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LIFE CYCLE ASSESSMENT: A TOOL FOR INNOVATION IN LATIN AMERICA

Environmental life cycle assessment of biodiesel produced with palm oil from Colombia

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Abstract

Purpose Palm biodiesel life cycle studies have been mainly performed for Asia and focused on greenhouse gas (GHG) intensity. The purpose of this article is to present an environmental life cycle assessment (LCA) of biodiesel produced in Portugal from palm oil (PO) imported from Colombia, addressing the direct effects of land-use change (LUC), different fertilization schemes, and biogas management options at the extraction mill.

Methods An LC inventory and model of PO biodiesel was implemented based on data collected in five Portuguese biodiesel plants and in a palm plantation and extraction mill in the Orinoquía Region of Colombia. The emissions due to carbon stock changes associated with LUC were calculated based on the Colombian oil palm area expansion from 1990 to 2010 and on historical data of vegetation cleared for planting new palm trees. Five impact categories were assessed based on ReCiPe and CML-IA methods: GHG intensity, freshwater and marine eutrophication, photochemical oxidant formation, terrestrial acidification. A sensitivity analysis of alternative allocation approaches was performed.

Results and discussion Palm plantation was the LC phase which contributed the most to eutrophication and acidification impacts, whereas transportation and oil extraction contributed the most to photochemical oxidation. An increase in carbon stock due to LUC associated with the expansion of Colombian oil palm was calculated (palm is a perennial crop with higher carbon stock than most previous land-uses). The choice of the fertilization scheme that leads to the lowest environmental impacts is contradictory among various categories. The use of calcium ammonium nitrate (followed by ammonium sulfate) leads to the lowest acidification and eutrophication impacts. The highest GHG intensity was calculated for calcium ammonium nitrate, while the lowest was for ammonium sulfate and poultry manure. Biogas captured and flared at the oil extraction mill instead of being released into the atmosphere had the lowest impacts in all categories (GHG intensity reduced by more than 60 % when biogas is flared instead of released).

Conclusions Recommendation on the selection of the fertilization scheme depends on the environmental priority. ReCiPe and CML showed contradictory results for eutrophication and photochemical oxidation; however, uncertainty may impair strong recommendations. GHG intensity and photochemical oxidation impacts can be significantly reduced if biogas is flared instead of being released. However, more efficient biogas management should be implemented in order to reduce the impacts further.

Keywords Allocation · Biogas · CML · Fertilization · Land-use change (LUC) · Palm oil biodiesel · ReCiPe

1 Introduction

Palm oil (PO) is a major feedstock accounting for 34 % of the world vegetable oil production (OECD-FAO 2013). The significant increase of PO production, mainly due to its use as food and feedstock in the production of biodiesel, has been a focus of discussion and controversy due to the potentially high environmental impacts associated with land-use change

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(LUC) (Reijnders and Huijbregts 2008; Reinhard and Zah 2009; Castanheira et al. 2014). The environmental impacts of PO biodiesel also depend on the land-use practices, palm oil mill effluent (POME) treatment, biogas management options, and residue disposal practices (Choo et al. 2011; Hansen et al. 2012; Harsono et al. 2012; Lam et al. 2009; Patthanaissaranukool et al. 2013; Achten et al. 2010; Lam and Lee 2011; Stichnothe and Schuchardt 2010).

The life cycle studies that accounted for carbon emissions from LUC (e.g., Reijnders and Huijbregts 2008; Harsono et al. 2012; Hassan et al. 2011; Siangjaeo et al. 2011; Yee et al. 2009; Wicke et al. 2008; Schmidt 2010; Rodrigues et al. 2014; Souza et al. 2010, 2012) showed that it has an important influence on the greenhouse gas (GHG) intensity of PO biodiesel; however, a wide range of results was reported since the estimation of the impacts of oil palm area expansion has high uncertainty associated (Lechon et al. 2011; Castanheira et al. 2014). The calculation of nitrogen (nitrous oxide N_2O, nitrates NO_3^-, ammonia NH_3, nitrogen oxides NO_x), and phosphorus field emissions from palm plantation is also a critical aspect of a life cycle assessment (LCA) of PO biodiesel, since it influences the results of several environmental impacts, such as eutrophication, acidification, and GHG intensity (Choo et al. 2011; Harsono et al. 2012; Souza et al. 2010, Achten et al. 2010; Reijnders and Huijbregts 2011).

There are substantial disagreements in current LCA studies due to the use of different multifunctionality approaches (Castanheira et al. 2015, 2014; Manik and Halog 2012; Malça and Freire 2011, 2010; van der Voet et al. 2010). There are several possible multifunctionality procedures to deal with the production of co-products in the PO biodiesel chain, and a sensitivity analysis of alternative multifunctionality procedures should be conducted to evaluate the influence on the results for the various impact categories. However, in the majority of the LCA studies for PO biodiesel, only a single approach was adopted, while only few studies performed a sensitivity analysis for alternative approaches (Reinhard and Zah 2009; Castanheira et al. 2015, 2014; Papong et al. 2010; Schmidt 2010).

Several life cycle studies of PO have been published in article journals; however, the majority have focused on GHG emissions and energy requirements (e.g., Angarita and Lora 2009; Castanheira et al. 2014; Kaewmai et al. 2012; Choo et al. 2011; Papong et al. 2010; Hassan et al. 2011; Patthanaissaranukool et al. 2013; Hansen et al. 2012; Harsono et al. 2012; Lam et al. 2009; Pleanjai and Gheewala 2009; Thamsiriroj and Murphy 2009; Souza et al. 2010; Siangjaeo et al. 2011; Yee et al. 2009; Wicke et al. 2008; Queiroz et al. 2012; Rodrigues et al. 2014) and only a few LCAs addressed a wider set of environmental impacts (e.g. Achten et al. 2010; Stichnothe and Schuchardt 2011; Schmidt 2010; Silalertruksa and Gheewala 2012; Reinhard and Zah 2009). In addition, most of the mentioned life cycle studies were performed for PO produced in South-East Asia and Brazil and no LCA articles (with a set environmental impacts) were published for Colombia (the first producer of PO in Latin America and the fourth largest producer worldwide). This article builds on Castanheira et al. (2014), a life-cycle GHG assessment of LUC scenarios, fertilization schemes and biogas management options, and Castanheira et al. (2011), a preliminary LCA of PO in Colombia presented in a conference.

The main goal of this article is to present an environmental LCA of biodiesel produced in Portugal based on PO imported from Colombia, addressing four fertilization schemes and two biogas management options at the oil extraction mill. A comprehensive assessment of carbon stock changes due to LUC was performed based on historical data of Colombian palm area expansion. The ReCiPe 1.10 (Goedkoop et al. 2012) and CML-IA 3.01 (Guinée et al. 2002) methods were adopted to calculate various environmental impact categories and to determine the extent to which the results are influenced by the method applied. Different LCIA methods can lead to different results (Schmidt 2007), which jeopardizes the consistency across these methods and the comparison between studies (Cavalett et al. 2013, Dreyer et al. 2003). The influence of different allocation approaches (mass, energy, and price based allocation) is assessed for the various impact categories. This article is organized in four sections, including this introduction. Section 2 briefly describes the life cycle model and inventory. Section 3 presents and discusses the results, whereas section 4 draws the conclusions together.

