli et al. (2008) are also much lower (26% and 40%) than the yields in the table. The yield of 3,040 kg/ha is used in this study, which is 17% higher than the yield stated by Panichelli et al. (2008).

^pBased on Pathanaissaranukool and Polprasert (2016), who give an average and a standard deviation. The range is based on two standard deviations.

^qGlyphosate, alachlor and paraquat are used as herbicides and cypermethrin as insecticide (Pathanaissaranukool & Polprasert, 2016). The numbers were given in L/ha and are converted to kg/ha by using densities of 1.70, 1.13, 1.25 and 1.25 kg/L for glyphosate, alachlor, paraquat and cypermethrin, respectively.

^rThe irrigation water is based on the average water productivity in Northeast Thailand stated by Promkhambut, Caldwell, and Polthanee (2014) multiplied with the yield stated in Pathanaissaranukool and Polprasert (2016). The yields between these different sources are almost similar (1,646–1,971 kg/ha vs. 1,720 kg/ha) indicating that the calculated amount of irrigation water would not be unreasonable. The range in freshwater is calculated by using the minimum and maximum water productivity in Northeast Thailand, while keeping the yield constant.

^sFor Thailand, two seasons are mentioned, a season from January to April and a second season from June to October (AMIS, 2012). The inputs for these two seasons are similar, except for a higher water demand and the energy required to pump the water in the dry season (January–April; Pathanaissaranukool & Polprasert, 2016). In this study, the first (drier) season is used because of water data availability (Promkhambut et al., 2014).

^tBased on Mousavi-Avval, Rafiee, Jafari, and Mohammadi (2011), who mention an average and a standard deviation. The range is based on two standard deviations.

^uMousavi-Avval et al. (2011) only mentioned a standard deviation (of the energy equivalent) of the total amount of fertilizer and total amount of pesticide. To distribute this range, it is assumed that it will correlate with the energy equivalent of each individual fertilizer/pesticide.

^vIn Iran, soya bean can be grown as second crop in Golestan and is planted after the harvest of the first crop in early summer and then harvested in the fall (Biabani, 2010). This is interpreted as planting the soya bean in July and harvesting it in November.

total GHG emissions. The total transportation distance in Brazil is about 3,300 km, which is all bridged by heavy-duty trucks, due to the remote location of the soybean fields.

In Figure 3, two dotted lines indicate a 60% and 80% GHG reduction potential compared to the maximum of the two fossil fuel cases. None of the cases achieves an 80% reduction, while a 60% reduction is achieved in Argentina (for all cases), for the average and minimum case in Brazil and the United States.

4.2 | Water intensities and water scarcity

In Figure 4, the water consumption intensity of conventional diesel and soya bean-based biodiesel is given for the different cases on a logarithmic scale. Note that only blue water is included meaning that green (i.e., rain) water is excluded. The ranges in water consumption intensity for fossil fuel are considerably smaller than for soya bean-based biodiesel. The water consumed in crushing and transesterification processes is negligible compared to cultivation if (part of the) soya bean is irrigated, as is the case in Iran, Thailand and (the average and maximum case of) the United States. If soya bean is not irrigated, the water consumption intensity of soya bean-based biodiesel (0.8–30 L/GJ_{fuel}) is roughly comparable to conventional fossil fuel-based diesel (8–24 L/GJ_{fuel}). Also, the water withdrawal intensity is roughly comparable with 1.9–142 L/GJ_{fuel} for biodiesel based on rainfed soya beans and 26–59 L/GJ_{fuel} for conventional diesel. If soya bean is irrigated, the water intensities are about three orders of magnitude higher for soya bean-based biodiesel (about 17,000–104,000 L/GJ_{fuel}) than for conventional diesel. For biodiesel based on irrigated soya beans, the difference between water withdrawal and water consumption intensities is negligible (<0.5%).

In Table 4, the water scarcities are given for the relevant periods of the three different nodes, feedstock production (i.e., soya bean cultivation or oil production), feedstock preparation (i.e., soya bean crushing) and fuel production (i.e., transesterification or oil refinery).⁵ In the average case, there is no or low water stress at all nodes in U.S., Argentina, Brazil, Iran and the European fossil fuel case. However, extreme water stress is present at Node 2 and Node 3 in Thailand and high water stress is present at Node 1 and Node 3 of the U.S. fossil fuel case.

4.3 | Eutrophication

In Figure 5, the specific eutrophication potential is given for the different cases. Most of the specific eutrophication

potential is caused by fertilizer usage in agriculture. Other contributors are electricity generation, fossil fuel use and hydrochloric acid.⁶ Hydrochloric acid is the main reason for the higher specific eutrophication potential in the transesterification process in the United States and Thailand, compared to other regions.

4.4 | Radar diagrams

Figure 6 shows the risk categorization of GHG emissions, eutrophication potential and the contribution to water scarcity of the relevant nodes of the supply chain for the different cases analysed in this study. The five different colours indicated the likelihood that risks will be present with respect to that indicator, where dark green refers to low risk and red refers to high risk. The water scarcity risks are based on the regional WTA and the direct water consumption of the node. For instance, the U.S. case has very low risks related to eutrophication, low risks related to GHG emissions, high risks related to water consumption of Node 1 (cultivation) and neutral risks related to the water consumption of Node 2 (crushing) and Node 3 (transesterification). In this way, the risks for all cases can be evaluated and trade-offs can be assessed. Note that the fossil fuel cases consist only of two nodes (feedstock and fuel production), and therefore, there is no water scarcity risk classification for the intermediate node.

