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The modelling approach determines the carbon footprint of biofuels: The role of LCA in informing decision makers in government and industry

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ABSTRACT

Concerns over climate change have led to the promotion of biofuels for transport, particularly biodiesel from oilseed crops and ethanol from sugar and starch crops. However, the climate-change mitigation potential of the various biofuels estimated in published studies tends to vary significantly, questioning the reliability of the methods used to quantify potential impacts. We investigated the values published in the European Commission's Renewable Energy Directive (RED), and recalculated the climate-change impacts of a range of biofuels using internally-consistent attributional and consequential modelling approaches to enable comparison of these approaches. We conclude that the estimated results are highly dependent on the modelling approach adopted, to the detriment of the perception of the robustness of life cycle assessment as a tool for estimating the climate-change impacts of biofuels. Land use change emissions are a determining parameter which should not be omitted, even if modelling it introduces a large variability in the results and makes interpretation complex. Clearer guidelines and standardization efforts would be helpful in the harmonization of LCA practice, so that the results can be more useful, robust and reproducible.

1. Introduction

Concerns over climate change have led to the promotion of biofuels for transport, particularly biodiesel from oilseed crops and bioethanol from sugar and starch crops, for replacing fossil diesel and gasoline, respectively. In its original Renewable Energy Directive (EU, 2009), the European Union aimed at reducing the climate-change impacts of its transportation sector by supporting biofuels that showed at least 35% greenhouse gas (GHG) savings against fossil fuels, a target which was later revised to 65% GHG savings from 2021 onwards (EU, 2018).

Recognising the need to take into account the emissions that occur along the supply chain of the biofuel (e.g. fertilizer production and fuel use in crop cultivation), the European Commission (EC) adopted a life cycle assessment (LCA) approach for systematically estimating the climate-change mitigation potential of biofuels from various feedstocks.

LCA can elucidate the absolute and relative climate change impacts of bioenergy systems and thereby aid in the identification of systems that reach the targets adopted by policy makers and other decision makers. In the case of biofuels, LCA accounts for emissions over the life cycle of the biofuel and compares it to those over the life cycle of a fossil fuel comparator (normalized to a functional unit, e.g. 1 MJ or 1 km travelled), in a comprehensive and systematic manner, so as to elucidate the consequences of supporting either system.

Many LCA studies of biofuels have been published, and the results tend to vary widely, even for the same feedstocks with similar conversion processes and fuel products (e.g. Cherubini et al., 2009; Chum et al., 2011; Rocha et al., 2014; Garcia et al., 2020). A number of factors contribute to the wide range of results in the LCA of biofuel systems. Agricultural and other bio-based systems are naturally variable, given their dependence on seasonal climate and other agro-ecological factors. Furthermore, variability arises due to inherent differences between the systems being modelled, such as differences in input data regarding the specific crop, cultivation and processing technologies, transport modes and distances. However, methodological choices, including the impact assessment method (see Brandão et al., 2019) and reference system for land use and energy system (Koponen et al., 2018), are also an important source of variability (Cherubini et al., 2009; Pereira et al., 2019), as is the level of spatial resolution, emission factors, level of aggregation of carbon

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stocks and land classification systems (Donke et al., 2020). Another key methodological choice is the modelling approach adopted. There are two distinct LCA modelling approaches recognised: *viz.* Attributional (ALCA) and consequential (CLCA). This paper focuses on the choice of modelling approach, in order to determine the extent to which this particular methodological choice affects the results for climate change impact assessments of biofuels.

The choice of modelling approach is fundamental, and is made during the goal and scope definition of the study. According to the Shonan LCA database guidance principles, the two LCA modelling approaches are defined as (Sonneman and Vigon, 2011):

- Attributional approach: "System modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule."
- Consequential approach: "System modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit."

The two approaches answer different questions: whilst ALCA attributes a share of the global environmental burden to a product or activity, CLCA quantifies the consequences that an increase in supply or demand for a particular product is likely to have on the environment. It has been argued that ALCA is not useful to support decision-making, as ALCA does not attempt to estimate consequences of decisions to use or avoid a product, while CLCA is well-suited to this purpose (Brandão et al., 2014); some authors even argue that ALCA is unequivocally misleading in guiding policy, e.g. climate policy (Plevin et al., 2014). However, other research in the context of biofuels shows a more positive view on the usefulness of ALCA for decision making (e.g. Prapaspongsa and Gheewala, 2017).

In practice, the main differences between the two approaches are: i) the data adopted (average for ALCA and marginal for CLCA), e.g. for modelling the input of electricity supply mix, and ii) the manner in which co-production is handled. ALCA allocates environmental burdens among co-products according to a physical or other relationship between the co-products. In contrast, CLCA applies substitution, whereby the determining product (e.g. rapessed-oil biodiesel) is credited with the avoided burdens that the use of the by-product (e.g. oilseed cake, used as livestock feed) incurs via displacing a marginal product yielding the same function as the by-product (e.g. x kg protein and y MJ energy in oilseed cake displacing the same amount of protein and energy from soybeans and feedwheat). More information on these two modelling approaches can be found in e.g. Weidema (2003), Brandão et al. (2014), Brandão et al. (2017) and Ekvall (2019). The ISO standard for LCA (ISO 2006a,b) provides a hierarchy for handling co-products, giving priority to system expansion (i.e. substitution), followed by allocation according to an underlying physical relationship, and finally allocation according to another relationship such as economic value (ISO, 2006). LCA has been applied in different manners, which has contributed to the large variability in the reported values for GHG emissions from bioenergy systems (see e.g. Garcia et al., 2020).