2 Life cycle model and inventory

2.1 Goal and scope

A life cycle (LC) model and inventory of PO biodiesel was implemented based on data collected in five Portuguese biodiesel plants and in a representative palm plantation and oil extraction mill in Colombia (Castanheira and Freire 2011; Castanheira et al. 2014). The farm is located in the Orinoquía Region and has 14000 ha with an average productivity similar to the national average (Fedepalma 2009); however, other plantations in Colombia may have different practices, which were not addressed in this article. In 2014, Colombia was the fourth largest producer of palm oil worldwide, and it is expected that Colombia will become an exporter of biodiesel in the medium term (Pinzon 2012).

A flowchart of PO biodiesel production is presented in Fig. 1, in which the main system inputs, products, and yields are also shown. The functional unit adopted was 1 MJ of biodiesel energy content (measured in terms of the lower heating value, LHV, 37 MJ kg^{-1}).

The system is multifunctional, with palm kernel oil (PKO), palm kernel meal (PKM), and glycerin being also produced

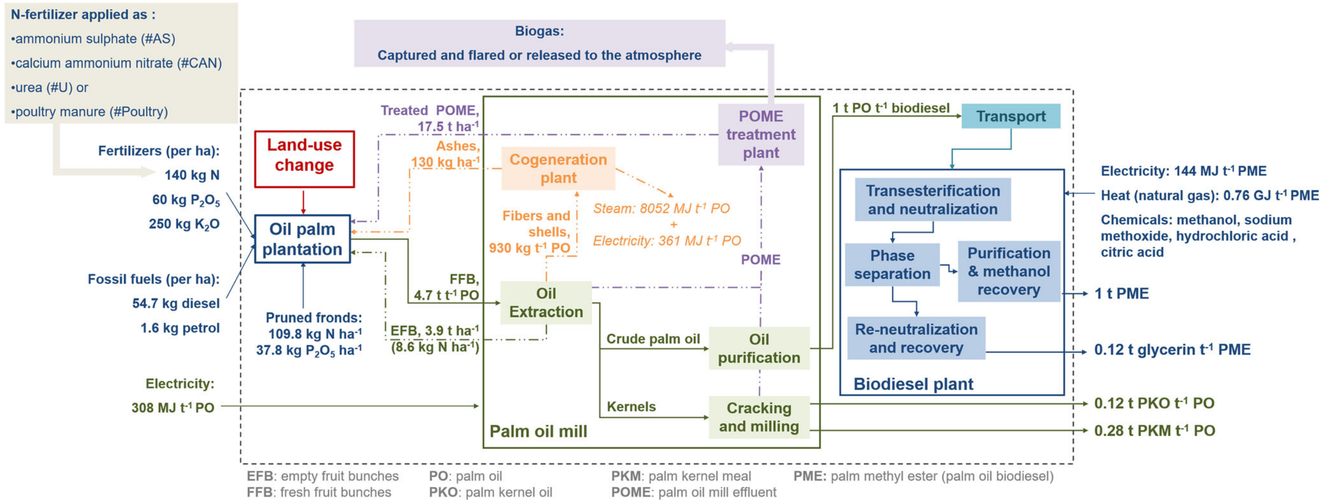

Fig. 1 Palm oil biodiesel production: main inputs, products and yields

(Fig. 1). Three allocation procedures were adopted based on physical properties (mass and energy content) and price of products. Table 1 presents the physical properties and prices of products, as well as the allocation factors. Energy allocation factors were calculated based on the lower heating value (LHV) of products, and price allocation factors were obtained based on the world average annual prices (US$) of oil and meal (2009–2013 period) (FAO 2013; World Bank 2013). The average annual price of biodiesel (2009–2013 period) was based on the price paid to biodiesel producers, according to the Portuguese regulation. The price of glycerin was based on market information provided by Portuguese biodiesel companies. To account for price variability, two scenarios were implemented based on the ratio of oil and meal prices; however, it was concluded that using another price allocation procedure will not influence the results (Castanheira et al. 2014).

2.2 Land-use change emissions

Information on LUC in Colombia as a result of oil palm expansion is sparse (Henson et al. 2012). The emissions due to carbon stock changes (ΔCS) associated with LUC were calculated based on the Colombian oil palm area expansion from 1990 to 2010 and on historical data of vegetation cleared for planting new oil palm. Colombian oil palm area expanded by 84 % from 1990 to 2010 (FAO 2013), mainly from shrubland (50.7 % of the total LUC area), savanna/grassland (41.5 %), cropland (6.8 %), and forest (1 %) (Fedepalma 2009). This is in agreement with other sources, including Romero-Ruiz et al. (2012), Rincón (2009) and Cenipalma (2010). Romero-Ruiz et al. (2012) identified oil palm cultivation as one of the main drivers for the alteration of savannas in the Orinoquia region (1987 to 2007); Rincón (2009) reported that the majority of land converted to palm in this region (1972 to 2009) was either pasture and savanna, herbaceous vegetation, or annual crops, while land with high biomass (such as forests) almost not being used. Cenipalma (2010) showed that most LUC from other uses to oil palm has involved pastures and other crops.

The ΔCS were calculated based on the difference between the average carbon stock associated with previous land uses and the carbon stock of oil palm plantation, following IPCC Tier 1 methodology (IPCC 2006), the European Directive 2009/28/EC, and the guidelines for the calculation of land carbon stocks (European Commission 2009, 2010b). Figure 2 presents the ΔCS due to palm area expansion in Colombia from 1990 to 2010.

Indirect land-use change (ILUC) was left out of the scope of this LCA since the aim was to calculate local LUC based on specific carbon stocks in Colombia, and there is no consensus on how to account for ILUC (Schmidt et al. 2015; European Commission 2010a). Several methods have been developed to address ILUC (Audsley et al. 2009; Cederberg et al. 2011; Schmidt et al. 2015) but significant discrepancies on the results were obtained among different approaches (Vazquez-Rowe et al. 2013). Furthermore, the ILUC methods are based on the assumption that markets are global and for this reason the differentiation between direct and indirect LUC is complex (Munoz et al. 2014; Finkbeiner 2013).

2.3 Palm plantation, oil extraction, and transport

The palm requirements for nutrients were met by the application of fertilizers and residues from the oil mill (pruned fronds and empty fruit bunches). To assess the influence of applying different types of N-fertilizers on the results, four N-fertilization schemes were considered: ammonium sulfate (#AS), calcium ammonium nitrate (#CAN), urea (#U), and poultry manure (#Poultry). Ammonium sulfate and urea are the preferred nitrogen source for palm (von Uexküll and Fairhurst 1991), whereas urea, AS, and CAN are the main N-fertilizers consumed in Colombia (IFA 2013). Poultry

Table 1 Multifunctional palm biodiesel chain: allocation factors

Co-products	Allocation approach								
	Mass	Energy		Market price					
	Factor (%)	LHV (MJ kg^{-1})	Factor (%)	Average price (US\$ t^{-1}, € t^{-1})	Factor (%)	Max ratio (US\$ t^{-1})	Factor (%)	Min ratio (US\$ t^{-1})	Factor (%)
Palm oil	72	36.5	81	856	83	644	85	761	83
Palm kernel oil	8	39.0	10	1104	12	700	11	876	11
Palm kernel meal	20	15.1	9	170	5	102	4	187	6
Biodiesel	89	37.0	95	1078	99	–	–	–	–
Glycerin	11	15.2	5	100	1	–	–	–	–

manure was considered to compare the impacts of applying an organic fertilizer (with a lower availability of mineral N) and a mineral fertilizer.