Brazilian soya bean-based biodiesel has very low risks on the three different water indicators and neutral risks related to eutrophication potential and GHG reduction (Figure 6). For the U.S. case, it is the other way around, low risks related to eutrophication potential and GHG reduction and neutral risks related to water consumption of feedstock production. Argentina scores (very) low risks on all indicators. Soya bean-based diesel from Iran scores worse on GHG emissions and eutrophication potential than the fossil fuel alternatives.

Four of the five indicators for soya bean-based diesel from Thailand fall within the orange/red category and the other indicator (i.e., eutrophication) in the yellow risk category. If soya beans are grown in the wet (June–Oct) rather than in the dry season (January–April) in Thailand, the average WTA of the grow season would be 0.38 rather than 2.35.⁷ If the same volume of water is assumed to be used, the water scarcity risk category of cultivation would

⁶Chlorine is needed to produce hydrochloric acid. The production of chlorine is very energy intensive (mainly electricity), which lead to eutrophication.

⁷Soya bean is grown in the dry as well as in the wet season in Thailand. Similar inputs are used (except for a higher energy input to pump the water in the dry season), and the average annual yield of 1.7 tonnes/ha is used for both cases (Patthanaissaranukool and Polprasert, 2016).

⁵An overview of which water provinces are used and the water stress levels in these water provinces over time is provided in the Supporting Information Appendix S1.

TABLE 3 Input values for soybean crushing, oil extraction and transesterification for the different cases

	Unit	U.S.	Brazil	Argentina	Thailand	Iran
Soya bean crushing and oil extraction						
Electricity	MJ/kg oil	1.0 ^a (0.73–1.4)	0.71 ^c (0.36–1.1)	0.64 ^f (0.45–0.83)	0.92 ^g (0.64–1.2)	1.5 ⁱ (1.0–1.9)
Natural gas	MJ/kg oil	4.2 ^{ab} (3.0–5.5)	5.2 ^e (2.6–7.8)	4.8 ^f (3.3–6.2)		6.4 ⁱ (4.5–8.3)
Biomass	MJ/kg oil	0.065 ^{ab} (0.045–0.084)				
Heat fuel oil	MJ/kg oil	0.10 ^{ab} (0.068–0.13)			4.8 ^g (3.4–6.3)	
Coal	MJ/kg oil	2.1 ^{ab} (1.5–2.7)				
Land fill gas	MJ/kg oil	0.032 ^{ab} (0.023–0.042)				
Hexane	g/kg oil	2.6 ^a (1.8–3.4)	11 ^c (5.4–16)	0.53 ^f (0.37–0.69)	11 ^g (7.4–14)	12 ⁱ (8.3–15)
Freshwater withdrawal	L/kg oil	2.5 ^{ac} (0.021–4.3)	2.2 ^{ce} (0.021–4.3)	2.5 ^{ac} (0.021–4.3)	2.5 ^{ac} (0.021–4.3)	2.5 ^{ac} (0.021–4.3)
Freshwater consumption	L/kg oil	1.2 ^{ac} (0.021–1.7)	1.2 ^{ac} (0.021–1.7)	1.2 ^{ac} (0.021–1.7)	1.2 ^{ac} (0.021–1.7)	1.2 ^{ac} (0.021–1.7)
Water discharge	L/kg oil	1.4 ^{ac} (0–2.6)	1.0 ^c (0–2.6)	1.4 ^{ac} (0–2.6)	1.4 ^{ac} (0–2.6)	1.4 ^{ac} (0–2.6)
Meal production	kg meal/kg oil	4.1 ^a	4.5 ^e	3.7 ^f	4.2 ^g	4.5 ⁱ
Oil production	kg crude oil/kg soy	0.19 ^a	0.18 ^e	0.19 ^f	0.18 ^g	0.17 ⁱ
Transesterification						
Electricity	MJ/L SME	0.11 ^a (0.080–0.15)	0.12 ^e (0.06–0.17)	0.11 ^f (0.078–0.14)	0.11 ^h (0.06–0.17)	0.048 ⁱ (0.024–0.071)
Natural gas	MJ/L SME	0.77 ^a (0.54–1.0)	1.1 ^e (0.55–1.7)	1.3 ^f (0.93–1.7)	0.77 ^h (0.39–1.2)	
Methanol	g/L SME	81 ^a (56–105)	94 ^e (47–142)	88 ^f (62–114)	81 ^h (40–121)	176 ⁱ (88–264)
Sodium methoxide	g/L SME	21 ^a (14–27)	11 ^e (5.3–16)		21 ^h (10–31)	
Hydrochloric acid	g/L SME	39 ^a (27–50)	6.8 ^e (3.4–10)	3.0 ^f (2.1–3.8)	39 ^h (19–58)	2.0 ⁱ (1.0–3.0)
Sodium hydroxide	g/L SME	0.86 ^a (0.60–1.1)		1.4 ^f (1.0–1.8)	0.86 ^h (0.43–1.3)	
Phosphoric acid	g/L SME	0.56 ^a (0.39–0.73)		1.5 ^f (1.1–2.0)	0.56 ^h (0.28–0.84)	
Citric acid	g/L SME	0.65 ^a (0.45–0.84)			0.65 ^h (0.32–0.97)	
Potassium hydroxide	g/L SME					17 ⁱ (8.5–26)
Freshwater withdrawal	L/L SME	0.30 ^{ad} (0.06–3.4)	0.36 ^{de} (0.06–3.4)	0.30 ^{ad} (0.06–3.4)	0.30 ^{ad} (0.06–3.4)	0.30 ^{ad} (0.06–3.4)
Freshwater consumption	L/L SME	0.26 ^{ad} (0.02–0.39)	0.26 ^{ad} (0.02–0.39)	0.26 ^{ad} (0.02–0.39)	0.26 ^{ad} (0.02–0.39)	0.26 ^{ad} (0.02–0.39)
Water discharge	L/L SME	0.04 ^{ad} (0.04–3.0)	0.10 ^{ad} (0.04–3.0)	0.04 ^{ad} (0.04–3.0)	0.04 ^{ad} (0.04–3.0)	0.04 ^{ad} (0.04–3.0)

