LCA of perennial crops: implications of modeling choices through two contrasted case studies

C. Bessou[1,*], C. Basset-Mens[2], C. Latunussa[1], A. Vélu[1], H. Heitz[2,3], H. Vannière[2], J.P. Caliman[1,4]

[1] CIRAD, UPR Perennial Crops, Av. de l'Agropolis, TA B-34/02, F-34398 Montpellier Cedex 5, France
[2] CIRAD, UPR Hortsys, Bvd. de la Lironde, PS4, F-34398 Montpellier Cedex 5, France
[3] ENVILYS, Domaine du Chapitre - 170 bd du Chapitre 34750 Villeneuve-lès-Maguelone, France
[4] SMART Research Institute, Jl. Tengku Umar 19, Pekanbaru, 28112, Indonesia
[*] Corresponding author. E-mail: *cecile.bessou@cirad.fr*

ABSTRACT

As highlighted in several recent reviews, there is a need to harmonize the way LCA of perennial crops is conducted (Bessou et al. 2013; Cerutti et al. 2013). In most published LCA on perennial crops, the agricultural production is based on data sets for just one productive year. This may be misleading since performances and impacts of the system may greatly vary year by year and the evolution of the stand over the cycle induces specific mechanisms (nutrient re-mobilization, yield alternating, resistance etc.) that must be included. Without a proper mechanistic model, the only way to account for such phenomena is to wider the data sets to at least account for each stage of the stand development and, if possible, all years of the crop cycle. Three modeling choices for the perennial crop cycle were tested in parallel in two contrasted LCA case studies: oil palm fruits from Indonesia, and small citrus from Morocco. Modeling choices tested were: i) a chronological modeling over the complete crop cycle of orchards (Bessou et al. 2013), ii) a three years average from the productive phase and iii) a selection of different single years from the productive phase. In both case studies, the system boundary included all processes from the seed production until the harvested fruits at farm-gate. The functional unit was 1 kg of fresh fruits. The chosen approach to model the perennial cycle influences the final results and deserves specific attention.

Keywords: perennial crop, LCA, chronological modeling,

1. Introduction

First LCAs including perennial crops were mostly cradle-to-grave assessments of renewable products or services based on agricultural feedstock, e.g. biofuel, heat and power, biomaterial. Despite the importance of the cropping system in terms of impact contribution over the whole process chain (e.g. 10%-80% of the total primary energy input and more than 25% of the GHG balance in most bioenergy chain *In* JEC, 2008), cultivation remained secondarily addressed (Fazio and Barbanti 2014; Monti et al. 2009). Hence, in most published LCAs on perennial crops, data on the cropping system is scarce and is often based on one productive year without accounting for the whole perennial production cycle (Bessou et al. 2013). However, assessing perennial crops in the same way as annual ones may induce bias notably due to the variability in practices and yields over the plantation lifespan or the potential importance of changes in carbon stocks (Mithraratne et al. 2008). Recent reviews highlighted the need to better account for the specificities of perennial cropping systems within LCA and to harmonize the way LCA of perennial crops is conducted (Bessou et al. 2013; Cerutti et al. 2013; Cerutti et al. 2011).

The aim of this study is to illustrate the potential bias due to varying choices in modeling the perennial crop cycle within cradle-to-gate LCAs. The baseline assumption is that a chronological assessment is the closest way to model the real perennial crop cycle, since it uses a continuous data set for a single plantation plot followed over its whole lifespan (Bessou et al. 2013). We hence compared this chronological assessment with two other ways to model the cycle: 1) a three-year average of three consecutive productive years; and 2) various single years taken randomly within the productive phase, which may be seen as approximating perennial to annual crop. We selected two contrasted case studies in different pedoclimatic conditions and with different crop managements in order to test the sensitivity of the modeling choices to contrasted perennial cropping systems. The first case study concerns oil palm fruit production in Indonesia; the second one implies small citrus produced in Morocco. We first present the data sets used for the LCI and the LCIA results, then we discuss the effect of modeling choices and further needed improvements to increase the accuracy of perennial crop LCAs.

