the production chain from sugar beet followed by maize grain and stover (Table 1). On the other hand, the production chain with sugarcane from the North-East region of Brazil followed by wheat yield the lowest output per hectare.

In the case of CRP (Fig. 3a), Müller-Wenk and Brandão (2010) argue that the results of this impact category should be added to other GHG emissions (Fig. 1). We have not done so in Fig. 1 because CRP relates to the 'foregone sequestration', i.e. the amount of C not fixed in biomass due to a past LUC, and not to actual GHG emissions. If CRP was converted to CO_2 eq and added to the cradle-to-grave GHG emissions, the results would still be favourable for all options of bio-based ethanol when compared to fossil-based ethanol, although the performance of wheat-based ethanol would be significantly eroded, with GHG emissions only 20 % lower than those of the fossil-based ethanol.

3.4 Sensitivity analyses

Several aspects were subject to a sensitivity analysis to check their influence on the results of the ReCiPe impact indicators. Below, we describe these analyses and the results obtained.

3.4.1 Allocation in ethanol production

Due to increased demand of ethanol as a fuel and basic chemical, its price could rise, therefore affecting the economic allocation in the production process. We modelled the system assuming as that, as a worst case, 100 % of the environmental burdens are allocated to ethanol and 0 % to any co-product (DDGS, electricity, etc.). The results (Fig. 1 in ESM) showed a sharp increase in all impacts for ethanol from sugarcane, but much lower for the other feedstocks. Due to the equally valuable by-product sugar, the allocation factor for ethanol from sugarcane is doubled, resulting in a doubled score in all impacts, with the exception of GHG emissions, which increase by 63 %. However, given that there is an increasing global demand for sugar, it is unlikely that 100 % of the revenue from sugarcane products will be attributed to ethanol in the future. In terms of overall ranking of feedstocks, this sensitivity analysis does not change the main results obtained, i.e. bio-based feedstocks still present lower GHG emissions than fossil-based ethanol, but the former are still more impactful in many of the other ReCiPe impact categories.

3.4.2 Pre-harvest burning of sugar cane

The Brazilian State of Sao Paulo aims for zero pre-harvest burning in 2021. This will lead to a reduction in impacts from open burning of biomass but also to increased mechanisation. When sugarcane is modelled without pre-harvest burning, there is a reduction in impacts (Fig. 2 in ESM), most notably in POFP (66 % reduction), but also in other indicators such as GHG emissions (9 % reduction) and TAP (20 % reduction). The big reduction in the POFP category is related to the avoidance of emissions of volatile organic hydrocarbons, nitrogen oxides and sulphur dioxide from open burning, which are key contributors to this impact category. Similarly, in the climate change impact category, the reduction is associated with avoiding the dinitrogen monoxide and methane emissions