(Continues)

TABLE 3 (Continued)

Unit	U.S.	Brazil	Argentina	Thailand	Iran
Oil intake kg oil/L SME	0.88 ^a	0.74 ^c	0.93 ^f	0.88 ^b	1.1 ⁱ
Glycerine output kg/L SME	0.11 ^a	0.15 ^e	0.10 ^f	0.11 ^b	0.16 ⁱ

^aFrom Omni Tech International (2010), which is also used as input in the GREET study (Han, Elgowainy, Cai, & Wang, 2014). The crushing data are based on a survey conducted by 50–60 U.S. soya bean crushing plants in 2008 (Omni Tech International, 2010), and therefore, an uncertainty range of $\pm 30\%$ is used. ^bA boiler efficiency of 85% is assumed for all fuels. ^cWater withdrawal minus water discharge is water consumption, because no water is produced as by-product. Therefore, only two of the three are needed. For crushing, water withdrawal and discharge are mentioned for the United States (Omni Tech International, 2010) and water withdrawal for Brazil (Esteves et al., 2016). Data from the United States are used if data are missing. Literature gives a water withdrawal range of 0.021–4.3 L/kg oil (Esteves et al., 2016; Schneider & Finkbeiner, 2013), while no uncertainties are mentioned for water consumption or water discharge. In this study, water consumption is assumed to vary with $\pm 50\%$. The lower limit of water consumption is adapted to equal the minimum water withdrawal intensity, because water consumption cannot be higher than water withdrawal. ^dWater data of the United States are used if no regional-specific data are mentioned and the uncertainty ranges are based on literature ranges. Water withdrawal intensities for transesterification are estimated between 0.30 and 1.0 L/L (Fernández-Tirado, Parra-López, & Romero-Gómez, 2016; O'Connor, 2010; Omni Tech International, 2010; Schneider & Finkbeiner, 2013), while water consumption intensities of 0.02 L/L (Fernández-Tirado et al., 2016) and 0.26 L/L (Omni Tech International, 2010) are given. Water discharge intensities are given of 0.04–3 L/L (Daud, Sheikh Abdullah, Abu Hasan, & Yaakob, 2015; Omni Tech International, 2010; Veljković, Stamenković, & Tasić, 2014) and even up to 10 L/L (Atadashi, Aroua, Aziz, & Sulaiman, 2011), but this latter figure is considered to be an outlier. Interestingly, many of the water discharge intensities given in the literature are considerably higher than the previously mentioned water withdrawal range, although no water is chemically formed within the transesterification process. Explanations for this were not found. For the uncertainty range, the water discharge intensity of 0.04–3.0 L/L is used and a water consumption of 0.02–0.39 L/L is assumed (based on the lowest estimation in literature and $\pm 50\%$ of the base case). This leads to a water withdrawal intensity of 0.06–3.4 L/L biodiesel, which is larger than the water withdrawal range mentioned in literature. ^eBased on the average of four different literature sources (Esteves et al., 2016) and an uncertainty range of $\pm 50\%$ is assumed (see text). ^fFrom Hilbert, Donato, Muzio, and Huerga (2010), who used survey data from two soybean crushing and four transesterification facilities in Argentina (Donato & Huerga, 2009). The uncertainty is assumed to be $\pm 30\%$ (see text). ^gBased on Pathanaissaranukool and Polprasert (2016), who collected data from three soya bean oil refining facilities in Thailand. The uncertainty is assumed to be $\pm 30\%$ (see text). ^hNo data are given for Thailand; therefore, the U.S. data are used as approximation. The uncertainty is assumed to be $\pm 50\%$. ⁱFrom Rajaeifar et al. (2014), who collected crushing data from three Iranian manufactures and based the transesterification data on literature estimations. The uncertainty is assumed to be $\pm 30\%$ for the crushing and $\pm 50\%$ for the transesterification process (see text).

become yellow, that is, water-related risks may occur. If almost no irrigation water is used, then the water scarcity risk category of cultivation would become light green, that is, water-related risks are unlikely to occur. The water scarcity risk categories of crushing and transesterification will not be influenced and remain orange. Hence, even if the soya beans are cultivated in the wet season (assuming the same inputs), water-related risks for soya bean-based biodiesel are not eliminated. For the Thailand case, the seasonal aspect of water scarcity is obvious.