2. Methods

2.1. LCA goal and scope

The LCA goal is to assess the environmental impacts of the production of 1 kg fresh fruit from continued agricultural land use. The approach is an attributional LCA without any assessment of rebound effect. There is hence no consideration of any direct or indirect land use change. The system boundary is a cradle-to-farm gate one (Figure 1), including land preparation and all upstream processes to produce, transport and apply inputs to the field, plus field operations and field emissions up to fruit collection at the edge of the orchard or plantation. Downstream processes to conserve or transport the fruits to storehouses are excluded. The land preparation consists of the destruction of the previous crop (as for a re-planting procedure), hole digging, and seedling planting. Seed and seedling productions are accounted for as field inputs. Seed and seedling productions, as well as land preparation, are amortized over the whole crop cycle. At the field gate, there is no co-product production; crop residues are recycled internally in the field. Allocations or system expansion were not needed in these case studies.

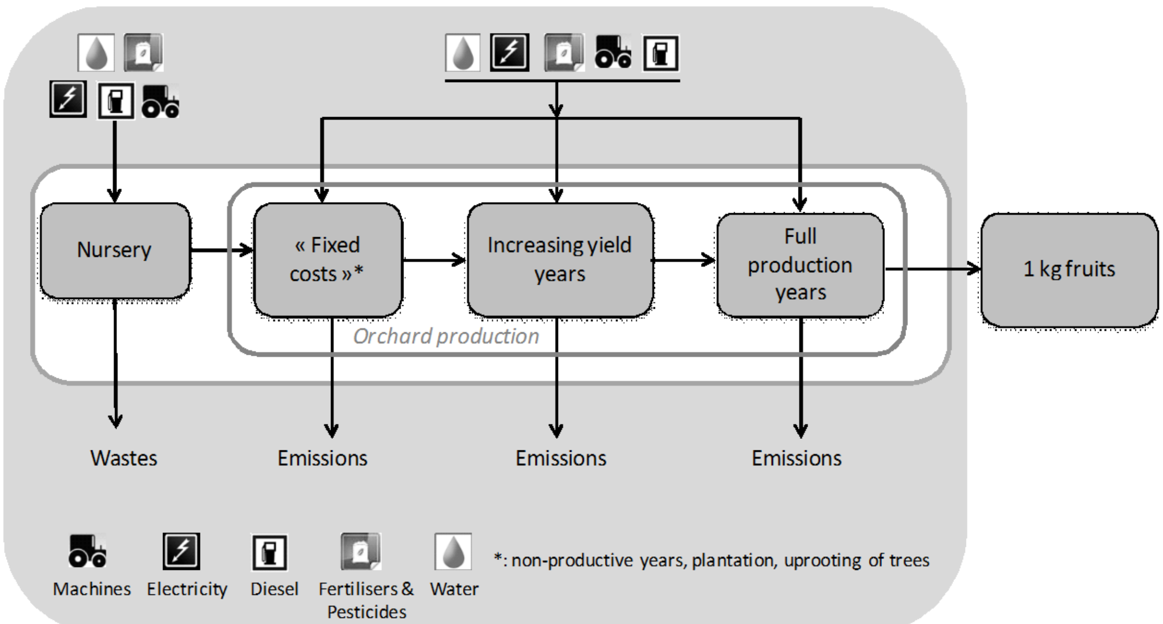

Figure 1. Simplified flow diagram for studied systems for oil palm from Indonesia and small citrus from Morocco

2.2. Data source and LCI

Primary data were collected through field surveys (2010-2013) and are recorded within the CIRAD LCA DATABASE ©-2014. These encompass the following parameters characterizing the cropping systems: input origins, types, doses, and transport distances; fuel consumption for all field operations; planting density and yield outputs. Details are given for each case study in sections 2.2.1.-2.2.2. Secondary data were taken from Ecoinvent v.2.2 database and encompass: production of synthetic inputs (fertilizers, pesticides, material to the nursery) and energy vectors (fuels, electricity); machines and fuel consumptions for input transportation (oversea and road transports); machines for field operations.