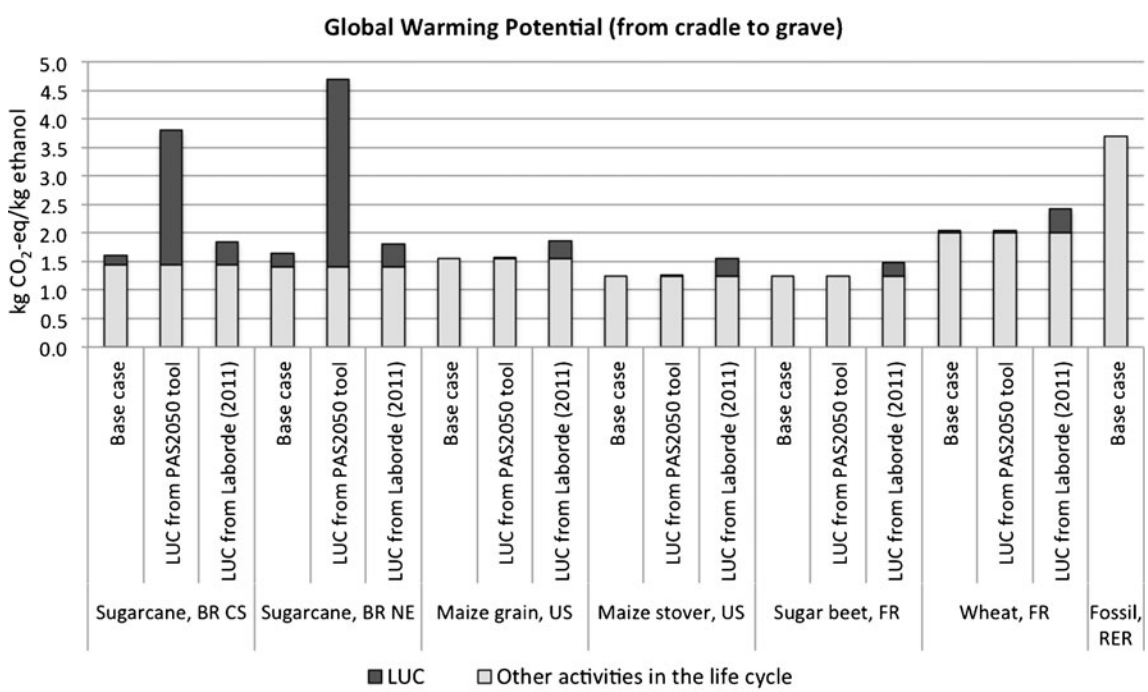

Fig. 4 Results of the sensitivity analysis on GHG emissions from LUC

from open burning, whereas in TAP the reduction is associated to lower nitrogen oxides and sulphur dioxides. Even though increased mechanisation increases fuel use, there is a net reduction in impacts with the exception of FAP, which increases by 11 % mainly due to phosphorus emissions in the background processes of the operation of a tractor. Overall, though, the ranking of bio-based feedstocks does not change based on the results of this sensitivity analysis.

3.4.3 Maize grain drying

Maize grain loses moisture naturally, but in wet weather conditions, additional drying can be necessary. As a base case, we assumed no drying, and in the sensitivity analysis, we added the drying step to check its environmental relevance. This was done by means of the ecoinvent dataset for maize drying (Nemecek et al. 2007). The results (Fig. 3 in ESM) showed that GHG emissions increase by 17 % when this step is added and makes maize grain the most GHG-intensive bio-based feedstock after wheat. In the remaining impact categories, the increase is of less magnitude and do not change the ranking of bio-based feedstocks.

3.4.4 GHG emissions from LUC

We carried out two alternative calculations of GHG emissions from LUC: (1) using the tool developed to support the application of the British standard PAS 2050–1:2012 (BSI 2012) and (2) using data from a study commissioned by the European Commission (Laborde 2011).

Both the PAS2050 tool and the method by Milà i Canals et al. (2012) are based on the use of retrospective FAOSTAT data to ascertain whether or not and how much LUC occurring in a country can be attributed to a crop. According to the PAS 2050 tool using the 'Calculation of averages' option, all crops but sugar beet in France were attributed LUC emissions, namely 11.5 tonnes of CO_2 eq/ha/year for sugarcane in Brazil, 0.01 tonnes of CO_2 eq/ha/year for maize in the USA and 0.07 tonnes of CO_2 eq/ha/year for wheat in France. In comparison, the method from Milà i Canals et al. (2012) led to GHG emissions of 0.75 tonnes CO_2 eq/ha/year for sugarcane in Brazil and of 0.1 tonnes of CO_2 eq/ha/year for wheat in France, whereas for maize no LUC was identified. We have not been able to identify all the possible reasons for these differences between the two methods, although a key factor in our opinion is that the amount of LUC is crop-specific in the PAS2050 tool, whereas in Milà i Canals et al. (2012) the amount of LUC is not crop-specific, but a country average. It can be seen in Fig. 4 that the choice of LUC estimation method has a dramatic effect in sugarcane-based ethanol from Brazil, to the extent that if the PAS 2050 method is used, its life cycle GHG emissions exceed those from fossil-based ethanol.

In a second sensitivity analysis, we replaced the GHG emissions estimated with our base-case method with those by Laborde (2011), who estimated global GHG emission factors from LUC for ethanol from maize, sugarcane, sugar beet and wheat based on general equilibrium modelling. Due to lack of detailed data in that study, it was not possible to distinguish between maize grain and stover; therefore, the same factor was used for both. The resulting GHG emissions (Fig. 4) are higher for all feedstocks, from 9 to 24 % when compared to the original results. In the latter, LUC emissions for Brazilian sugarcane were of 0.16 and 0.24 kg CO_2 eq/kg ethanol for the Centre-South and North-East regions, respectively, whereas the value from Laborde (2011) is higher, of 0.4 kg CO_2 eq/kg ethanol.[1] For wheat, the difference is even higher, since the original emissions from the method by Milà i Canals et al. (2012) were of 0.04 kg CO_2 eq/kg ethanol whereas the value from Laborde (2011) is of 0.42 kg CO_2 eq/kg ethanol.