We considered that to obtain an average annual yield of 19.5 tons of fresh fruit bunches (FFB) per hectare, the same quantity of nutrients (N, P and K) was applied in the different fertilization schemes, corresponding to different quantities of fertilizers, since the nutrient concentrations vary. Regarding N balance, an application of 140 kg N ha^{-1} requires 400 kg ha^{-1} of ammonium nitrate (N concentration = 35 %), 528 kg ha^{-1} of calcium ammonium nitrate (27 %), 300 kg ha^{-1} of urea (46 %), and 3000 kg ha^{-1} of poultry manure (5 %). In the #AS, #CAN, and #U fertilization schemes, the same quantities of single superphosphate (as P_2O_5) and potassium chloride (as K_2O) were applied as mineral fertilizers. In the #Poultry scheme, palm phosphorus (P) needs were fulfilled by manure, while potassium (K) needs were fulfilled by the poultry manure together with the application of potassium chloride (174 kg K_2O ha^{-1}).

Table 2 presents the field emissions from fertilizers and residues application for the four fertilization schemes. The IPCC tier 1 methodology (IPCC 2006) was adopted to calculate direct and indirect N_2O emissions. Indirect N_2O emissions were calculated considering the nitrate (NO_3^-), ammonia (NH_3), and nitrogen oxides (NO_x) emissions. The NO_3^- emissions were calculated based on Faist Emmenegger et al. (2009), NH_3 emissions were estimated based on the rate of N-volatilization for the different N-fertilizer types (Erisman et al. 2009; Asman 1992), and NO_x emissions were calculated based on the emission factors for each group of fertilizer (FAO and IFA 2001). The calculation of phosphate (PO_4) and phosphorus (P) emissions was based on the models provided in Prasuhn (2006). Regarding the NO_3^- and P emissions, it was considered an annual precipitation of 2500 mm $year^{-1}$ and a

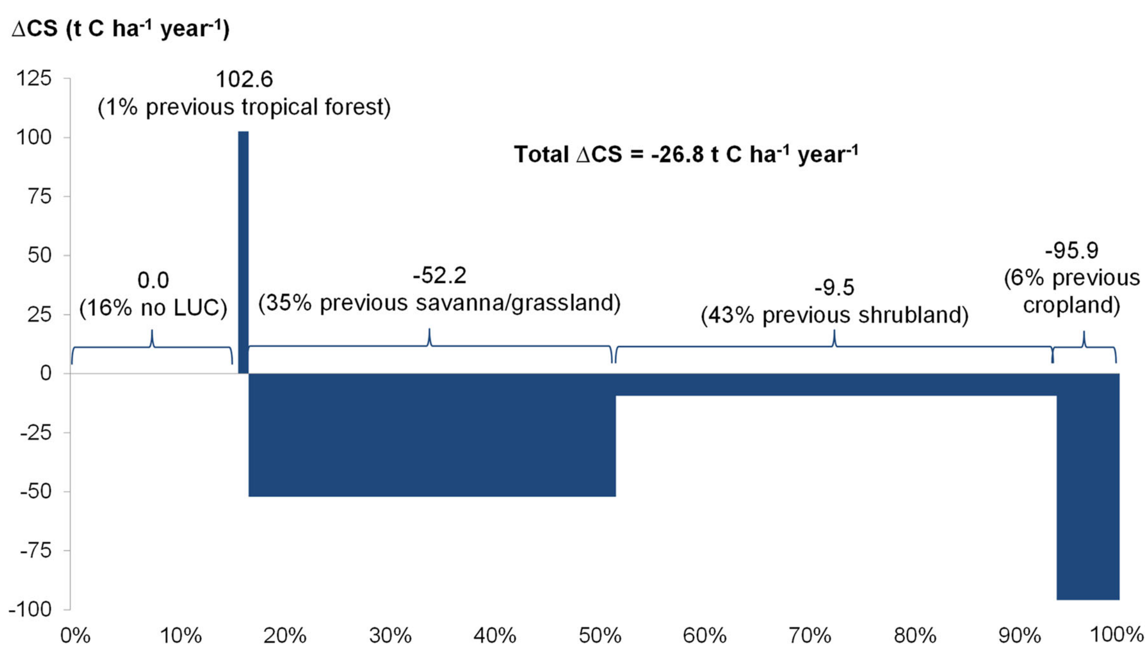

Fig. 2 Carbon stock change (ΔCS) associated with oil palm area expansion in Colombia from 1990 to 2010

Table 2 Field emissions from oil palm plantation—four fertilization schemes

		Fertilization scheme[a]			
		#AS	#CAN	#U	#Poultry
Air emissions	*Ammonia (kg NH_3 ha^{-1})*	13.60	3.40	25.50	42.50
	Carbon dioxide (kg CO_2 ha^{-1})	–	–	223.19	–
	Nitrous oxide (kg N_2O ha^{-1})	5.60	5.47	5.75	6.03
	Nitrogen oxides (kg NO_x ha^{-1})	1.80	1.80	1.80	1.20
Water emissions	*Phosphorus (kg P ha^{-1})*	1.01	1.01	1.01	1.01
	Phosphate (kg PO_4 ha^{-1})	0.91	0.91	0.91	1.15
	Nitrate (kg NO_3^- ha^{-1})	235.73	235.73	235.73	235.73

#AS ammonium sulfate, *#CAN* calcium ammonium nitrate, *#U* urea, *#Poultry* poultry manure

[a] Fertilization schemes

clay content in the soil of 54 % (USDA 1999). It was also considered a nitrogen uptake of 6 kg N per ton of FFB harvested (Corley and Tinker 2003). The CO_2 fixed in the urea production process that is released when urea is applied as fertilizer was also calculated (IPCC 2006).

Direct N_2O emission factor from fertilizer application from IPCC (2006) is largely based on Bouwman et al. (2002a, b) that found significant differences in emission factors depending on fertilizer type. If direct N_2O emission factors specific for the fertilizer type (based on Bouwman et al. 2002a, b) were used in our calculations, the direct N_2O emissions would be lower for #CAN (−16 %), #Poultry (−11 %), and #AS (−1 %) but slightly higher for #U (+4 %) relatively to emissions calculated based on IPCC tier 1 (2006).