2.2.1. Oil palm fruit system

The studied oil palm production system consisted of an industrial plantation block on mineral soil (Typic Dystropept, Acrisol) in Riau Province, Sumatra, Indonesia. Data on seed and seedling productions were based on both company standards and field interviews. Data on land preparation were also based on company standard. The palms were planted in 1992 with a density of 136 trees/ha. The plantation was not irrigated, and water use only took place at seed and seedling production stages as well as for pesticide dilution. Primary data on fertilizer inputs were collected over the period 1992-2012. Yield records started after the immature phase and covered the period 1995-2012. Finally, pesticides and field operations were recorded over the period 2008-2012 (Table 1). Fertilizers were applied mechanically twice a year, whereas pesticide application and harvest were done manually.

Table 1. Key agronomic data for the oil palm fruit system in Indonesia; [min and max values].

	Units	Average for the non-productive years (0 - 2 years)	Average for the productive years (3 - 21 years)	Average for the whole cycle	Average for the last three years of the cycle	Year 1995	Year 1996	Year 2006
Fertilizers								
N	kg/ha/yr	38 [32 ; 44]	112 [109 ; 156]*	101	109	156	109	109
P_2O_5	kg/ha/yr	44 [38 ; 51]	16 [15 ; 31]	20	15	31	15	15
K_2O	kg/ha/yr	86 [13; 193]	43 [41 ; 82]	49	41	82	41	41
MgO	kg/ha/yr	7 [6; 8]	32 [0 ; 46]	28	37	46	27.5	37
Borate (boric acid)	kg/ha/yr	3 [0; 4]	4 [0 ; 6.5]	4	6.5	0	0	6.5
Fossil fuel	L/ha/yr	4.3	4.3	4.3	4.3	4.3	4.3	4.3
Total pesticides	kg/ha/yr	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	L/ha/yr	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Yield	t/ha/yr	0	22 [10.9 ; 30.5]	19	22	11	25	21

* Minimum and maximum values encountered in specific years over the time period of the productive years. Treatments during the non-productive years do not vary annually. Pesticides are herbicides used on a routine basis to clean circles and harvest pathways.

2.2.2. Small citrus system

In agreement with our Moroccan partner: a big producer of agricultural products, a 9-years old small citrus orchard was selected from the region of Beni Mellal in Morocco. This orchard showed recent technologies of production and had already reached its full production phase. The variety of small citrus was “Sidi Aïssa” grafted on “Citrange Troyer”. Over the first 9 years, detailed accounting data were collected to describe all agricultural operations. Large variations of input rates and yield were observed across the first nine years. The orchard was assumed to last 25 years. From the 10th to the 25th years an annual agronomical scenario was designed with the partner based on average data for all inputs and yield for the years 7, 8 and 9. The average yield of 42 t/ha corresponded to the expected yield by the farmer. Key agronomic data for the different phases of the small citrus orchard are presented in Table 2. The orchard, planted at a density of 5 x 4 m was fertigated. Several pumps were used to pump water in the groundwater and lagoons allowed 10 days of autonomy in water during the dryer season in case of pumps’ failure.

Table 2. Key agronomic data for the three phases of a nine years old small citrus orchard in Morocco. Data for the full production phase are extrapolated from the average data for the 3 previous years (7-9). [min and max values]