4.5 | Indirect water consumption

Table 5 lists the direct and indirect water consumption intensity of the different biofuel cases. Note that these volumes only refer to the consumption of river and groundwater (i.e., blue water) as the consumption of rain (i.e., green) water is excluded. If soya bean is irrigated, the contribution of indirect water consumption to the total water consumption is very small ($<1\%$). However, the relative contribution is significant if soya bean is rainfed, as is the case in Argentina and Brazil.

In Figure 7, the contribution of the various inputs to the indirect water consumption is given for Argentina and Brazil. The differences between the cases are mainly caused by the different fertilizer, pesticides and lime application rates and different chemicals used within the transesterification process. Furthermore, the type of pesticides and the differences in electricity mix between the regions are of importance. For instance, glyphosate has a water consumption intensity of 298 L/kg, while 2,4-D has a water consumption of 61.2 L/kg and the water intensity of electricity ranges from 0.5 L/kWh in Brazil to 11 L/kWh in Argentina (Wernet et al., 2016). An overview of the input data related to indirect water consumption is provided in the Supporting Information Appendix S1.

Whether this indirect water consumption contributes to water scarcity depends on the location where the water is used. This does not only depend on where the input products are produced (which is often possible to trace back), but also where the required inputs of the input products are produced (which is much harder to determine). This indirect water consumption of the input products is the main contributor to the water consumption for many chemicals, such as hydrochloric acid, phosphate fertilizer and methanol.

4.6 | Sensitivity analysis

4.6.1 | Data uncertainty

Radar diagrams for base, optimistic and pessimistic cases are constructed by using the average, minimum and

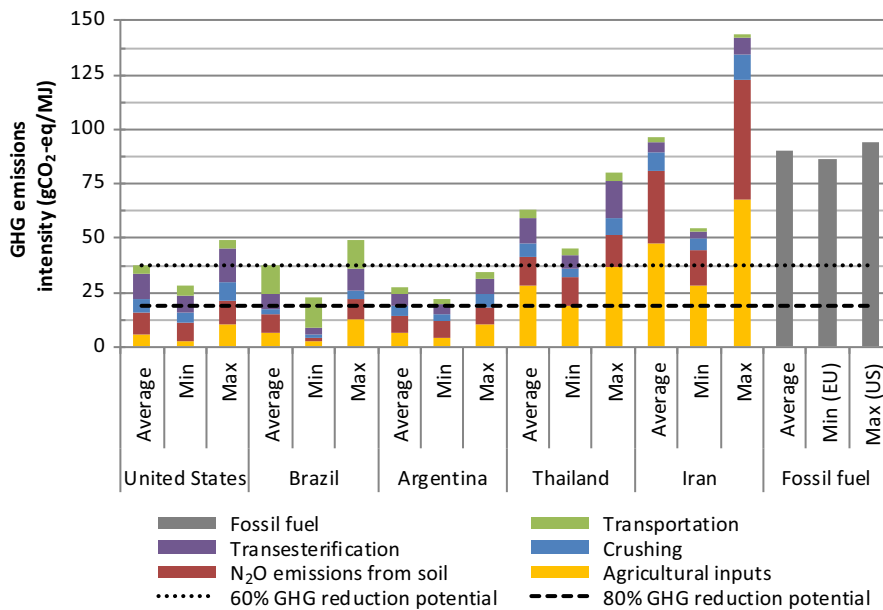


FIGURE 3 Average, minimum and maximum GHG emission intensity for the different biodiesel and fossil fuel cases and lines of the 60% and 80% GHG reduction potential (compared to the maximum fossil fuel case). For details of the fuel cases, see main text or Figure 2

maximum data given in Tables 2 and 3. In Figure 8, the results are given for the Brazil case. The other cases can be found in the Supporting Information Appendix S1. For Brazil, all variables are in the light or dark green area for the optimistic case. For the optimistic U.S. case, all variables are in the dark green area, except for eutrophication which is in the light green area. This indicates that good agricultural practice (i.e., no irrigation, limited use of fertilizers and pesticides) and state-of-the-art crushing and transesterification plants reduce the environmental and business risks, related to soya bean-based biodiesel production and use, to the green risk categories in Brazil and the United States.

For Iran, the optimistic case leads to four of the five categories in the light and dark green area, while the GHG emission reduction is in the yellow area. However, the

GHG emission reduction of 44% is not enough to classify the biodiesel as renewable fuel in the European Union (European Commission, 2015). In the optimistic Thailand case, the water-related risk is (still) in the orange and red risk water scarcity risk category, due to the very high water stress level in Chiang Mai.

Overall, Argentina is the most robust case. Even in the pessimistic case, four of the five variables are in the dark green area while the other variable (GHG reduction potential) is in the light green area.