PO extraction emissions arise from POME treatment and from the production of energy. POME (4.2 kg kg^{-1} PO) was treated in anaerobic and stabilization lagoons. Biogas produced from POME treatment (22 m^3 t^{-1} POME) is captured and flared; however, before the year 2005, biogas was released into the atmosphere (nowadays also occurring in some other mills). Thus, both situations were assessed. Methane (CH_4) emissions from POME treatment were calculated considering: (i) a chemical oxygen demand (COD) of untreated POME of 60 g L^{-1}, (ii) a COD removal efficiency of 97 %, (iii) a flare efficiency of 90 % (i.e., 10 % of CH_4 emissions in biogas flared), and (iv) a CH_4 emission rate of 0.22 L CH_4 g^{-1} COD removed. The variability of the CH_4 emission rate (from 0.15 to 0.42 L CH_4 g^{-1} COD removed, Lam and Lee 2011) in the results was also assessed. Hydrogen sulfide, N_2O, and ammonia emissions from biogas released into the atmosphere, as well as carbon monoxide, sulfur dioxide, nitrogen oxides, and particulates emissions from biogas captured and flared were calculated based on Schmidt (2007).

Fibers and shells (14 and 6 % of FFB processed) were used as a fuel in a cogeneration plant to produce electricity and steam. Total energy use at the extraction mill was 1875 MJ t^{-1} FFB processed: steam (1731 MJ t^{-1} FFB) was totally produced onsite from the combustion of fibers and shells, whereas the electricity consumed (144 MJ t^{-1} FFB) was supplied by the cogeneration plant (54 %) and the grid (46 %).

The emissions from fertilizer production, fossil fuel production, and combustion from agricultural operations, as well as the emissions from fibers and shells combustion at the cogeneration plant (some adjustments were implemented according to the dry matter content and low heating value of fibers and shells) were adopted from Bauer (2007); Spielmann et al. (2007) and Nemecek and Kägi (2007). The emissions of electricity from grid were calculated based on the Colombian electricity mix (IEA 2009).

The palm oil mill is surrounded by the palm plantation and for this reason it was considered that there is no emissions associated with the transport of fresh fruit bunches from plantation to the mill. It was assumed that palm oil is transported from the mill to the port of Santa Marta by lorry (1300 km) and by transoceanic freighter to the port of Lisbon, in Portugal (7077 km). Regarding transport of palm oil from port of Lisbon to biodiesel production plant, a distance of 100 km by lorry was adopted. Emissions have been calculated based on factors of Spielmann et al. (2007).

2.4 Biodiesel production

Biodiesel production consists on the transesterification reaction of the triglyceride of the fatty acid in the oil with methanol, catalyzed by a base or acid to produce methyl ester (biodiesel) as main product and glycerin as co-product. The life cycle inventory of biodiesel production was implemented based on a data collected in five Portuguese plants for 2009 and 2010 (Castanheira and Freire 2011). Emission factors for chemicals and process energy were adopted from Jungbluth et al. (2007), Althaus et al. (2007), Sutter (2007), Faist Emmenegger et al. (2007) and Jungbluth (2007). The emissions of electricity from grid were calculated based on the Portuguese electricity mix (Garcia et al. 2014).

3 Results and discussion

3.1 Life cycle impact assessment

This section presents the life cycle impact assessment (LCIA) for PO biodiesel, calculated with two LCIA methods (ReCiPe (version 1.10) and CML-IA (version 3.01)) to determine the extent to which the results are influenced by the method applied and focusing on the contribution of each LC phase for four environmental impact categories: GHG intensity, freshwater and marine eutrophication/eutrophication, photochemical oxidant formation/photochemical oxidation, terrestrial acidification/acidification. The impact categories were selected to address a comprehensive set of environmental issues related to cultivation and biofuels, following state-of-art LCA on these topics. Despite land use and land-use change being pointed out as the main drivers of biodiversity loss and degradation (Frischknecht et al. 2016), these were not assessed since there is no clear consensus on how to quantify land-use impacts on biodiversity. The ReCiPe and CML methods were adopted because they are widely used and accepted as reliable among LCA practitioners.

The results presented in this section were calculated (adopting energy allocation approach) for the different fertilization schemes (ammonium sulfate #AS, calcium ammonium nitrate #CAN, urea #U, and poultry manure #Poultry) and biogas management options (biogas is captured and flared or is released into the atmosphere). The software Simapro 7.1 (www.pre.nl) was used to compute the LCA.

3.1.1 Greenhouse gas intensity

Figure 3 shows the GHG intensity of PO biodiesel. ReCiPe and CML results were not compared since the same characterization model (IPCC 2007) was adopted in both methods. GHG intensity of PO biodiesel ranged from 4 g CO_2eq MJ^{-1} (#AS and biogas flared) to 25 g CO_2eq MJ^{-1} (#CAN and biogas released), showing the significant influence of the fertilization scheme and biogas management option. A huge variation in the GHG intensity of PO biodiesel can be observed for the two biogas management options: for biogas released, the GHG intensity was three to five times higher than for biogas flared. The GHG intensity of PO extraction for biogas flared (2.3 g CO_2eq MJ^{-1}) was about eight times lower than for biogas released into the atmosphere (19.0 g CO_2eq MJ^{-1}). For both biogas management options, methane emissions from POME treatment are those that contributed most to GHG intensity of oil extraction (more than 80 %). GHG intensity of PO biodiesel can be reduced 65–80 % for biogas flared instead of being released. The GHG intensity ranges obtained for the variability of the CH_4 emission rate are presented in the chart as error (range) bars. A significant variation in the total GHG intensity can be observed, particularly for biogas released into the atmosphere.

The results greatly depend on the LUC emissions, which represent 33 to 46 % of the GHG intensity of PO biodiesel. An increase in the carbon stock due to LUC associated with the expansion of Colombian oil palm area was calculated (−24 g CO_2eq MJ^{-1}). Palm is a perennial crop with a higher carbon stock (mainly in the vegetation, C_{veg}) than in most previous land-uses (mainly shrubland and savanna). These findings are consistent with the previous research from the authors (Castanheira et al. 2014) that showed that the lowest GHG intensity of palm oil was obtained for conversion of savannas, shrublands, and croplands.

The GHG intensity of palm plantation varies from 13 to 17 g CO_2eq MJ^{-1}. Field N_2O emissions from fertilization

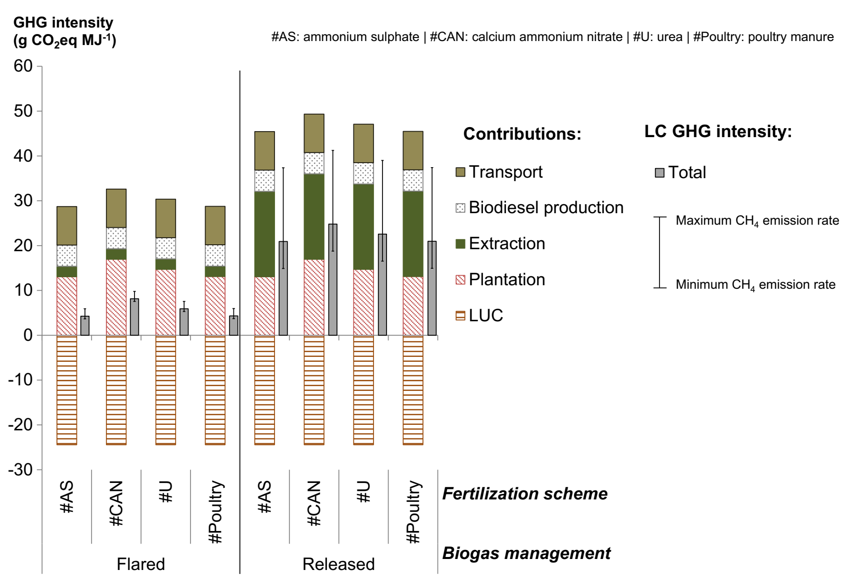

Fig. 3 Greenhouse gas intensity: alternative fertilization schemes and biogas management options