	Units	Non-productive years (0 - 3 years)	Increasing yield years (3 - 9 years)	Full production years (9 - 25 years)
Fertilizers				
N	kg/ha/yr	55 [46 ; 69]	155 [66 ; 224.5]	214
P_2O_5	kg/ha/yr	24 [8.5 ; 43]	48 [24 ; 67]	65
K_2O	kg/ha/yr	1.6 [0 ; 4.6]	140 [57 ; 221]	186
Fe	kg/ha/yr	0.45 [0.44 ; 0.46]	0.4 [0.04 ; 1.5]	0.8 [0.17 ; 1.48]
Zn	kg/ha/yr	0	0.39 [0.12 ; 0.9]	0.43 [0.20 ; 0.64]
Mn	kg/ha/yr	0	0.51 [0.03 ; 1.31]	0.57 [0.21 ; 0.91]
Irrigation				
Water (groundwater)	m3/ha/yr	6112 [5835 ; 6496]	7982 [6633 ; 11054]	8906
Fossil energy	L/ha/yr	1305 [1158 ; 1428]	1550 [1091 ; 1723]	
Electrical energy	kWh/ha/yr	0	0	7661
Total insecticides	kg/ha/yr	0.52	3.35	4.79
Total herbicides	kg/ha/yr	2.58	1.92	2.25
Total pesticides	kg/ha/yr	3.10	5.27	7.04
Yield	t/ha/yr	0	29 [5.5 ; 66]	42

2.2.3. Field emissions

For oil palm system, field emissions were calculated as following. Emissions due to fertilizer field application were estimated according to IPCC 2006 Tier 1 guidelines for both N- and C-compounds. P-compounds emissions were estimated based on SALCA-P model (Prasuhn, 2006) considering only run-off and leaching risks, in our case studies of perennial plantation with permanent soil cover on zero-slope land area (0-3%). Finally, heavy metals and active substances from applied pesticides were assumed to all end up completely in the soil. Heavy metals contents were recorded for synthetic fertilizers (Freiermuth, 2006) and organic fertilizers (primary data from measured recycled crop residues).

For small citrus: Ammonia, NO_2, phosphate and pesticides emissions were estimated following recommendations from Nemecek and Kägi (2007). Nitrous oxide emissions were based on IPCC emission factors but following Brentrup et al. (2000) approach. Following Brentrup et al. (2000) again, the nitrate leached was evaluated by calculating the leachable nitrogen from a nitrogen budget and by applying a drainage factor based on a water budget and the field capacity of the soil. As part of the N budget, N export in fruits was based on Vannière (1992) and N sequestered in trees (roots, stand, branches) was modeled using expertise from H. Vannière.

2.3. Modeling of the perennial crop cycle

Three modeling choices for the perennial crop cycle were tested in parallel in the two contrasted LCA case studies. Modeling choices tested were: 1) a chronological modeling over the complete crop cycle of orchards, 2) a three years average from the full production phase and 3) a selection of different single years from the full production phase. The chronological assessment consists in describing the whole cycle following the historical course of the crop development (Bessou et al., 2013). This approach is the closest way to the reality of a perennial crop development, since delayed effects from agricultural practices or intrinsic crop physiology features can be accounted for. However, the data set on the whole cycle of a perennial crop is hardly available in most of the cases. Therefore, it is important to try to quantify the bias due to truncated perennial crop modeling.

When individual years or the 3-year average were considered in this study, inputs upstream the investigated years were not accounted for, *i.e.* land preparation and planting, seeds and seedling production and all other years, including the costs of the non-productive years. The comparison between individual years and the 3-year average aimed at assessing how much of the inter-annual variability could be captured and how far it might then a better proxy to model the whole cycle compared to individual years.

2.4. Impact characterization method

The impact assessment was performed using the ReCiPe Midpoint life cycle impact assessment method (Goedkoop et al., 2009), adopting the Hierarchist perspective. The following environmental impact categories were considered: climate change (100 years IPCC 2007; kg CO_2eq), terrestrial acidification (g SO_2eq), freshwater and marine eutrophication (g P-eq and g N-eq respectively, based on the nutrient-limiting factor of the aquatic environment), terrestrial and freshwater ecotoxicity (g 1,4-DB-eq: 1,4-dichlorobenzene), agricultural land occupation (m^2.year), water depletion (m^3-eq) and fossil depletion (kg oil-eq). The non-renewable energy consumption (fossil and nuclear; MJ-eq) was assessed using the Cumulative Energy Demand method (Hischier et al. 2009).