The approach adopted by the European Commission for the RED is essentially a hybrid modelling approach: it allocates supply chain emissions between co-products according to energy content but also expands the system boundary using the substitution approach, by including credits for electricity from co-generation (e.g. avoided coal emissions due to the co-production of straw, used for power, in ethanol from wheat-grain systems) (EU, 2009).

Accounting for climate change impacts is further complicated by indirect effects, such as indirect land use change (iLUC) – quantification of which is elusive, as by definition iLUC cannot be observed or measured (Muñoz et al., 2015). The EU (2015) describes iLUC as "where pasture or agricultural land previously destined for food and feed markets is diverted to biofuel production, the non-fuel demand will still need to be satisfied either through intensification of current production or by bringing non-agricultural land into production elsewhere. The latter case represents indirect land-use change and when it involves the conversion of high carbon stock land it can lead to significant greenhouse gas emissions". However, different interpretations of iLUC exist. Some consider that all land use incurs an iLUC effect (e.g. Audsley et al., 2010; Schmidt et al., 2015), while others consider only the market-mediated effects that potentially arise via compensation for the diversion of crop use, e.g. from food to fuel (e.g. Searchinger et al., 2008; Brandão, 2012). While the former approach attributes global LUC to all global land occupation, the latter approach models iLUC as the balancing of agricultural-commodity markets (or also non-agricultural markets, as is the case for general-equilibrium models like MIRAGE, whose values were adopted by the European Commission for the RED). The modelling implication of this seemingly unimportant distinction is that iLUC is compatible with ALCA in the former approach, but incompatible with the latter. For an overview of the different models that capture iLUC, see De Rosa et al. (2016).

Table 1
Biofuel production pathways modelled in this study and associated co-products.

Biofuel	Feedstock	Co-products*
Ethanol	Corn	- DDGS (45.4%)[a] - Electricity (credit)[a]
	Sugar beet	- Sugar beet pulp (28.7%)[a]
	Sugarcane	- N/A
	Wheat	- DDGS (40. 5%)[a] - Electricity (credit)[a]
Biodiesel (Fatty Acid Methyl Ester, FAME)	Rape seed	- Rapeseed cake (38.7%)[b] - Refined glycerol (4.3%)[c]
	Sunflower	- Sunflower cake (34.2%)[b] - Refined glycerol (4.3%)[c]
	Soybean	- Soybean cake (65.6%)[b] - Refined glycerol (4.3%)[c]
	Palm oil	- Kernel meal (4.8%)[b] - Refined glycerol (4.3%)[c]
	Waste oil	- Refined glycerol (4.1%)[b] - Bio-oil (1.4%)[c]
Hydrotreated Vegetable Oil (HVO)	Rape seed	- Rapeseed cake (38.7%)[b] - Electricity (credit)[d]
	Sunflower	- Sunflower cake (34.2%)[b] - Electricity (credit)[d]
	Palm oil	- Kernel meal (4.8%)[b] - Electricity (credit)[d]
Pure Vegetable Oil (PVO)	Rape seed	- Rapeseed cake (38.7%)[b]
Biogas as compressed natural gas (CNG)	Manure	N/A

*as handled in the EC-approach to co-production: via energy allocation (factors given for the co-products) and by crediting electricity displacement, as calculated under RED (EU, 2009). Under REDII (EU, 2018) the methodology for GHG calculations has been updated to include exergy allocation in case of excess electricity produced along the supply chain of the biofuel.

[a] at the ethanol plant.

[b] at the extraction of oil.

[c] at esterification.

[d] at hydrogenation.

Further to the insights gained in Whittaker (2014), who compared the RED approach with a substitution approach for modelling the GHG emissions of wheat-based ethanol, our paper compares the two main LCA modelling approaches with each other and with the EC approach to elucidate the degree to which results are sensitive to the approach adopted. The preference for a particular modelling choice is discussed with reference to the variability of results in the biofuel production pathways modelled, while critically assessing the specific algorithms contained within the different approaches.

2. Methods

We modelled the 20 biofuel production pathways for ethanol, fatty

Table 2
Summary of base models, features and methodological choices adopted.