4.6.2 | Maximum rather than average water scarcity index

There is (almost) no difference between the average and maximum WTA for Brazil, Argentina, Iran, and the EU

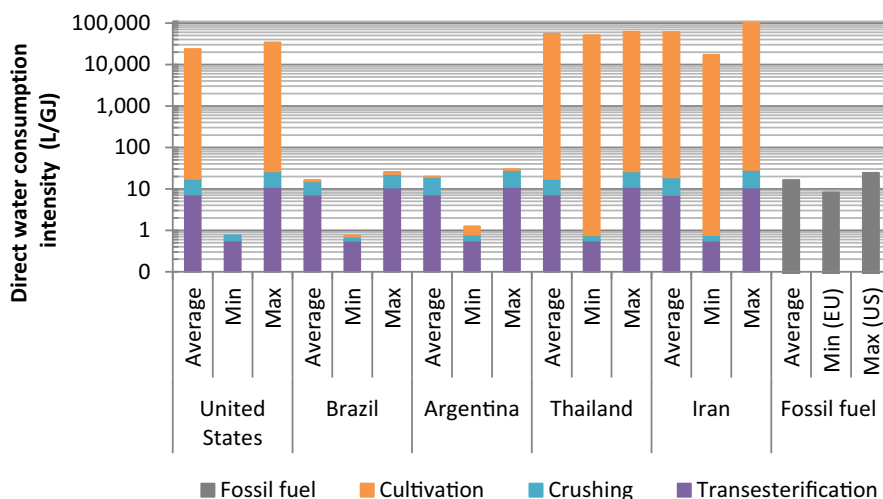
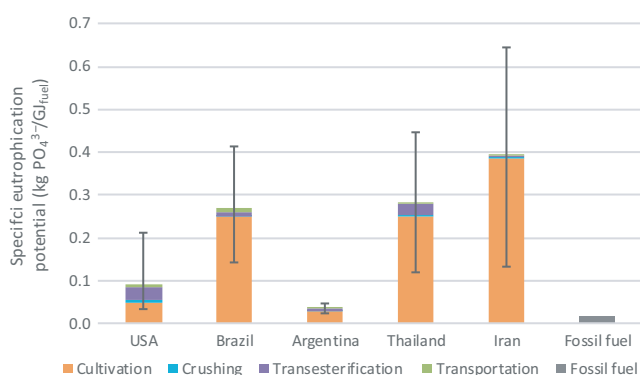


FIGURE 4 Average, minimum and maximum (blue) direct water consumption intensities for the different biodiesel and fossil fuel cases on a logarithmic scale. For details of the fuel cases, see main text or Figure 2

TABLE 4 Overview of the average (Av) and maximum (Max) WTA of the different nodes for the relevant periods

	United States.		Brazil		Argentina		Thailand		Iran		Fossil fuel cases			
											Min (EU)		Max (U.S.)	
	Av	Max	Av	Max	Av	Max	Av	Max	Av	Max	Av	Max	Av	Max
Node 1 (feedstock production)	0.13	0.25	0.00	0.00	0.01	0.01	2.35	8.9	0.05	0.08	n.a.	n.a.	0.49	1.5
Node 2 (feedstock preparation)	0.07	0.25	0.00	0.01	0.00	0.00	1.38	8.9	0.04	0.08	n.a.	n.a.	n.a.	n.a.
Node 3 (fuel production)	0.01	0.01	0.00	0.01	0.00	0.00	1.38	8.9	0.04	0.08	0.00	0.00	0.49	1.5

**FIGURE 5** Specific eutrophication potential of the different cases. For details of the different cases, see main text or Figure 2

fossil fuel case (see Table 4). This means that also the water scarcity risk categorisation does not change if the maximum rather than the average WTA is used.

However, the water scarcity risks are higher for some biodiesel and fossil fuel nodes in the United States, if the maximum rather than the average water scarcity is used. In the U.S. fossil case, both oil production (node 1) and oil refining (node 3) change from yellow to orange if the maximum rather than the average WTA is used. For U.S. biodiesel, Node 2 (crushing) falls in the light green instead of the dark green water scarcity risk category.

4.6.3 | Water withdrawal

The withdrawal intensity is 77%, 60% and 160% higher than the water consumption intensity in the base case for Argentina, Brazil and the average fossil fuel case, respectively. This is caused by oil refining, crushing and transesterification process. If irrigation takes place, the difference between withdrawal and consumption is very small (<0.5%).

If water withdrawal rather than water consumption intensity is used to estimate water-related risks, only one node (i.e., crushing in the United States) falls within a higher risk category, namely orange instead of yellow. This does not change the overall conclusions.

4.6.4 | Choice of allocation methods

GHG emissions and water volumes are allocated to soyameal and glycerine. However, the conversion efficiencies to soya oil and biodiesel as well as the soyameal and glycerine output differ slightly for each region, see Table 3. Hence, the allocation factors differ slightly per region, even if the same allocation method is used. The allocation factor for soyameal ranges from 62.1% to 66.8%, 78.6% to 81.9% and 64.2% to 68.7% for energy, mass or economic-based allocation, respectively. For glycerine, the allocation factor ranges from 4.5% to 6.8%, 10.4% to 15.3% and 1.1% to 1.6%, respectively.

In Figure 9, the GHG emission intensity of the biodiesel cases is given for the different allocation principles. Allocation on energy or economic basis gives almost similar GHG intensities for all cases, that is, the difference is <1%. If allocation is conducted on a mass basis, the GHG intensities are about 31%–48% lower compared to the other allocation methods, because less GHG emissions are allocated to soy-oil and more to soyameal. The water-related risks categorisation does not change with the different allocation methods.