3. Results

Across the cradle-to-farm-gate life cycle of oil palm fruit (Figure 2a), the productive years that account for 18/21 of the whole cycle contributed to the larger share of most impact categories (75-95%) except for freshwater eutrophication and water depletion. Since the palm plantations were not irrigated, the water depletion category, which only considers used tap water, was half related to used water to produce seeds (germination cycles) and irrigate the seedlings in the nursery, and half due to pesticides dilution during both non-productive and productive years. Across the other impact categories, fertilizers (production, transport and field emissions) during productive years contributed greatly to climate change, terrestrial acidification, marine eutrophication, and fossil depletion (70-90%); whereas other interventions (including mostly pesticides application) contributed more to the toxicity impact categories (~75%) but also to freshwater eutrophication (25%), water depletion (28%), and fossil depletion including fuel use (22%). Fossil depletion is notably related to fossil fuel used for field operations such as annual plantation maintenance or fertilizer broadcasting.

Across the cradle-to-farm-gate life cycle of small citrus, the tree planting and non-productive years (non-productive stage) contributed between 6.5% for terrestrial acidification and 29% for terrestrial ecotoxicity (Figure 2b). For categories other than toxicity impacts and land occupation, fertilization and irrigation represented the two main contributors. This was due to the production of fertilizers and fossil fuel (for irrigation) and their emissions after use at field level. For terrestrial ecotoxicity, the on-field emission of pesticides was the almost exclusive contributor shared between the non-productive stage (29%) and the productive years (70%). The share of non-productive stage was large for terrestrial ecotoxicity due to the application of toxic insecticides at the nursery stage (abamectin) and during the three first years of trees (methomyl). The freshwater ecotoxicity was due primarily to irrigation (production and combustion of fossil fuel) and secondarily to field pesticide emissions for productive years (27.6%) and for non-productive years (18.8%). Water depletion was due almost exclusively to water use for irrigation shared between non-productive years (8.8%) and the rest of the orchard's life (91%). Finally, agricultural land occupation was mostly due to the productive years (87.4%) and secondarily to non-productive years (12%).