Approach	Biofuel supply chain	Direct land-use change	Indirect land-use change
		(dLUC)	(iLUC)
RED-dLUC	BioGrace I (2015) [a]	DLUC tool (Blonk, 2014)[d]	N/A
RED-iLUC	BioGrace I (2015) [a]	N/A	EU (2015)[d]
ALCA	BioGrace I (2015) [b]	DLUC tool (Blonk, 2014)[d] and BRLUC tool for Brazil (Novaes et al., 2017)	Schmidt et al. (2015) [d]
CLCA	BioGrace I (2015) [c]	DLUC tool (Blonk, 2014) and BRLUC tool for Brazil (Novaes et al., 2017) [d,e]	Schmidt et al. (2015) [d,e]

[a] co-production resolved via both energy allocation and electricity displacement; updated average electricity mix.
[b] co-production resolved via energy allocation; updated average electricity mix.
[c] co-production resolved via substitution; marginal electricity mix.
[d] applied to the foreground land use (i.e. land growing the biofuel crop).
[e] applied to the background land use (i.e. land growing the substituted crops).

acid methyl ester (FAME), hydrotreated vegetable oil (HVO), pure vegetable oil (PVO) and biogas, for which GHG default values are given in the RED (EU, 2009): ethanol (7 pathway options), FAME (6), HVO (4), PVO (1) and biogas (2); see Table 1. Each of these is modelled in four different ways: EC-RED (with dLUC and iLUC variants), ALCA and CLCA. The base models adopted were modified to reflect more recent data and more representative assumptions[1] relevant for each modelling approach (see Table 2).

2.1. EC default (RED)

This approach consists of the values published in RED (2009), modified with the updated values for Global Warming Potential (GWP) and electricity supply mix. Two sub-approaches were distinguished: one assuming dLUC and one assuming iLUC.

In order to ensure consistency with the reference values of the EC across all approaches, and test how the ALCA and CLCA modelling approaches deviate from the EC default values, *ceteris paribus*, we have adopted the same activity data (i.e. yields, efficiencies, technosphere inputs) as those reported in BioGrace I (BIOfuel GReenhouse gas emissions: Align Calculations in Europe), version 4d (2015), which is the version of the tool that represents the EC default values. More information on the tool can be found in www.biograce.net, Hennecke et al. (2013) and Pereira et al. (2019). The only deviations are that we updated the characterisation factors for the different GHGs to reflect the Global Warming Potentials (GWPs) from the IPCC Fifth Assessment Report (Stocker et al., 2013), used different EU electricity mixes for ALCA (average) and CLCA (marginal) taken from the ecoinvent 3.5 databases (ecoinvent, 2020), and different land-use change considerations to align with the specific modelling approaches of ALCA and CLCA (see *2.6 Direct land use change (dLUC) and indirect land use change (iLUC)*).

2.2. Attributional LCA (ALCA)

This approach borrows from the RED approach all the updated activity data but handles co-production consistently by applying energy allocation throughout the biofuel system. It considers both dLUC and iLUC, the former by adopting the Blonk approach (Blonk (2014) that was updated with recent statistical data (e.g. FAOSTAT, 2020) and iLUC by applying the model developed by Schmidt (2015) (see 2.6). It is useful to note here that not all researchers find iLUC to be compatible with the ALCA approach, as mentioned in the introductory section. This is because the iLUC emissions of one crop could be considered the dLUC emissions incurred by another, i.e. the one(s) succeeding LUC, and should not be attributed to both crops as this would lead to double counting.

2.3. Consequential LCA (CLCA)

This approach also borrows the updated activity data from the RED approach but applies substitution consistently. Furthermore, it includes dLUC and iLUC to both the land growing the biofuel crop, as well as the feedcrops being displaced by biofuel by-products, also using recent FAOSTAT data for the Blonk approach for dLUC (Blonk, 2014) and the Schmidt et al. (2015) approach for iLUC. See Fig. 1 for the system boundary adopted in CLCA modelling.

2.4. Identifying the source of supply

The origins of the biofuel feedstocks were assumed to be as follows: France and Germany for rapeseed, sugar beet and wheat; USA for corn; Brazil for sugarcane; Brazil and Argentina for soybean; Indonesia and Malaysia for palm oil; and Ukraine for sunflower. The share of each country's supply was based on their relative share over a 10-year period (2009–2018) from FAOSTAT (2020). Barley from Canada was assumed to be the marginal source of feed energy (required to calculate substitution effects in CLCA scenarios, as described below).

2.5. Co-production

From the unallocated systems from BioGrace I, we modelled ALCA by applying energy allocation consistently whenever co-production was encountered and by using the average supply mix for the inputs, e.g. electricity. Conversely, we handled co-production via substitution for the CLCA scenarios, where e.g. the various by-products used for feed are balanced by their marginal counterparts, i.e. co-products were assumed to displace the marginal feed sources based on their biophysical attributes (i.e. content of protein, metabolizable energy and vegetable oil). The marginal feed sources were assumed to be soybean meal for feed protein, barley for feed energy and palm oil as the marginal vegetable oil, from Brazil/Argentina, Canada and Indonesia/Malaysia, respectively (Schmidt and De Rosa, 2020).