5 | DISCUSSION

Several water provinces have monthly median WTA ratios that are well above one, meaning that more water is withdrawn than is available within that month by using, for instance, non-renewable groundwater. For instance, the median WTA of January is 8.7 in the water province where the soya beans are cultivated in Thailand. Months with very high median WTA ratios influence the yearly average considerably. However, no adaptations were made (by setting the maximum WTA ratio, for instance, to three or five) because very water scarce months would lead to very high water-related risks. This ignores that water may be stored during water abundant months (in artificial reservoirs) to overcome water scarce months (Quinteiro, Ridoutt, Arroja, & Dias, 2018). However, average water scarcity levels as well as maximum monthly medians ignore the occurrence of dry years, which leads to more water scarcity and water-related risks than other years.

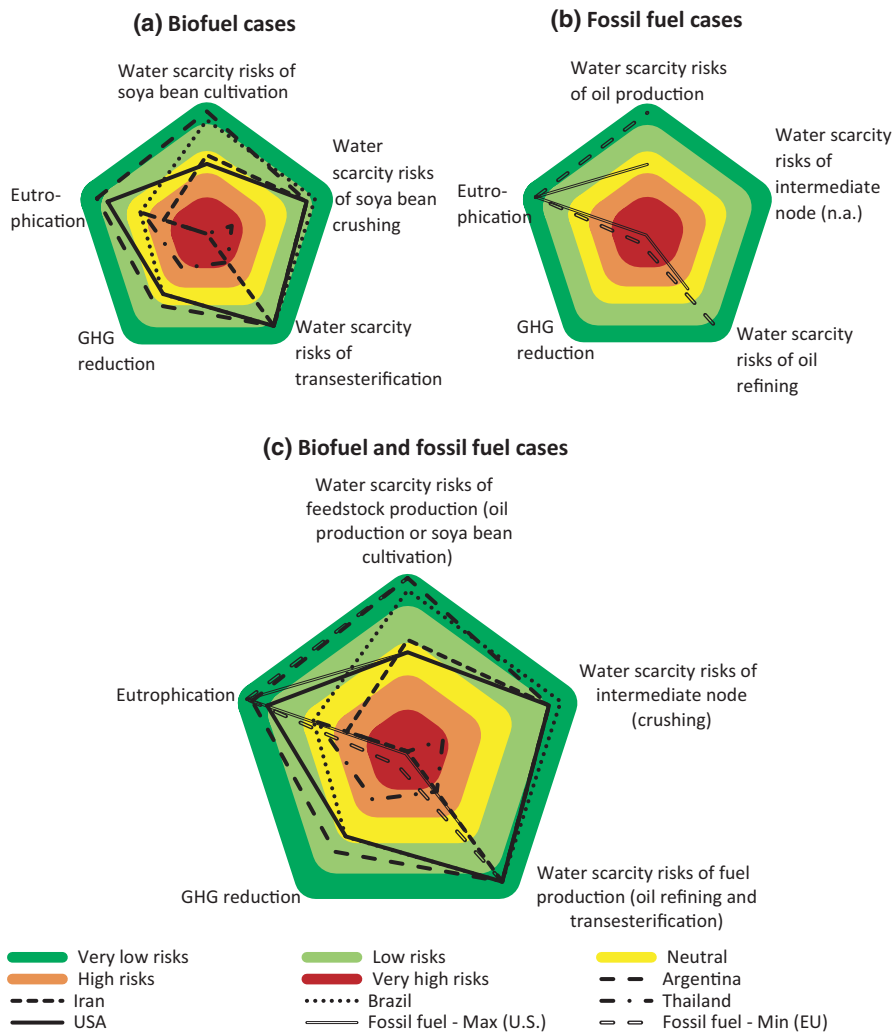


FIGURE 6 Radar diagrams to show trade-offs between GHG emissions, eutrophication potential and water scarcity risks for (a) soya bean-based biodiesel in five different regions, (b) two fossil fuel cases and (c) all analysed cases (bottom). The five different colours indicated the likelihood that risks will be present with respect to that indicator. Note that the fossil fuel cases consist only of two nodes (feedstock and fuel production), and therefore, there is no water scarcity risk classification of the intermediate node

	Unit	United States	Brazil	Argentina	Thailand	Iran
Direct water consumption	L/GJ	23,670	16.3	19.8	55,730	60,608
Indirect water consumption	L/GJ	161	198	121	290	420
Share indirect water consumption	%	0.7	92	86	0.5	0.7

TABLE 5 Direct and indirect water consumption intensity for the different biofuel cases

Large ranges of water volumes are mentioned. Overall, the availability and reliability of water data are lacking in publicly available sources. More attention should be spent on establishing water intensities in databases and validation of volumes for specific technologies and regions.

Note that the uncertainty ranges for the optimistic and pessimistic cases, as in Figure 3, are calculated in different ways, depending on data availability. For instance, the ranges of agricultural data are based on two standard deviations (Thailand, Iran), minimum–maximum values (Brazil), or $\pm 30\%$ (Argentina, United States) if no uncertainty

ranges were provided in the data sources. Although based on different measures, the uncertainty around each case is in a similar order of magnitude with, for instance, 25%, 28%, 30%, 31% and 49% lower GHG emission intensity in the optimistic vs. the base case for Argentina, Thailand, United States, Brazil and Iran case, respectively. Nevertheless, caution is needed when comparing uncertainty ranges of the various cases with each other.