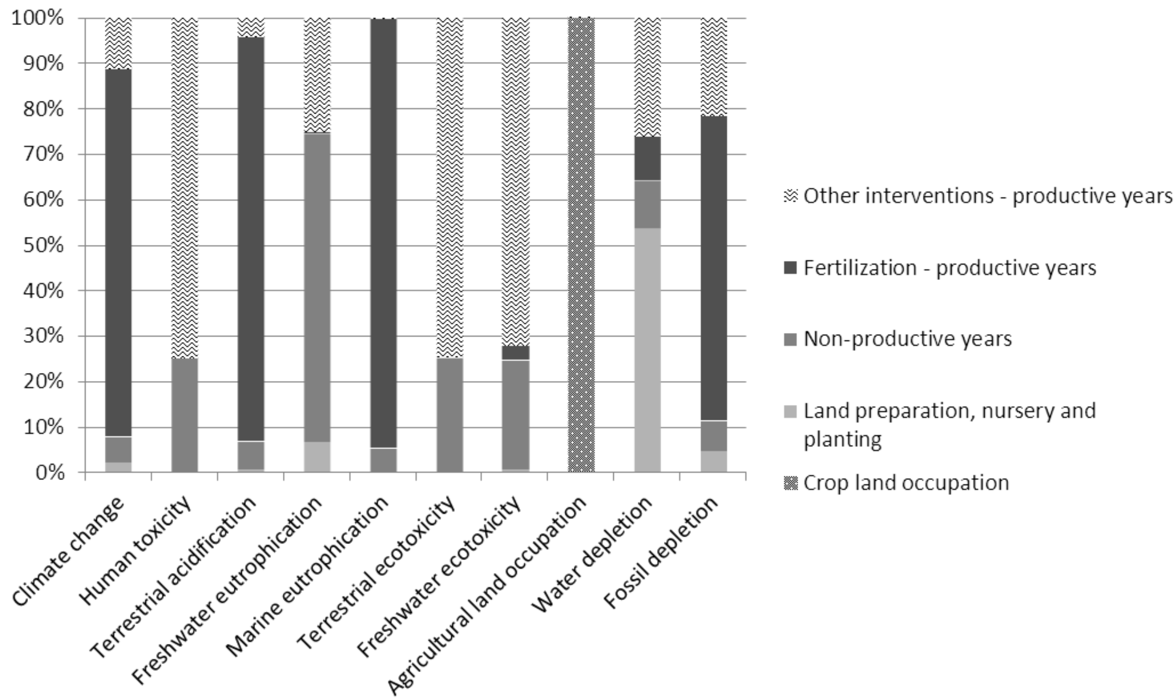

Figure 2a. Contribution analysis from cradle-to-farm-gate for environmental impacts (ReCiPe-Midpoint (H)) of palm oil fruit from Indonesia. Results are expressed per kg of fresh fruit bunches

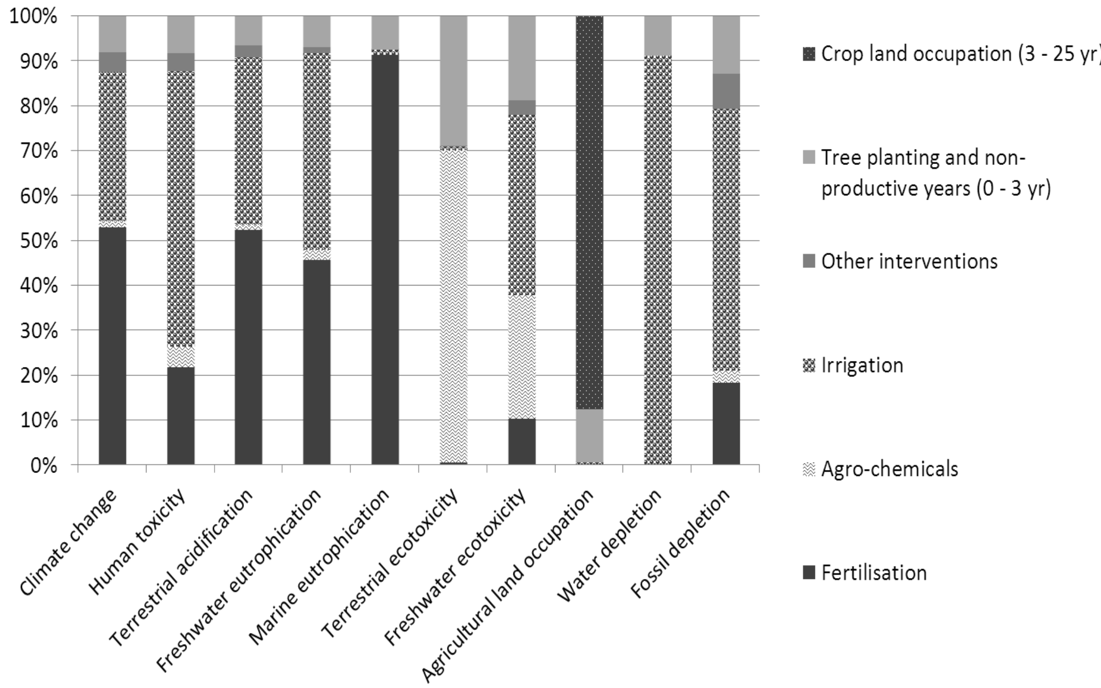

Figure 2b. Contribution analysis from cradle-to-farm-gate for environmental impacts (ReCiPe-Midpoint (H)) of small citrus from Morocco. Results are expressed per kg of raw fruit.

3.1. Sensitivity analysis to modeling approach for perennial crop cycle

In Figures 3a and 3b, modeling approaches are compared to the baseline scenario modelling the whole cycles. In both cases, the results were highly sensitive to the modeling approach used for the perennial crop cycle. Relative variations in results among the approaches are not homogeneous across impact categories.

In the case of oil palm fruit, the year 1995 showed a very specific pattern with lower yields and more inputs that the average productive years.