contributed the most to the GHG intensity of plantation but the variation on the GHG intensity of the different fertilization schemes is mainly caused by the emissions from fertilizer production: the GHG intensity of calcium ammonium nitrate production is about 6 g CO_2eq MJ^{-1} whereas the GHG intensity of ammonium sulfate or poultry manure production is less than 2 g CO_2eq MJ^{-1} (considering the application of 140 kg N ha^{-1}). A reduction of about 4 g CO_2eq MJ^{-1} on the GHG intensity of PO biodiesel can be achieved by replacing the nitrogen fertilizer. The GHG intensity of palm plantation addressing direct N_2O emissions from fertilizer application based on Bouwman et al. (2002a, b) instead of IPCC (2006) would be slightly higher for #U (+2 %) but lower for #CAN and #poultry (both around −6 %). No differences were found for #AS.

3.1.2 Freshwater and marine eutrophication (ReCiPe) versus eutrophication (CML)

Figure 4 presents freshwater and marine eutrophication (FE and ME) versus eutrophication impacts of PO biodiesel. The majority (more than 80 %) of FE, ME, and eutrophication impacts were caused by the emissions from palm plantation in all fertilization schemes. No variation on results occurs among biogas management options.

Comparing the fertilization schemes using ReCiPe method, contradictory results were obtained for FE and ME impacts: #CAN presented the highest FE impact (10.3 mg Peq MJ^{-1}) and the lowest ME (0.28 g Neq MJ^{-1}), whereas #Poultry was the scheme with the highest ME (0.30 g Neq MJ^{-1}) and the lowest FE (9.5 mg Peq MJ^{-1}). Regarding FE impact, #CAN (and remaining schemes of mineral fertilization) had the highest impact due the phosphate emissions from production and application of single superphosphate. Even though the phosphate emissions from poultry manure application were higher than those from the application of single superphosphate, mineral P-fertilizer was not applied in #Poultry scheme and therefore there were no emissions of its production. Concerning ME, nitrate (NO_3^-) emissions were the most important. Despite ammonia emissions slightly contribute to ME, #Poultry scheme had the highest ME impact due to higher ammonia emissions from poultry application compared to the other fertilization schemes.

Eutrophication impact calculated with CML method varies from 0.19 g PO_4^{3-}eq. MJ^{-1}(#CAN) to 0.25 g PO_4^{3-}eq. MJ^{-1} (#Poultry). Nitrate emissions contributed the most to this impact; however, the difference on results among the fertilization schemes was mainly related to the ammonia emissions from fertilization, which depends on the type of fertilizer: a rate of N-volatilization (as NH_3) of 25 % for poultry manure and of 2 % for calcium ammonium nitrate were adopted from Erisman et al. (2009) and Asman (1992).

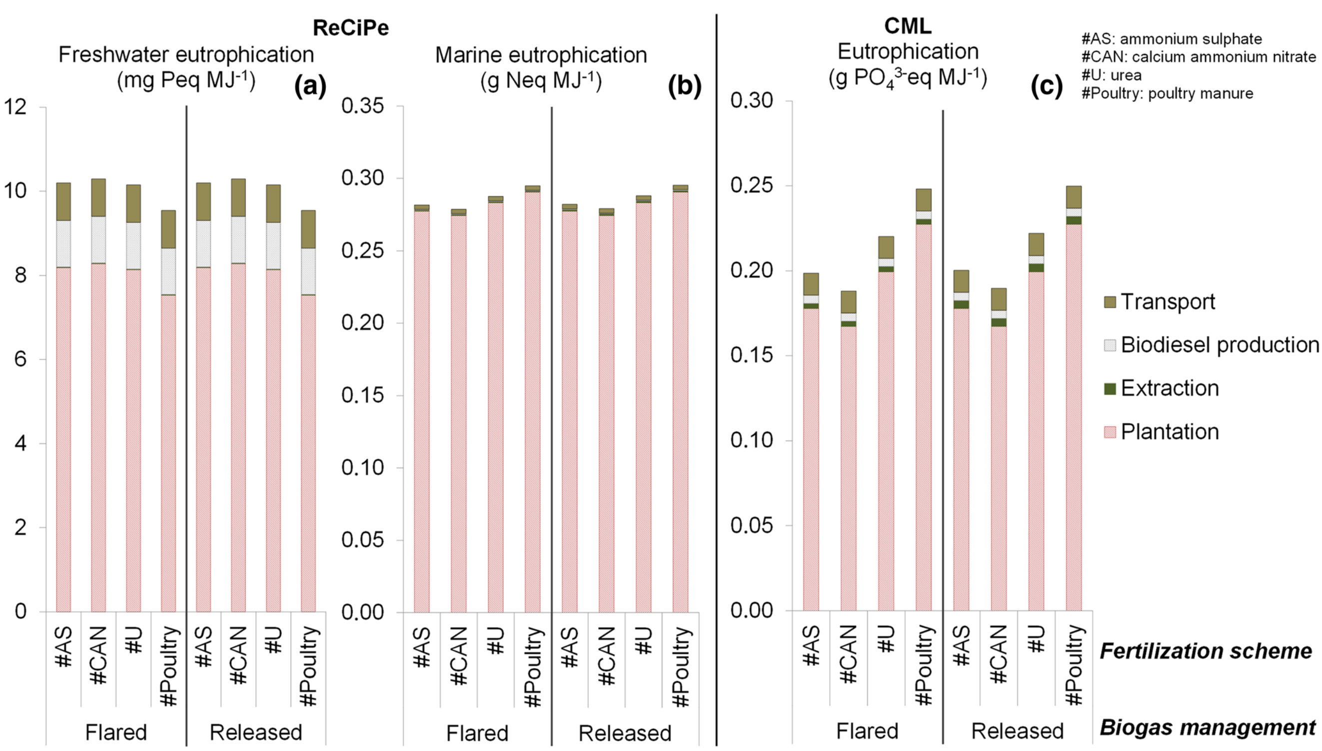

Fig. 4 Freshwater **a** and marine eutrophication versus eutrophication **c**: alternative fertilization schemes and biogas management options

3.1.3 Photochemical oxidant formation (ReCiPe) versus photochemical oxidation (CML)

The photochemical oxidant impacts (ReCiPe and CML) of PO biodiesel are presented in Fig. 5. CML results vary from 4.6 g C_2H_4eq MJ^{-1} (biogas flared, #Poultry) to 9.6 (biogas released, #CAN), whereas for ReCiPe, there is no significant differences for the biogas management options. Although the main substances contributing to photochemical oxidation are the same in both methods (SO_2, NO_x and biogenic CH_4), the characterization factors are different in ReCiPe and CML (e.g., in CML, biogenic CH_4 has a much higher characterization factor relatively to SO_2 and NO_x), which leads to different results. In ReCiPe, nitrogen oxides emissions contributed the most to photochemical oxidant formation, whereas with CML is sulfur dioxide and biogenic CH_4. Transportation emissions are those that contributed most to ReCiPe photochemical oxidant formation impact (51–56 %). For CML, PO extraction emissions contributed the most to this environmental impact when biogas was released (54–58 %), whereas for biogas flared transportation emissions are those that contributed the most (46–51 %). There is no significant variation in the impacts for the various fertilization schemes, but the life cycle phase which contributed the most to this impact depends on the LCIA method.