3.4.5 Choice of biomes

The choice of biome for agricultural land used in the foreground system was not always straightforward. A sensitivity analysis was carried out for sugarcane in North-East Brazil, assuming 'Tropical and Subtropical Moist Broadleaf Forests' instead of 'Deserts and Xeric shrublands'. This resulted in impacts substantially rising for some indicators such as 76, 35 and 78 % in CRP, BPP and ERP, respectively. In CRP, BPP and ERP, it involved the highest impact of all alternatives, and in FWRP, impacts increased to similar levels to those from maize grain, maize stover and sugar beet. On the other hand, other impacts reduced with WPP-MF, WPP-PCF and BDP lowering to similar levels as wheat.

3.5 Uncertainty analysis

Figure 5 in the ESM shows the results of the uncertainty analysis for the ReCiPe impact indicators. The dots in the figure represent the probabilistic mean, whereas the vertical lines cover the 2.5th and 97.5th percentiles.

When GHG emissions are compared in Fig. 5 in the ESM, it can be seen that all bio-based ethanol alternatives are likely to involve lower emissions than the fossil alternative, but it is difficult to distinguish a clear difference between the different bio-based alternatives, due to the overlap in distributions.

As for fossil ethanol, it shows comparatively lower uncertainty than the bio-based feedstocks. The generally higher uncertainty for bio-based materials is consistent with the notion in LCA that agricultural systems usually involve a high variability and uncertainty (see e.g. Roches et al. 2010; Röös et al. 2010; Nemecek et al. 2012).

[1] The GHG factors in the original source are given per MJ ethanol. They are transformed on a per kilogram basis using a calorific low value of 29.96 MJ/kg ethanol (Kosaric et al. 2001).

Overall, like in the deterministic modelling, the fossil ethanol shows clear advantages in MEP, TAP and ALO, whereas the best-performing bio-based alternatives in these indicators are sugarcane and sugar beet (MEP) and sugar beet (TAP, ALO).

4 Conclusions

LCA was applied to assess the global bio-based commodity ethanol, from several biomass sources and regions in the world. Bio-based ethanol was also compared to its fossil-based counterpart, produced from ethylene.

The results have shown that GHG emissions from cradle-to-gate for the bio-based ethanol production routes assessed vary by a factor of up to 5, with the sugar beet route in France showing the lowest emissions and wheat showing the highest, unless GHG emissions from LUC are assessed with the PAS 2050 tool for horticultural products, in which case sugarcane-based ethanol from Brazil shows the highest GHG emissions. Looking at cradle-to-grave emissions, all bio-based ethanol production routes involve lower emissions than fossil-based ethanol, with the exception of sugarcane-based ethanol, provided that GHG emissions from LUC are assessed with the PAS 2050 tool for horticultural products.

When other impact indicators are considered, trade-offs appear between bio-based and fossil-based ethanol. The latter performs better in all BES impact indicators as well as in agricultural land occupation, marine eutrophication and terrestrial acidification. A parallel water footprint study also clearly showed a much lower water demand and impacts on water scarcity from fossil-based ethanol (Flury et al. 2012). In terms of the novel BES impact categories considered in this study, they allowed to clearly identifying fossil-based ethanol as the preferred alternative, and this is linked to its lower land occupation. On the other hand, when comparing bio-based ethanol production routes, the choice of biomes was not straightforward. This is an area that requires further guidance for practitioners.

This latter conclusion also points to the general issue of trading climate change for land use impacts when transitioning to a bio-based economy. This transition may be unavoidable in the face of climate change and fossil resource depletion, but adequate consideration of impacts on BES will be required in order to minimise detrimental trade-offs.

The biomass feedstock showing the best environmental performance in most indicators assessed was sugar beet, and this is clearly linked to the high yields of this crop. With regard to ethanol from sugarcane grown in the two assessed regions of Brazil, differences were found to be small in all impact indicators. However, water consumption was found to be three times higher in the North-East region when compared to the Centre-South region by Flury et al. (2012).

In general, we can conclude that environmental impacts from bio-based ethanol are highly dependent on the characteristics of the production chain considered, as well as on modelling and scenario choices, such as the choice of allocation factors, or the need to dry the product after harvest. However, key factors found in this study to describe the environmental impacts of bio-based products are the net product yield per hectare and year (combination of agricultural yield plus yield in the processing stage) and especially modelling of emissions caused by LUC. Given the increasing importance of bio-based products in the global economy, we call the LCA community to initiate a debate to harmonise the modelling of LUC emissions.

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