Applied Energy 114 (2014) 958–967

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Greenhouse gas intensity of palm oil produced in Colombia addressing alternative land use change and fertilization scenarios

Érica Geraldes Castanheira [a], Helmer Acevedo [b], Fausto Freire [a,*]

[a] ADAI-LAETA, Department of Mechanical Engineering, University of Coimbra, Pólo II Campus, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal
[b] Department of Mechanical Engineering, Engineering Faculty, National University of Colombia Campus Bogotá D.C., Carrera 30 # 45-03, Edificio 453, Oficina 418, Bogotá D.C., Colombia

## HIGHLIGHTS

- A comprehensive evaluation of alternative LUC and fertilization schemes.
- The GHG intensity of palm oil greatly depends on the LUC scenario.
- Colombian palm area expansion resulted in negative or low palm oil GHG intensity.
- GHG emissions from plantation vary significantly with $N_2O$ emission parameters.

## ARTICLE INFO

*Article history:*
Received 28 February 2013
Received in revised form 31 August 2013
Accepted 7 September 2013
Available online 1 October 2013

*Keywords:*
Carbon footprint
Carbon stock change
Fertilization
Global warming
Palm oil biodiesel
Vegetable oils

## ABSTRACT

The main goal of this article is to assess the life-cycle greenhouse gas (GHG) intensity of palm oil produced in a specific plantation and mill in Colombia. A comprehensive evaluation of the implications of alternative land use change (LUC) scenarios (forest, shrubland, savanna and cropland conversion) and fertilization schemes (four synthetic and one organic nitrogen-fertilizer) was performed. A sensitivity analysis to field nitrous oxide emission calculation, biogas management options at mill, time horizon considered for global warming and multifunctionality approach were also performed. The results showed that the GHG intensity of palm oil greatly depends on the LUC scenario. Significant differences were observed between the LUC scenarios ($-3.0$ to 5.3 kg $CO_2$eq $kg^{-1}$ palm oil). The highest result is obtained if tropical rainforest is converted and the lowest if palm is planted on previous cropland, savanna and shrubland, in which almost all LUC from Colombian oil palm area expansion occurred between 1990 and 2009. Concerning plantation and oil extraction, it was shown that field nitrous oxide emissions and biogas management options have a high influence on GHG emissions.

## 1. Introduction

The increase in palm oil (PO) production is being stimulated by the growing demand for food (e.g. margarine, ice cream and cooking oil) and numerous other non-food applications (e.g. biodiesel, plasticizers, paint and surface coatings) [1]. In the year 2010, the world's production of PO was more than 43 million tonnes, representing about 30% of the world's total vegetable oil production. The production of PO almost doubled between the years 2000 and 2010 [1]. Malaysia and Indonesia are responsible for 84% of the world's PO production (36.8 million tonnes), whereas Colombia has become the world's fourth largest producer in 2012 and the leading producer in Latin America [2]. Colombian PO production in 1998 was about 490 thousand tonnes, almost doubling to 960 thousand tonnes in 2012 [2]. There was an annual average production growth of 4% (2000–2010 period) mainly due to area expansion, since the annual average yield (about 19 tonnes of oil palm fruits per ha) has not significantly changed in that period [1].

Important environmental concerns have emerged concerning the impacts of oil palm area expansion, in particular concerning carbon stock changes due to land use change (LUC). LUC together with palm plantation and oil extraction can result in important greenhouse gas (GHG) emissions. However, the assessment of GHG intensity of PO is complex and results can vary widely due to several issues, namely: (i) the uncertainty of soil emissions, in particular carbon dioxide ($CO_2$) and nitrous oxide ($N_2O$) emissions from LUC and cultivation [3–7]; (ii) dealing consistently with biogenic carbon balances [5,6]; (iii) the diversity of agricultural and processing practices [8–10]; (iv) dealing with co-products and residues of the PO chain [11–14].

---

* Corresponding author. Tel.: +351 239790739; fax: +351 239790701.
*E-mail address:* fausto.freire@dem.uc.pt (F. Freire).

0306-2619/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.09.010

The life-cycle (LC) GHG intensity of PO-based products was assessed in various publications, particularly for South Asia [3,4,6,8,9,11–33] (no published articles were found for Colombia). However, only some studies accounted for carbon emissions from LUC and a wide range of results was reported. Some examples of the results obtained from studies that accounted for LUC: (i) Malaysia, −51 and 391 g $CO_2$eq $MJ^{-1}$ crude PO (previous degraded grassland and previous Peatland forest) [29]; −85 to 3300 g $CO_2$-eq $MJ^{-1}$ PO biodiesel (degraded grassland–peatland forest) [16]; (ii) Thailand, 1–248 g $CO_2$eq $MJ^{-1}$ PO biodiesel (cassava-forest) [33]; (iii) Indonesia, 53 and 150 g $CO_2$eq $MJ^{-1}$ PO biodiesel [14]; (iv) Malaysia and Indonesia, 2.6–3.45 kg $CO_2$eq $kg^{-1}$ PO [4]; (v) Malaysia and Thailand, 2.8–19.7 kg $CO_2$eq $kg^{-1}$ PO [6]. The differences in the results are mostly related with area of LUC, type of previous land use, soil type and how the effect of the carbon debt caused by LUC was spread out over the PO products during different time periods. The wide range of results shows that drawing general figures for the quantification of direct LUC in GHG intensity is difficult and each case should be addressed autonomously [34].