The sensitivity analysis performed for methane emissions from POME treatment (presented in the chart as error range bars) shows that photochemical oxidation impact of PO biodiesel varies widely depending on the CH_4 emission rate. This variation is more evident for the scenario in which biogas was released into the atmosphere and when CML method was adopted.

3.1.4 Terrestrial acidification (ReCiPe) versus acidification (CML)

Acidification impact of PO biodiesel ranged from 0.2 to 0.7 g SO_2eq MJ^{-1} (Fig. 6a) for ReCiPe and from 0.2 to 0.5 g SO_2eq MJ^{-1} (Fig. 6b) for CML. There is a huge variation in the results for the different fertilization schemes: the highest impact was obtained for #Poultry scheme and the lowest for #CAN (with both methods). The main reason for #Poultry scheme presents a terrestrial acidification/acidification impact two to three times higher than #CAN is that emissions from palm plantation (mainly NH_3 emissions from fertilization) contributed more than 42–85 % to this impact, and the NH_3 emissions were calculated on the basis of a rate of N-volatilization of 2 % for #CAN and 25 % for #Poultry.

Terrestrial acidification results are 10–40 % higher in ReCiPe than in CML due to a higher ReCiPe characterization factor for NH_3 (more 50 %). Ammonia (NH_3), NO_x, and SO_2 emissions contributed the most to terrestrial acidification/acidification impact. The emissions from transportation (73–75 mg SO_2eq MJ^{-1}) contribute 12 to 44 % to acidification. Terrestrial acidification/acidification impact of oil extraction is about 50 % higher for biogas released than for biogas flared. However, the biogas management option had a low effect in the total acidification impact of palm biodiesel since oil extraction contributes to less than 12 % of the total impact.

3.1.5 Relative comparison of ReCiPe and CML results

Figure 7 presents a relative comparison of ReCiPe and CML impacts (normalized relatively to the scenario with highest impact) for each set of similar categories. Eutrophication and

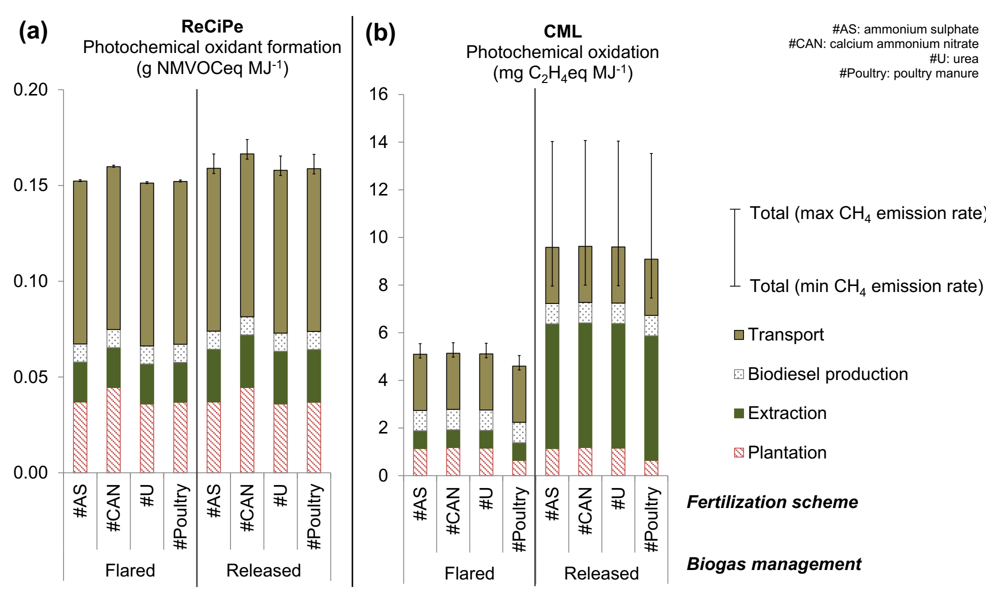

Fig. 5 Photochemical oxidant formation **a** versus photochemical oxidation **b**: alternative fertilization schemes and biogas management options