The radar diagrams reflect the current situation, but mitigation options may be available to decrease water-related risks, GHG emission intensity or specific eutrophication

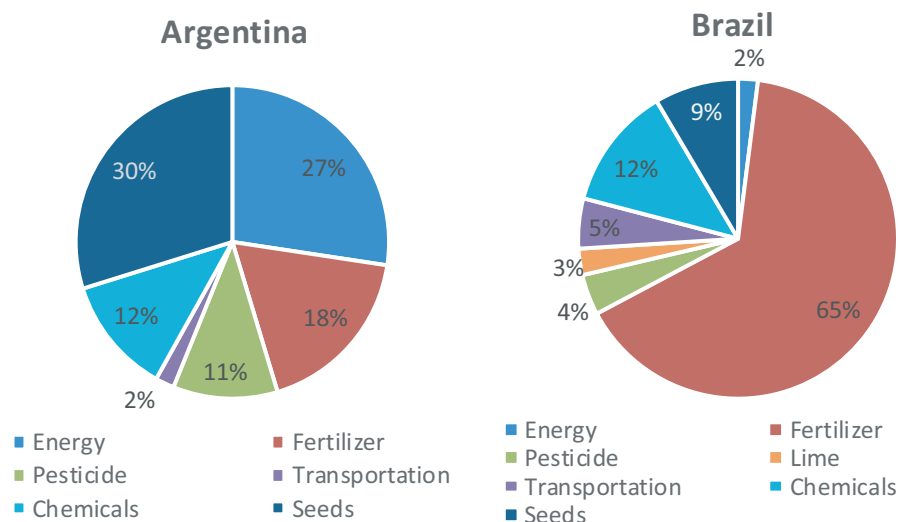


FIGURE 7 Break-down of indirect water consumption for Argentina (left) and Brazil (right) by inputs to soya bean biodiesel production

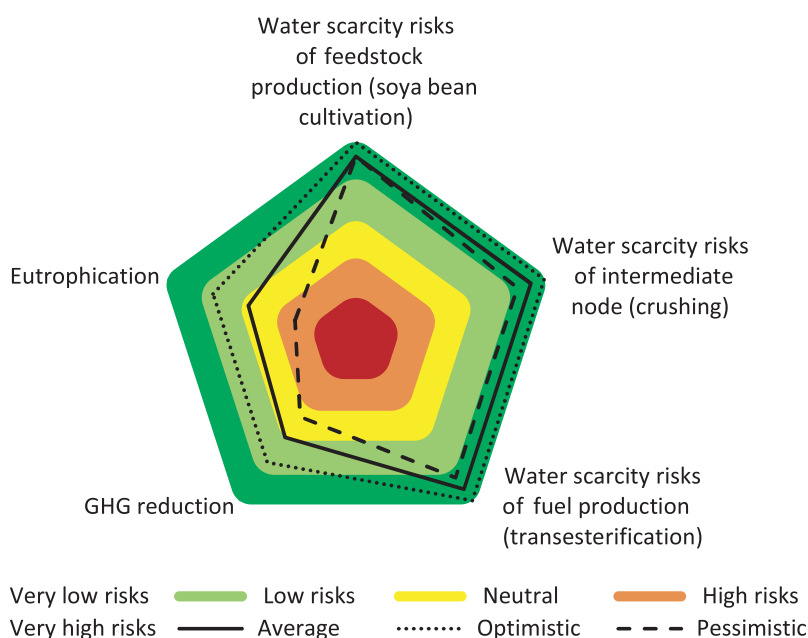


FIGURE 8 Influence of data uncertainty, shown in an optimistic and pessimistic case for Brazil

potential. In general, soya bean-based biodiesel production from the main global production regions (i.e., the United States, Brazil and Argentina) demonstrates low risks (Figure 6). In contrast, the globally insignificant soya bean production region of Thailand and Iran (<1%) appears less sustainable and efficient in use of resources across several dimensions in this analysis (Figure 6). It is unclear if this difference is the result of implemented mitigation options caused by regulatory, economic or reputational drivers in the United States, Brazil and Argentina. Nevertheless, the optimistic cases give an indication of the improvement potential if state-of-the-art technologies and best available agricultural practices are applied.

The GHG intensity of soya bean-based biodiesel is driven mainly by agricultural inputs (11%–51%) and soil N₂O emissions (9%–38%). A GHG reduction of more than 60%,

compared to the maximum fossil fuel case, is achieved for soya bean-based diesel in Argentina, United States and Brazil. Potential GHG reductions for soya bean-based biodiesel exclude GHG emissions from direct and indirect land-use change. Direct and indirect land-use changes are intertwined, and therefore, there is often referred to land-use change (LUC) emissions (Valin et al., 2015). LUC emissions can be significant and are estimated between 29.1 gCO₂-eq/MJ in the U.S. scenario (Air Resources Board, 2014) and 150 gCO₂-eq/MJ in the Europe scenario modelled by GLOBIOM (Valin et al., 2015) for soya bean-based biodiesel. Adding the lowest number would decrease GHG emission reduction potential from soya bean-based biodiesel in Argentina to 40% (leading to a yellow score in the radar diagram), while adding the highest number would lead to GHG emission intensities which are higher than