In the case of small citrus, compared to the full cycle scenario, the 3-years average scenario showed results between 47% for freshwater ecotoxicty and human toxicity up to 138% for marine eutrophication. As such, it did not appear as a good proxy for the full crop cycle because it excluded the non-productive years but also because it relied only on three years over 25 and did not reflect the whole orchard cycle properly. The single year scenarios showed extreme variations due to the yield variations, ranging from 20 t/ha for year 9 to 66 t/ha for year 8, but also to annual variations of rainfall, water use for irrigation and input rates. For instance, the year 9 scenario showed a very high marine eutrophication due to both a low yield and a high nitrate leaching due to a humid weather while year 7 and year 8 were very dry and associated to a nil nitrate leaching.

By selecting randomly one single year from the full production phase to evaluate a full crop cycle, the results could either be dramatically overestimated or underestimated. The most variable results were observed for the most climate-dependent impacts such as marine eutrophication and toxicity impacts due to variations in rainfall and pest pressure but also for toxicity impacts, to the use of different active molecules from one year to the other.

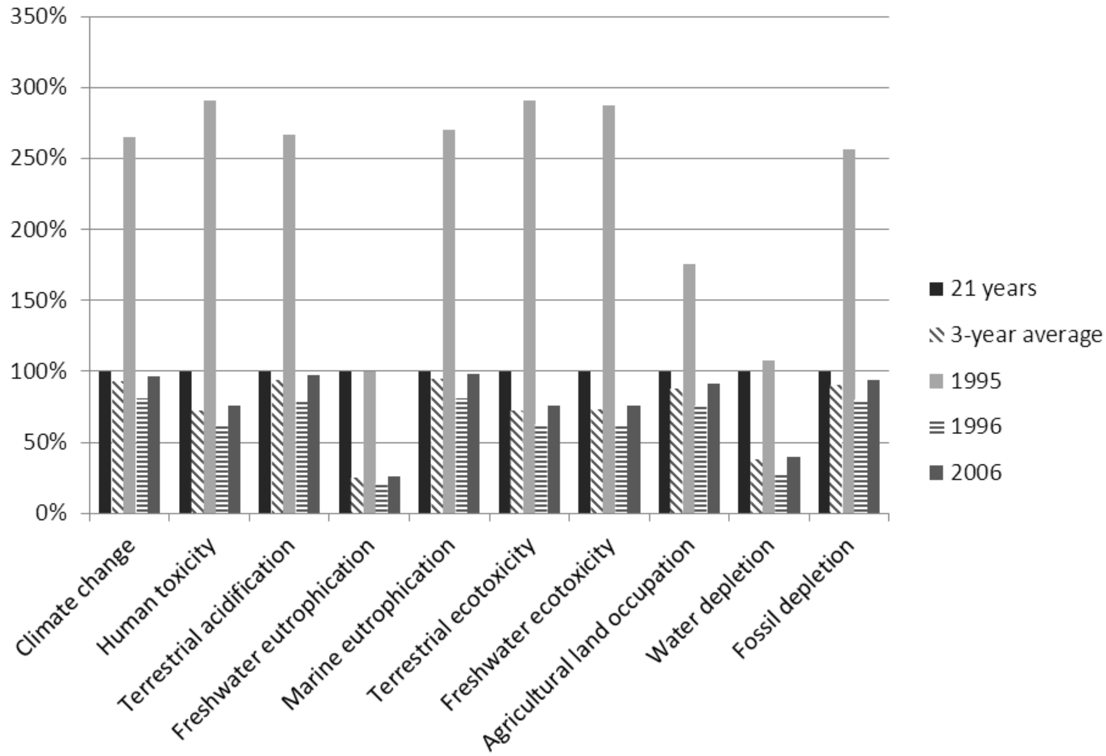

Figure 3a. Environmental impacts (ReCiPe-Midpoint (H)) for different modeling approaches of the perennial crop cycle for oil palm fruits from Indonesia: full cycle modeling (21 years, reference baseline 100%), 3-years average, years 7, 8 and 9. Results are compared per kg of fresh fruit bunches.