GHG intensity of PO also varies due to the diversity of farming systems, processing practices, waste water treatment and residue disposal [8,11,12,14,15,17,35]. Recent studies showed that $N_2O$ field emissions can contribute 31–69% for the GHG intensity of palm plantations [14,15,17,21]. Variation in $N_2O$ emission is associated with variability in system definition and modeling choices (cropping system, nitrogen inputs, climate and choice of the reference land-use system), as well as with uncertainty in direct and indirect $N_2O$ emission calculation (particularly emissions originating in the fraction of nitrogen lost via runoff, leaching and volatilization) [36,37]. Regarding GHG intensity of PO extraction, significant reductions can be achieved by applying advanced waste and wastewater treatment practices (biogas capture and use of residues for energy purposes and fertilization) [11]: biogas capture system could reduce the PO GHG intensity by 30% [12] and the use of residues in an optimized manner can reduce 95% of the emissions from PO biodiesel production [11].

The time horizon considered for global warming can also influence the GHG intensity of PO, as the greenhouse gas effect of emitted greenhouse gases depends on the time horizon chosen. Global warming potentials (GWP) in $CO_2$eq of $CH_4$ and $N_2O$ for time horizons of 20, 100 and 500 years vary significantly. Although in practice often a time horizon of 100 years is chosen, a time horizon of 500 years would reduce the importance of $CH_4$ emissions almost three times and $N_2O$ emissions almost by half [37,38]. The multifunctionality approach adopted to deal with PO co-products also influences the GHG intensity and different approaches were adopted in the literature: system boundary expansion [4,17], energy [12] and mass allocation [11,15].

The LC GHG intensity assessment of PO is complex. Previous research as focused in South Asia and PO produced in Latin America has not been addressed comprehensively. The main goal of this article is to present a LC GHG assessment of PO produced in a specific plantation equipped with its own mill in Colombia. A comprehensive evaluation of the implications of 65 scenarios (resulting from a combination of 13 LUC alternatives and 5 fertilization schemes) was performed together with a sensitivity analysis to field $N_2O$ emissions (to address uncertainties in $N_2O$ calculations). The influence of biogas management options at mill, time horizon considered for global warming and multifunctionality approach were also assessed. This article is organized in 4 sections, including this introduction. Section 2 presents the LC model and inventory of PO, including the LUC scenarios, oil palm plantation and oil extraction. Section 3 presents and discusses the main results. Section 4 draws the conclusions together.

## 2. Life cycle inventory and modeling

A LC model for PO addressing LUC, plantation (planting and harvesting) and oil extraction was implemented. A simplified flowchart is presented in Fig. 1, showing that the PO chain is multifunctional, with palm kernel oil (PKO) and meal (PKM) being also produced at the oil extraction mill. The functional unit chosen was 1 kg of PO. In order to evaluate the influence of allocation procedures on the GHG intensity of PO, a sensitivity analysis was performed. Four allocation procedures were adopted based on price (world average for 2007–2011 period) and physical properties (mass, energy and carbon content). Table 1 shows the allocation parameters calculated.

A detailed LC inventory was performed for a specific plantation with 14,000 ha, equipped with its own mill, in the Orinoquía Region of Colombia (based on primary data collected in a joint project between the National University of Colombia and the Center for Industrial Ecology at the University of Coimbra [42,43]). The GHG emissions arise from: (i) conversion of previous land use to PO plantation (LUC); (ii) field application of fertilizers and mill by-products (empty fruit bunches (EFB), treated PO mill effluent, ashes); (iii) fossil fuel used in agricultural operations; (iv) palm oil mill effluent (POME) treatment and (v) production of fertilizers, fuels, electricity (Colombian electricity mix). Detailed LC inventory and calculations to estimate the GHG emissions of the different production steps of PO are described in the next subsections. Some processes were found to be not significant, as shown in other studies [15,29], and were not included: oil palm nursery (until 9 month old) and immature plantation (first 2 years after planting the palms), fuel used for land clearing, emission embedded in infrastructure and machinery. Indirect LUC emissions were not addressed since there is no consensus on how to account for this [44].

The GHG intensity was obtained by multiplying the emissions of $CO_2$, $CH_4$ and $N_2O$ by their corresponding global warming potentials (GWP) for a time horizon of 100 years (GWP100) [38]. A sensitivity analysis was performed for 20 and 500 year time horizons [38]. A GWP factor of zero was adopted for biogenic $CO_2$ emissions since the carbon emitted is equal to the carbon fixed by the fresh fruit bunches (FFB) and oil palm. The net $CO_2$ from clearing and crop sequestration associated with replanting was considered zero, assuming that there are no difference in growth between successive oil palm crops [45]. GWP for biogenic methane was calculated based on the fossil methane GWP for each time horizon and taking into account that 2.75 kg (=(44/12)/(16/12)) of biogenic carbon dioxide was not released per 1 kg of biogenic methane emitted (GWP100 = 25, GWP20 = 72 and GWP500 = 7.6). The LC of PO was modeled using the software Simapro 7.1 (www.pre.nl).

### 2.1. LUC scenarios: carbon stock changes

A comprehensive evaluation of carbon stock changes caused by alternative LUC scenarios was performed, following IPCC Tier 1 methodology [36], the European Directive 2009/28/EC [46] and the guidelines for the calculation of land carbon stocks [47]. The carbon stock changes were calculated based on the difference between the carbon stock associated with Reference (previous) and Actual land use (oil palm plantation). Colombian oil palm area expanded by 84% from 1990 to 2009 [40], mainly from shrubland (51% of the total LUC area), savanna (42%), arable land (7%) and less than 1% from forest [48]. Thirteen reference LUC scenarios were selected based on the mentioned land uses combined with different input and management practices, using data from several sources. Table 2 describes the LUC scenarios and presents the corresponding carbon stock changes ($\Delta CS$). Carbon stocks of Reference ($CS_R$) and Actual land use ($CS_A$) were calculated based on two