2.6. Direct land use change (dLUC) and indirect land use change (iLUC)

Following the guidance of the RED (EU, 2009) and PAS 2050 (BSI, 2012) for calculating dLUC emissions (e_l in Equation 1 in SI), we included the estimated carbon-stock changes between the reference land use and the land used for the production of the feedstock, and amortized it over 20 years. In order to estimate the reference land-use mix, our algorithm reflected the trend over the past 20 years (1999–2018) of expansion/contraction of forest, grassland, annual cropland and perennial cropland in the particular country (or country-mix) from FAO data (FAOSTAT, 2020); see Fig. 2. Due to its sheer size and high heterogeneity, the algorithm for Brazil carbon stock changes was calculated differently: we used BRLUC regionalized-based estimates (Novaes et al., 2017; EMBRAPA, 2020) to overcome some of the drawbacks of adopting national-level algorithms in large and diverse countries (Bontinck et al., 2020; Donke et al., 2020). The resulting values, expressed in Table 3 and Fig. 3, are consistent with the methodological guidance given in RED (EU, 2009) and its amendment (EU, 2015), PAS2050 (BSI, 2012), Novaes et al. (2017), Blonk (2014), European Commission (2010), Carré et al. (2010), as well as the Buendia et al. (2019) guidelines for National

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[1] For example, the DLUC tool (Blonk, 2014) only considers the most representative climatic zones and soil types, while we have considered all climatic zones and soil types within each country or subnational region considered. We have also updated the land-use change and management factors using Buendia et al. (2019).

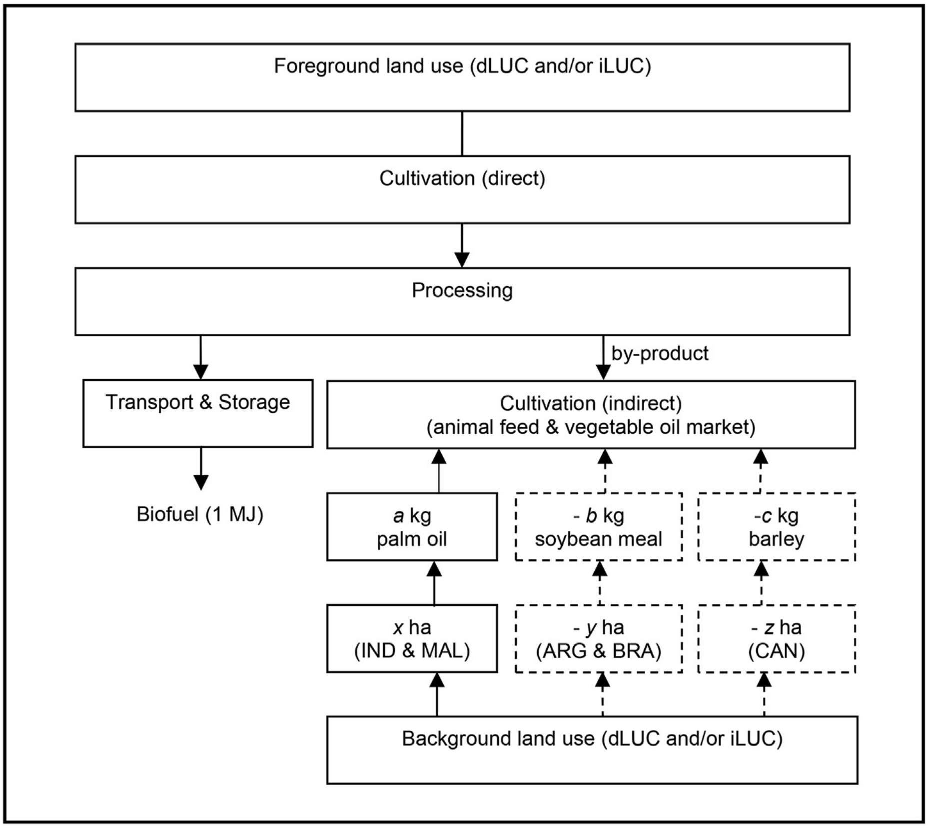

Fig. 1. Biofuel life cycle, including co-production. The fate of by-products is excluded in the EC and ALCA approaches (where energy allocation is used instead). Dashed elements indicate avoided products, included in CLCA only. The illustration refers to biofuels modelled with CLCA that incur the co-production of animal feed (e.g. wheat ethanol). The marginal producers of vegetable oil are assumed to be Indonesia (IND) and Malaysia (MAL), while those for soybean meal (marginal source of feed protein) are assumed to be Argentina (ARG) and Brazil (BRA), and for barley (marginal source of feed energy) it is assumed to be Canada (CAN).