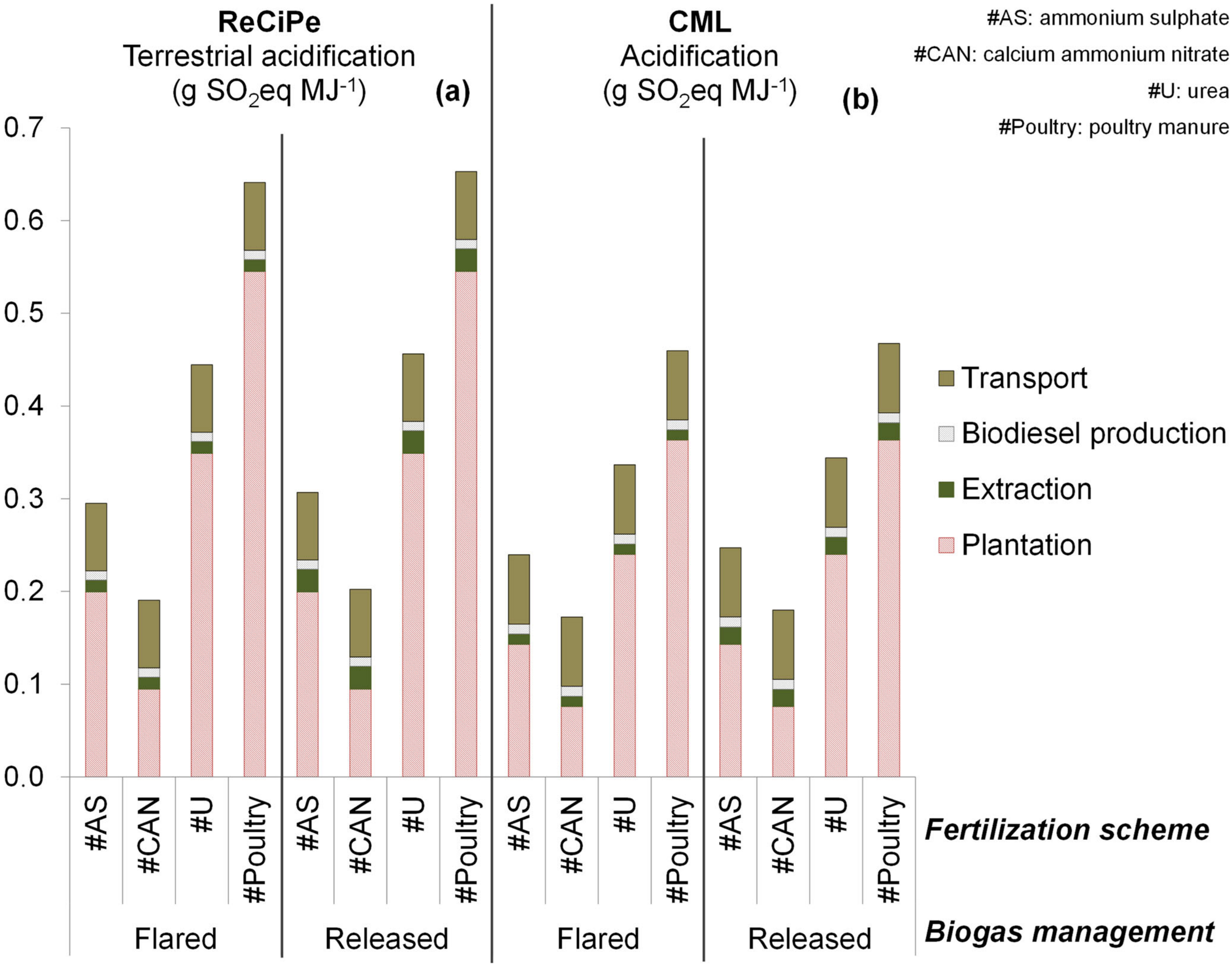

Fig. 6 Terrestrial acidification **a** versus acidification **b**: alternative fertilization schemes and biogas management options

photochemical oxidation calculated with ReCiPe and CML are contradictory: eutrophication calculated with CML varies among the various fertilization schemes, while for ReCiPe, there is no variation; photochemical oxidation with CML is 50 % lower for biogas captured and flared than for biogas released, whereas for ReCiPe, there is no significant difference between the two biogas management options. An analogous ranking of fertilization schemes is observed for marine eutrophication (ReCiPe) and eutrophication (CML) impacts (#CAN is the preferable fertilization scheme), while different ranking was obtained for freshwater eutrophication (the lowest impact was calculated for #Poultry).

The differences in eutrophication and photochemical oxidation can be explained by different impact models in CML and ReCiPe. CML photochemical oxidation model uses a simplified description of the atmospheric transport, whereas ReCiPe employs an atmospheric fate model combined with a dynamic model (Van Zelm et al. 2008). Eutrophication in Recipe is treated as two categories (freshwater and marine eutrophication) using the CARMEN model (Klepper et al. 1995) to calculate the changes in nutrient loads (European conditions) and assuming that aquatic ecosystems are saturated by either nitrogen or phosphorus but only the non-saturated element (the limiting nutrient) will cause eutrophication (N in marine waters, phosphorus in freshwaters) (Goedkoop et al. 2012). The eutrophication model in CML addresses together terrestrial and aquatic systems. Thus, eutrophication calculated with CML and ReCiPe cannot be fully compared. No significant differences were obtained for acidification calculated with ReCiPe and CML, despite the different characterization models (both address acidifying chemicals at the European scale, but ReCiPe only for terrestrial ecosystems).

To sum up, the results indicate that the LCIA method may influence PO biodiesel impacts and that further research is needed to harmonize LCIA methods and provide recommendations, in spite of previous relevant work (EC-JRC 2011).

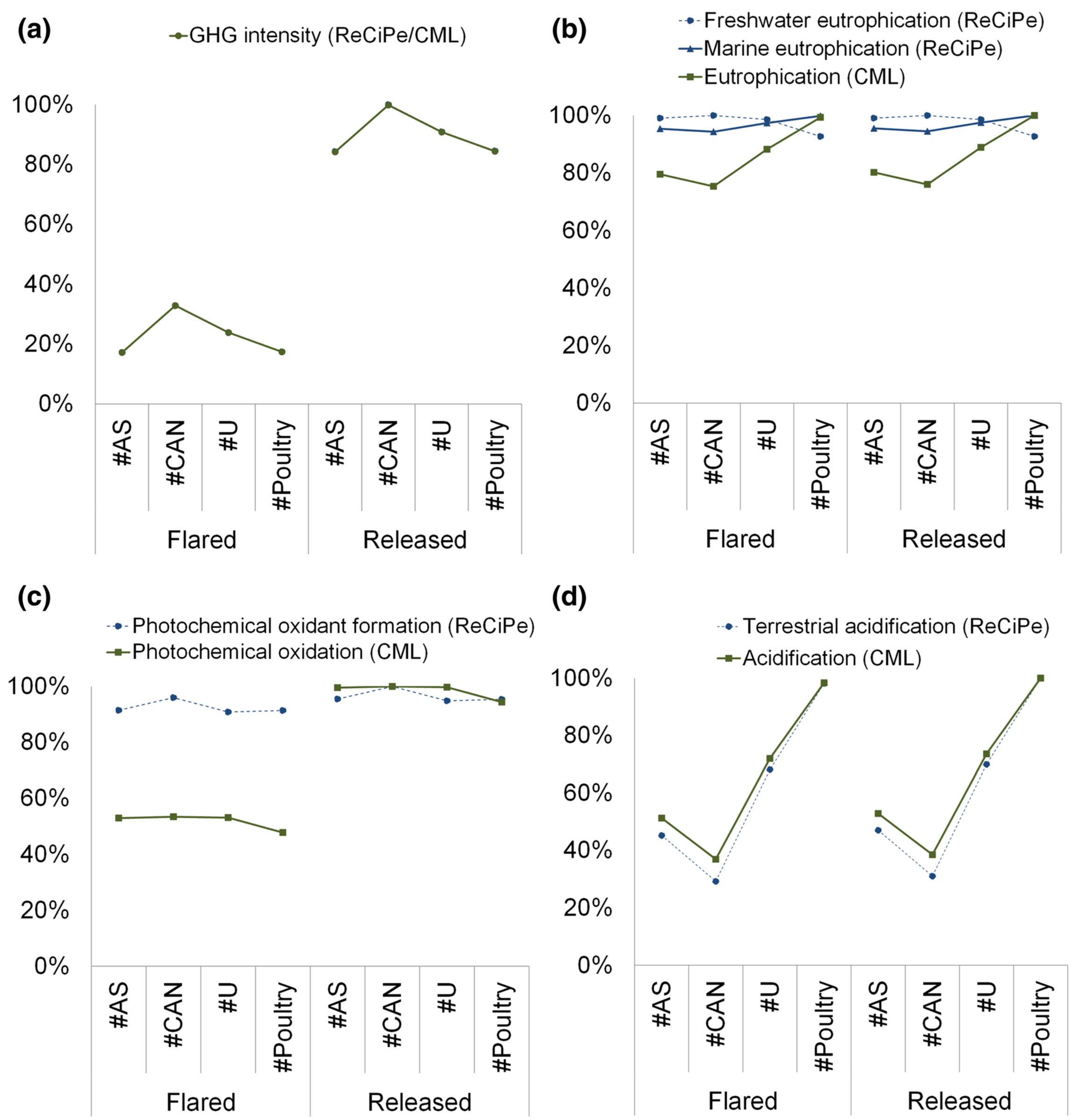

Fig. 7 Relative comparison of ReCiPe and CML results

This is the focus of ongoing work at the UNEP/SETAC Life Cycle Initiative (Jolliet et al. 2014).