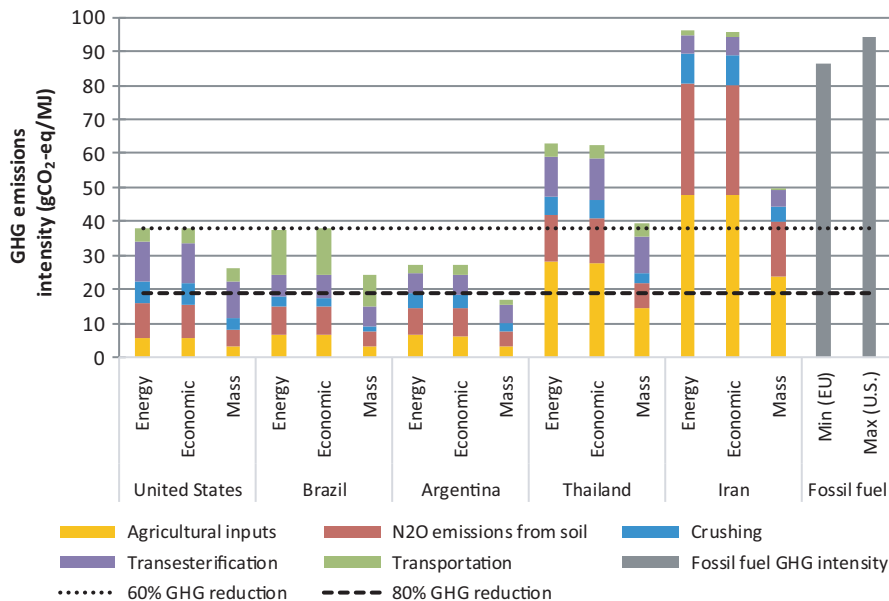


FIGURE 9 GHG emission intensities of soya bean-based biodiesel for the base case of all five regions, with energy, mass or economic-based allocation. The dotted lines refer to 60% and 80% GHG reduction potential compared to the max. fossil fuel case

conventional diesel (leading to a red category in the radar diagram). So, the uncertainty in LUC emissions is very large and can nullify the GHG reduction potential of soya bean-based biodiesel.

The specific eutrophication potential of the biofuel cases is mainly influenced by the amount of fertilizers used. Argentina, U.S. and the fossil fuel cases have low eutrophication risks, while Brazil, Thailand and Iran base cases have modest to high risks related to eutrophication. For these three cases, the risks related to eutrophication reduce to (very) low if minimum rather than average input values for fertilizers etc. are used. This reflects that good agricultural practices are important to reduce the impact of biofuels on the environment significantly.

The fertilizer application rates suggest that nutrients accumulate in the soil, especially in Iran, Thailand and Brazil. These nutrients can be used beneficially for a next crop (Patthanaisaranukool & Polprasert, 2016), but could also lead to pollution of subsurface and groundwaters (Sheikh Davoodi & Houshyar, 2009). The reason for the high fertilizer application rates is unclear, but it can be caused by lack of knowledge among farmers or improper methods in applying fertilizers (Sheikh Davoodi & Houshyar, 2009). In Iran, research suggests that soya bean yields keep increasing at rates of nitrogen application even higher than the ones used here (Shahkoohmahally & Shahkoohmahally, 2017). This combined with the fact that fertilizers are subsidized in Iran (FAO, 2005) may suggest that a high fertilizer rate is a local economic optimum.

The amount of fertilizers determines the eutrophication potential, because the CML-IA method does not include a fate model and ignores the sensitivity of the environment to additional nutrients (European Commission, Joint Research Centre, Institute for Environment, &

Sustainability, 2011). As some regions may have higher run-offs rates and are more vulnerable for eutrophication than others, this could influence the preference for some feedstock production regions. Therefore, it is recommended that regional-specific eutrophication potentials are developed. However, this used method gives at least a first indication about the presence of eutrophication risks.

The ranges in water consumption intensity for fossil fuel are considerably smaller than for soya bean-based biodiesel. If soya bean is rainfed, soya bean-based biodiesel has a direct (blue) water consumption intensity which is in the same order of magnitude than fossil diesel. If soya bean is irrigated, the water intensities are about three orders of magnitude higher. Overall, there are (very) low water-related risks attached to soya bean-based biodiesel if soya beans are rainfed and the biodiesel is produced in water abundant areas.

Seasonal variation in water scarcity can influence the water-related risk for agriculture, as the Thailand case show. If it possible to grow soybeans in the wet, rather than in the dry season in Thailand, the water-related risks reduce from very high to moderate. Therefore, it is important to consider seasonal aspects.

For industrial processes, water withdrawal intensities may be significantly higher than water consumption intensities. Therefore, it should be analysed whether using water withdrawal rather than water consumption intensities would change the conclusions related to water-related risks. This is less relevant for agricultural processes, because water withdrawal intensities and water consumption intensities are (almost) similar.

The indirect water consumption intensity, that is, water needed to produce energy and chemical inputs, is estimated at 120–420 L/GJ for soya bean-based biodiesel. This is

significant if the soya beans are rainfed. If irrigation is required, indirect water consumption is dwarfed by irrigation water. The contribution of indirect water consumption to water scarcity should be further investigated to ensure that the water-related risks of indirect water consumption do not change the preference between alternatives. An open question is the influence of climate change on future water stress levels and the impact that this may have on preferable areas and feedstocks for biofuel production.

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