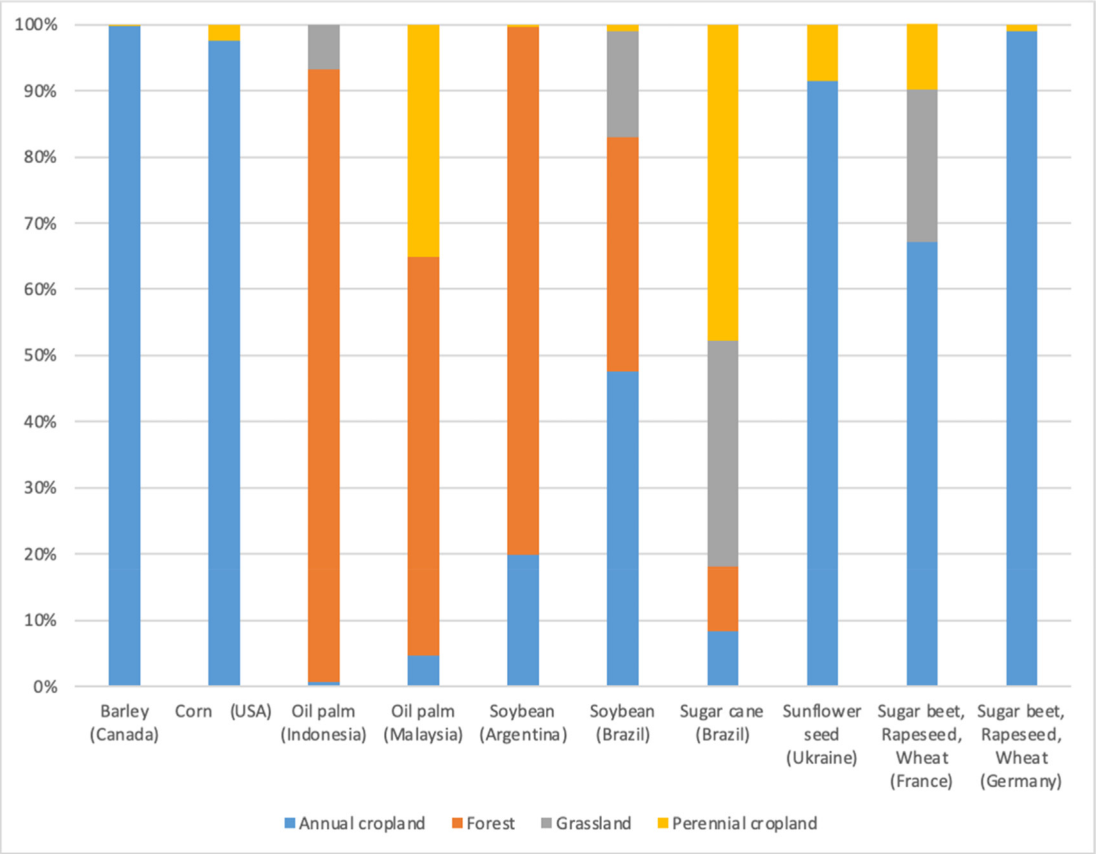

Fig. 2. Reference land-use mix (%) associated to the cultivation of feedstocks in the countries supplying the biofuel and marginal feed feedstocks (extrapolated from FAOSTAT, 2020 and BRLUC v1.3 for Brazil – EMBRAPA, 2020). Shares are estimated proportionally to the changes in the reference land uses.

Table 3
Land-use change emissions (weighted average) per crop and country of supply[a], and share of cropland expansion on total production over 20 years (1996–1998 to 2016–2018).

Feedstock and	n[b]	Land carbon stock (tC/ha)[c]		Land Use Change emissions[d]	Share from
country of supply		Reference supply mix	Actual biofuel crop	expansion (%)	
Barley from Canada	936	55.1	55.0	0.02 (−9.9–71.9)	0.0
Corn from USA	2224	48.6	47.8	0.15 (−10.6–73.3)	14.1
Palm oil from Indonesia (55%)	1336	135.1	57.9	14.08 (−19.7–28.1)	76.1
(corrected for 60% from organic soil)				48.77 (-19-7 – 71.9)	
Palm oil from Malaysia (45%)	808	115.4	68.5	8.60 (−19.7–28.1)	39.5
(corrected for 10% from organic soil)				14.75 (−19.7–70.1)	
Rapeseed from France (51%)	1104	58.1	46.9	2.06 (−10.6–17.9)	35.0
Rapeseed from Germany (49%)	1104	60.7	60.0	0.13 (−10.6–14.6)	28.0
Soybean from Argentina (36%)	1624	140.8	25.8	21.09 (−10.6–27.4)	59.5
Soybean from Brazil (64%)	1288	86.0	39.1	8.59 (−10.6–32.1)	65.6
Sugarbeet from France (57%)	1104	58.1	46.9	2.06 (−10.6–17.9)	0.9
Sugarbeet from Germany (43%)	1104	60.7	60.0	0.13 (−10.6–14.6)	0.0
Sugarcane from Brazil	1288	60.2	47.4	2.35 (−10.6–32.1)	52.2
Sunflower seed from Ukraine	816	53.2	48.0	0.95 (−9.9–14.1)	60.5
Wheat from France (61%)	1104	58.1	46.9	2.06 (−10.6–17.9)	4.5
Wheat from Germany (39%)	1104	60.7	60.0	0.13 (−10.6–14.6)	4.5

[a] including respective shares if more than one (calculated over a 10-year period: 2010–2019).
[b] n is number of permutations of climate zone, soil type, land use, land management – proportional representation according to area of each: weighted average share of climate zone, soil type and land use with estimation on tillage and input use (manure) for reference and actual land use.
[c] in mineral soils.
[d] Annual emission after 20-year LUC emission amortization.

Greenhouse Gas Inventories (Buendia et al., 2019), and include carbon stock changes in mineral and organic soils due to changes in land management in addition to changes in land use. IPCC tier 1 values for carbon stocks in soil and vegetation, according to soil type, vegetation type, land use and land management were applied, using the proportion of area of each soil/climate per country (or sub-national region, in the case of Brazil) to produce a weighted average.

The resulting dLUC values were used in all modelling approaches, although the CLCA approach excludes cropland already in use in the supply mix, implying that all biofuels come at the expense of cropland expansion and, thus, result in a supply mix with a higher impact. Furthermore, the EC approach is included with two variants: one where the growing of the biofuel feedstock incurs dLUC (RED-dLUC), and another where iLUC is assumed to take place (RED-iLUC), since the two are considered mutually exclusive (EU, 2015). See Table 3.