3.2 Sensitivity analysis to allocation approaches

The effect of multifunctionality approach on the environmental impacts of PO biodiesel (calculated with ReCiPe 1.10 method) is presented Fig. 8. It can be seen that the allocation approach adopted has a low influence on the results. This is due to the relatively high mass share of palm oil (72 %) compared with the palm kernel meal and oil (20 and 8 %). The environmental impacts calculated with energy and price allocation are, in general, similar and higher than those obtained with mass allocation. The extent of the influence of the allocation approach on the results is different for the various impact categories due to the contribution of each LC phase to the environmental impacts of PO biodiesel: the highest results were calculated with price allocation for all impact categories, except for GHG intensity in which the highest results were calculated with energy allocation.

4 Conclusions

This article presents a life cycle assessment of biodiesel produced in Portugal with palm oil imported from Colombia. A comprehensive evaluation was performed of the implications of LUC, different fertilization schemes, and biogas management options on the environmental impacts. GHG intensity, acidification, eutrophication, and photochemical oxidant

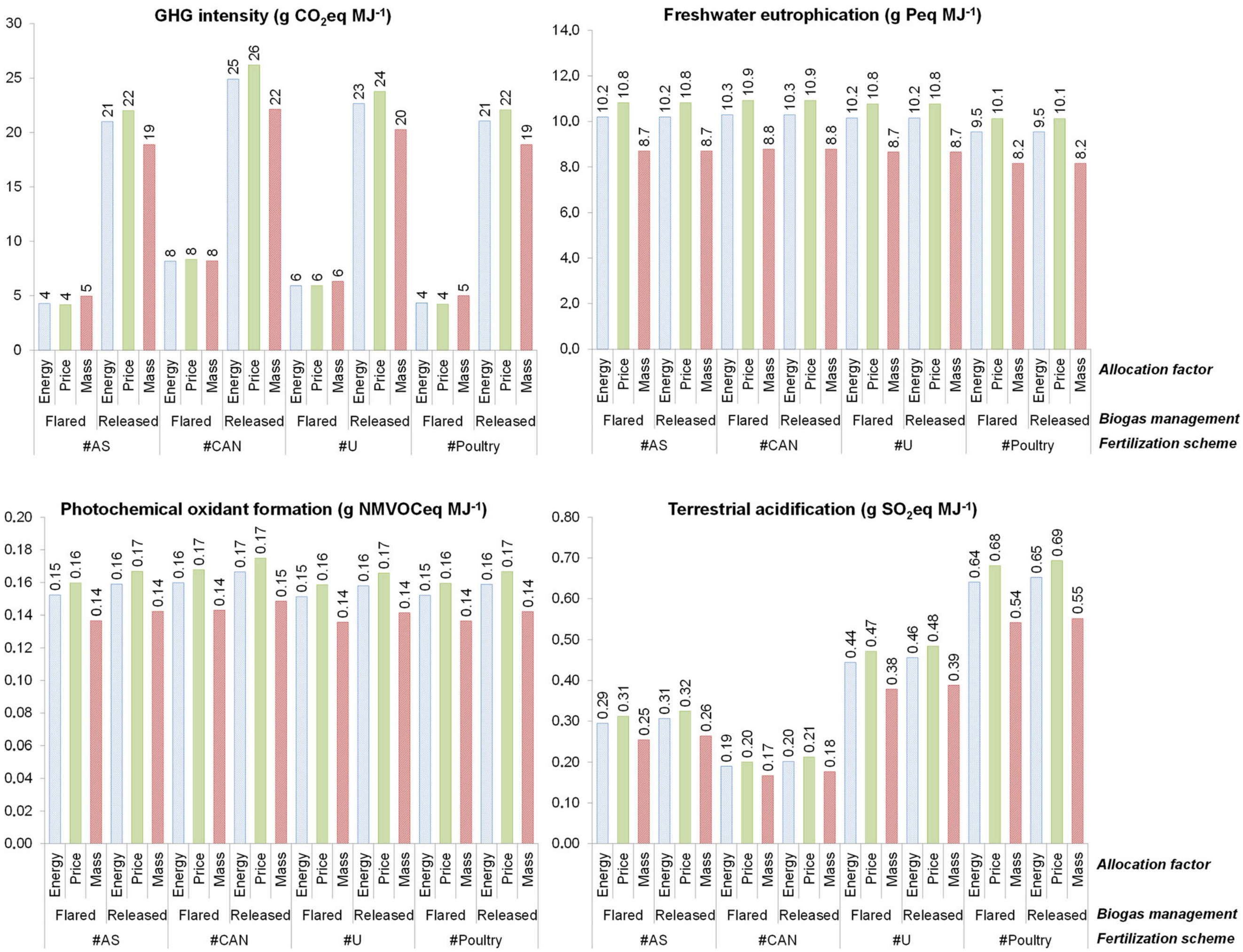

Fig. 8 Effect of allocation approach on the LCIA results: alternative fertilization schemes and biogas management options

formation were calculated based on two LCIA methods (ReCiPe and CML). The GHG intensity of PO biodiesel greatly depends on LUC emissions. We calculated an increase in carbon stock due to LUC associated with the expansion of Colombian oil palm, since palm is a perennial crop with higher carbon stock than most previous land-uses (shrubland, savanna/grassland and cropland). Palm plantation contributed the most to eutrophication and acidification impacts, whereas transportation and oil extraction contributed the most to photochemical oxidation. ILUC was left out of the scope of this LCA. Thus, the GHG intensity of PO biodiesel does not include potential emissions from ILUC, which is a controversial issue with no consensus on how to account for it.

The choice of the fertilization scheme that leads to the lowest environmental impacts of PO biodiesel is contradictory among various categories: on the one hand, the use of calcium ammonium nitrate (followed by ammonium sulfate) is the fertilization scheme that leads to the lowest acidification (both methods) and eutrophication (CML) impacts. On the other hand, the highest GHG intensity was calculated for calcium ammonium nitrate, while the lowest was for the use of ammonium sulfate and poultry manure as fertilizers. Recommendation on the selection of the fertilization scheme depends on the environmental priority. A choice focused on climate change will promote the use of ammonium sulfate or poultry manure, whereas focusing on local and regional impacts of agriculture will support calcium ammonium nitrate or ammonium sulfate. A trade-off choice addressing both priorities could be ammonium sulfate. However, it should be noted that the differences in the results are not very significant, and the uncertainty and variability of results (inherent to the LCA of agricultural products) may impair robust conclusions and recommendations.

Regarding biogas management options, biogas captured and flared at the oil extraction mill instead of being released into the atmosphere had the lowest impacts in all categories, in particular GHG intensity can be reduced by more than 60 % when biogas is flared instead of released. However, more efficient biogas management, namely, recovery for energy generation instead of flaring, should be implemented in order to reduce the impacts further.

The comparison of results calculated with ReCiPe and CML showed contradictory results for photochemical oxidation and eutrophication: photochemical oxidation calculated with CML is 50 % lower for biogas captured and flared than for biogas released, while for ReCiPe, there is no significant difference between the two biogas management options; eutrophication impacts calculated with CML vary among the various fertilization schemes, whereas for ReCiPe, there is no variation. A sensitivity analysis of alternative allocation approaches showed that price and energy allocation leads to similar impacts, slightly higher than those calculated with mass allocation.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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