For the RED-iLUC approach, we adopted the values for indirect land-use change (iLUC) that were published by the European Union (EU, 2015): 12 (8–16) gCO$_2$-eq/MJ for cereals and other starch-rich crops, 13 (4–17) gCO$_2$-eq/MJ for sugar crops and 55 (33–66) gCO$_2$-eq/MJ for oil crops, which were estimated as a weighted average of the results for individual crops in each crop group, as reported in Laborde et al. (2014). These come from the *Modeling International Relationships in Applied General Equilibrium* (MIRAGE), an economic general-equilibrium model developed by the International Food Policy Research Institute (IFPRI).

For both ALCA and CLCA, iLUC was estimated using the model by Schmidt et al. (2015), which provides factors for both approaches. As opposed to other approaches (e.g. PAS2050, GHG Protocol and PEF Guideline), Schmidt et al. (2015) acknowledge the limitations of choosing an arbitrary 20-year amortization period of LUC emissions and argue that the implications of these approaches are that LUC is overestimated at the frontier while ignoring iLUC for established arable land. Their model assumes that 1) land use changes are caused by demand for land, 2) there is a market for land, i.e. for land's capacity for growing biomass, 3) the market for land is global, 4) different markets for land can be distinguished (e.g. arable and forest), 5) demand for land results in land use change, intensification and crop displacement, although food-security impacts are not taken into account. No amortization over time takes place in this method.

In addition, for CLCA, both foreground and background dLUC for the energy crop and marginal feed and vegetable oil crops, respectively, were considered by updating the DLUC tool (Blonk, 2014) with the most recent FAOSTAT land-use data, as well as carbon-stock change data and factors from Buendia et al., 2019. Foreground and background iLUC emissions were calculated using the factors provided by Schmidt et al. (2015). Background iLUC in CLCA only reflects the additional and displaced LUC associated with the balancing of marginal products resultant from the additional use of by-products, while foreground iLUC excludes any social effects potentially caused by diverting food crops into biofuel production.

3. Results

In order to determine the annualized emissions from carbon stock changes caused by land use change (e_l), as per RED, the reference land-use mix for the supplier countries was estimated following the description above, as well as the associated carbon stock changes (see Table 3). The resulting carbon stock changes vary between <1 tC/ha in Germany, USA and Canada to >100 tC/ha in Argentina (Fig. 3).

Fig. 4 shows the climate-change impact of the all biofuel pathways estimated with the four approaches. Results vary considerably across the alternative modelling approaches, although the ALCA results are very similar to the RED-dLUC approach.

The ethanol pathways show a lower climate-change impact, in general, compared with the fossil-fuel reference, but higher than the minimum GHG emission savings of 33gCO2-eq/MJ (>65%), the revised target established in the RED II (EU, 2018). Ethanol from sugar cane has lower emissions than the fossil-fuel reference in all approaches, except for CLCA mainly due to dLUC, which still estimate the impact as not meeting the EC threshold. For all other ethanol pathways, the different approaches do not vary significantly, with the exception of CLCA, showing better results than the fossil-fuel comparator (94 gCO2-eq/MJ), but still not meeting the target, with the exception of the systems that use energy from straw (instead of fossil fuels) in the biofuel processing plant.

Palm oil FAME and HVO consistently show higher emissions than the fossil fuel they are assumed to replace, regardless of the approach. Both dLUC and iLUC are large contributors to the overall result. Rapeseed and sunflower oils are either around or below the value for the fossil-fuel

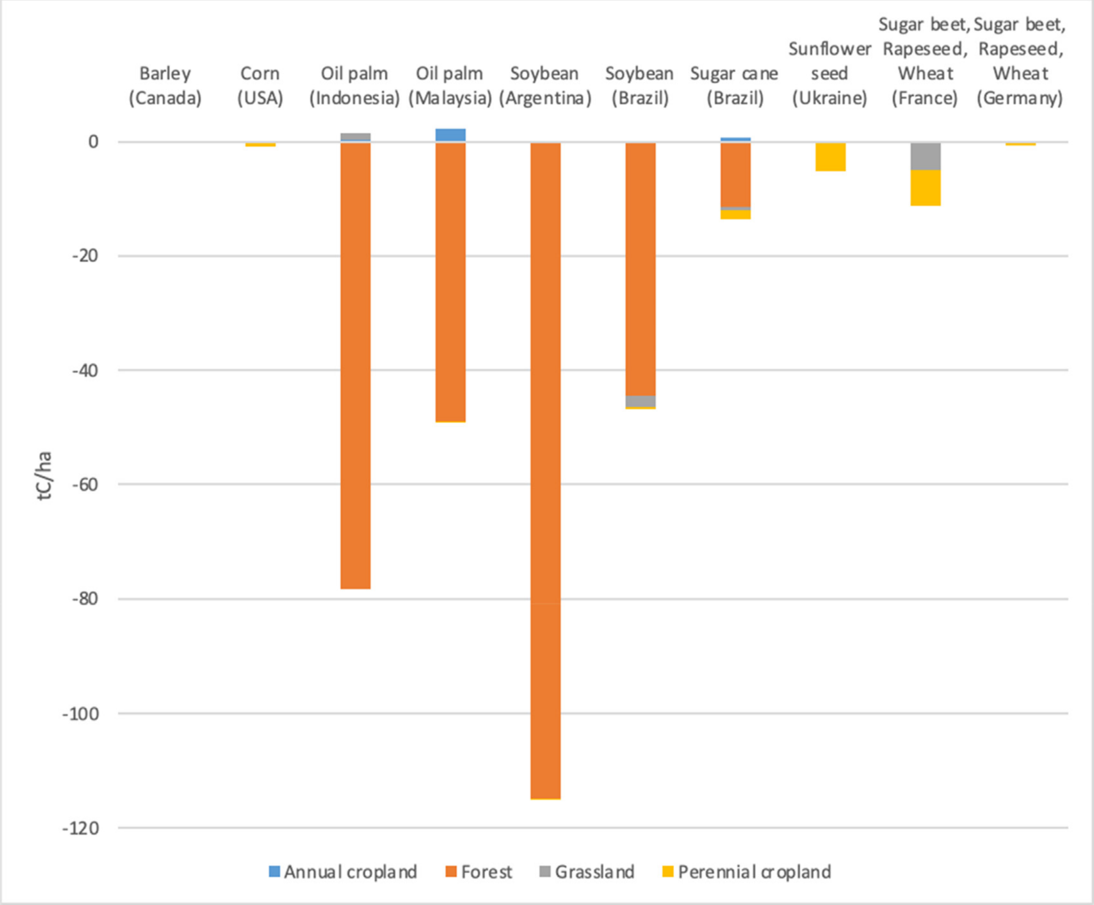

Fig. 3. Carbon stock changes from the reference land use to energy cropping in the selected countries. Positive values represent carbon-stock gains, while negative values represent carbon losses, expressed in tC/ha. Indonesia and Malaysia palm oil includes that from organic soils – 60% for Indonesia and 10% for Malaysia). Values for Indonesia and Malaysia show a gain in carbon due to the conversion of grassland and annual cropland to perennial cropping, which has a higher carbon stock. Brazil is included twice as it is the source of sugarcane, as well as soybean.

reference but do not meet the EC 2021 threshold. The exceptions are the CLCA results which, due to iLUC, show a net negative result. FAME from soybean oil shows consistently higher emissions than the fossil reference across all approaches. For rapeseed and sunflower (PVO, HVO and FAME), the RED-iLUC estimates are around double those estimated with the RED-dLUC and ALCA approaches, while the CLCA approach gives results of around −40 gCO2-eq/MJ.

The only pathways that meet the target that is required by the EC from 2021 onwards is that from waste oil, which is particularly favourable in the CLCA approach, and those producing biogas from wet and dry manure, which do not vary significantly with the modelling approach adopted. Wheat ethanol with energy recovery from straw also meets the EC target according to most approaches.

4. Discussion and conclusions

The results show that the modelled impacts are highly sensitive to the approach adopted. Most of the pathways do not meet the European target for emissions reduction when modelled via the ALCA and EC-RED approaches. The exceptions are biogas from manure and FAME from waste oil, and ethanol from wheat where the straw is used for energy recovery in a combined heat and power (CHP) plant. However, half of the ethanol and of the biodiesel-from-crops pathways (3/7 and 5/10, respectively) modelled with CLCA show net negative emissions, by a wide margin (around −50 gCO2-eq/MJ), which is due to the displacement of the assumed marginal feedstocks for feed and their large iLUC emissions. Ethanol from sugar beet results in lower GHG emissions than gasoline, but not low enough to meet EC requirements. Ethanol from sugarcane has lower emissions than gasoline in all approaches, with the exception of the CLCA approach, which shows emissions substantially above those of gasoline. This is due to the large emissions from dLUC in Brazil and no avoided emissions, as there are no co-products used outside of the system. The use of waste oil and manure for biodiesel and biogas, respectively, shows low levels of emissions, as no emissions from dLUC, iLUC or cultivation are included.

LUC emissions dominate over other stages of the life cycle (e.g. cultivation, processing, transport), and are often the largest term in CLCA. However, the land-supply mix in CLCA is composed only of land that is not already used for the particular crop under assessment, as opposed to the ALCA and hybrid EC approaches.

The choice between ALCA and CLCA clearly has a large impact on the results, particularly in cases where there are co-products, but the choice of which particular approach to follow depends extensively upon the research question at hand. The climate change mitigation potential of biofuels may be enhanced by the iLUC emission savings from using biofuel by-products in the feed market, displacing production that would otherwise incur GHG emissions.

Regardless of the biofuel pathways, the key result in CLCA is that: any biofuel option that co-produces feed and thereby displaces soybean meal as the marginal feedstock for feed protein will avoid LUC emissions. This is because some deforestation (or organic soil drainage) is avoided in Brazil, Argentina, Malaysia and Indonesia. However, this does not mean that biofuels that are co-produced with feed will necessarily outperform fossil fuels in all pathways and modelling approaches.

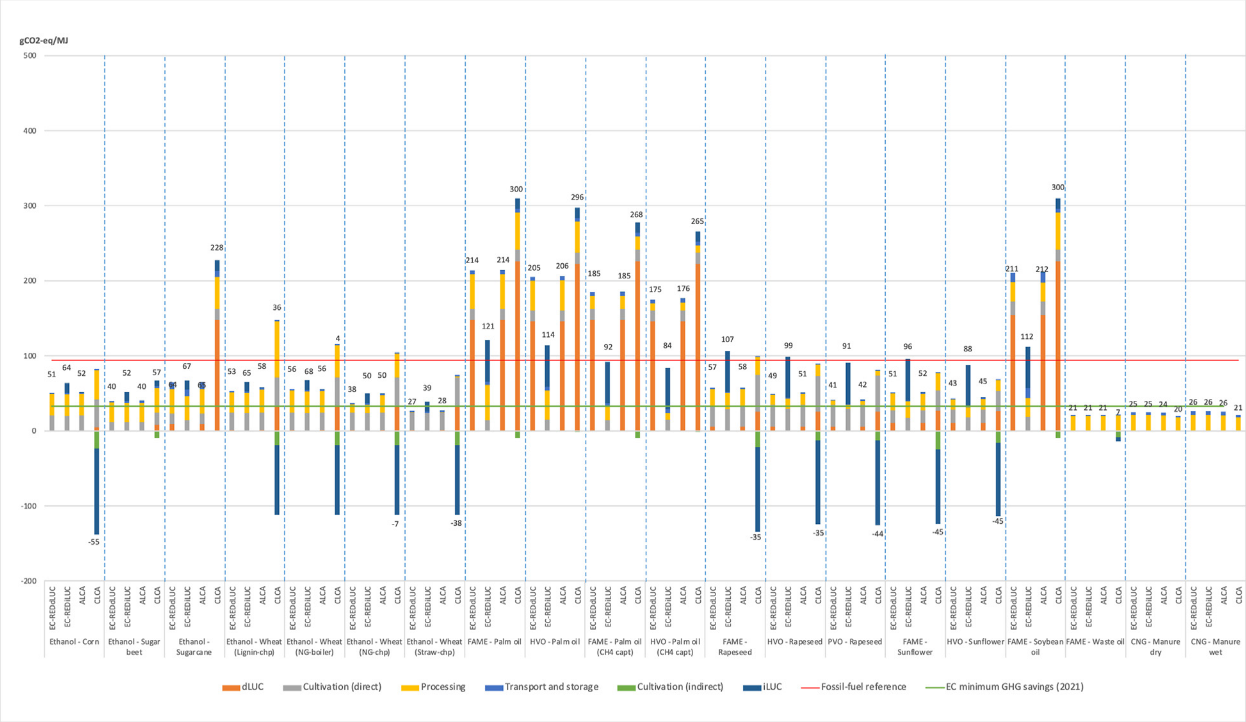

Fig. 4. Climate change impacts of ethanol, biodiesel and biogas produced from the different feedstocks (gCO_2-eq/MJ final fuel) estimated with the four different approaches.

The fact that both forms of land-use change - dLUC and iLUC – are commonly ignored in LCA implies that a significant parameter is excluded, which our results show to be a decisive factor in making the biofuel under assessment either compliant or not with the mitigation targets (e.g. EC threshold of 65% GHG savings relative to the fossil-fuel comparator from 2021).

In spite of its importance (see e.g. Gibbs et al., 2008), including LUC estimations is fraught with challenges. A recent study by Bontinck and co-workers (Bontinck et al., 2020) found the top-down approach used in the Blonk tool (Blonk, 2014) to be inappropriate when applied to Australia as it results in an overestimation of LUC emissions when compared to a bottom-up approach that better reflects the soil and vegetation carbon stocks where agricultural production – and therefore LUC – take place.

Previous studies comparing biofuel life-cycle GHG emissions assessment tools (e.g. ethanol produced from sugarcane, corn and wheat with GHGenius, BioGrace and GREET) have also found significant discrepancies between the tools (Pereira et al., 2019) and between LCA studies (e.g. Majer et al., 2009), where the delimitation of the agricultural system is key.

In elucidating insights for providing guidance on the application of these approaches – and their implications for decision making (see e.g. Brandão et al., 2012) – it is clear that the approaches vary significantly, particularly the CLCA approach, which stands out. The reason for this is that CLCA includes important market-mediated mechanisms, of which the interaction with the feed market is particularly important and may determine whether specific biofuel pathways make a positive or negative contribution to climate change mitigation. Including uncertain mechanisms may make results less precise but more accurate and representative of the system studied, which arguably may be a preferred modelling approach to excluding important factors at play (see e.g. Brandão et al., 2014; Weidema, 2009). Decisions that are expected to result in climate-change mitigation cannot be based on incomplete assessments of the effects of those decisions. Thus, it is important to ensure consistency between the goal and scope of the study and the modeling approach adopted, by choosing the appropriate approach for answering the particular research question at hand. Comprehensive assessments that include indirect market-mediated effects are particularly important when competing modelling approaches may lead to contrasting decisions, as we have shown. These challenges are relevant not only for biofuels, but also for any bio-based product.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2021.100027.

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