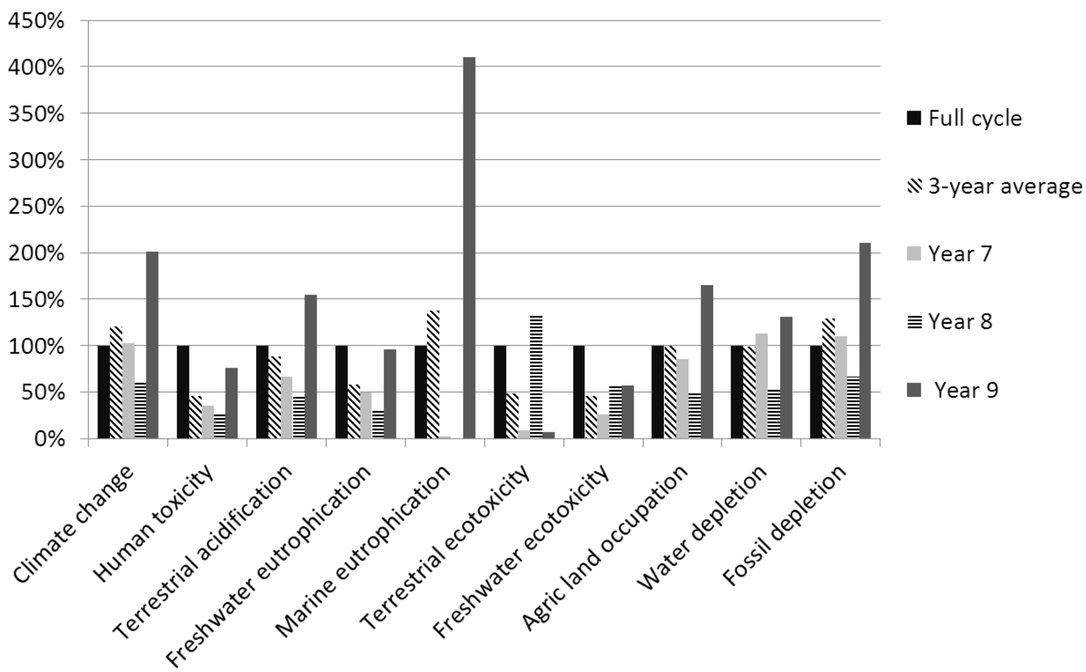

Figure 3b. Environmental impacts (ReCiPe-Midpoint (H)) for different modeling approaches of the perennial crop cycle for small citrus from Morocco: full cycle modeling, 3-years average, years 7, 8 and 9. Results are expressed per kg of raw fruit.

4. Discussion and conclusion

In two contrasted perennial case studies, one on palm oil from Indonesia, the other on small citrus from Morocco, different modeling approaches were developed to account for the perennial crop cycle. The baseline scenario included a complete modeling of the crop cycle while a 3-year average scenario and 3 single year scenarios were also tested. Key insights from these two analyses were consistent:

1. non-productive years have a large share in the environmental impacts of orchards and should be included;
2. choosing one single year from the full production phase leads to highly uncertain results and should be avoided especially for strongly alternating yield crops;
3. even a 3-year average scenario is not sufficient to capture properly the full perennial crop cycle and can be misleading
4. an effort should therefore be made to include the whole crop cycle ideally based on real data when available or at least on expert knowledge.

Although showing very different features, the two case studies contributed to draw consistent conclusions on the modeling of perennial crops in LCA. Analysing two contrasted LCA case studies, we highlighted the specific character of perennial crops in LCA and how important is the inclusion of all their phases in the assessment to account for their highly variable inputs and outputs over years. Other crucial and specific aspects of perennial crops especially in the Southern countries, which are under-represented in current statistical models to estimate field emissions (Bouwman et al. 2002; Stehfest and Bouwman 2006), still warrant further research and better modelling notably regarding:

(i) the inclusion of land use change (if any);
(ii) the modeling of field emissions of nutrients and pesticides combining parameters of soil, climate and practices and long-term recycling and re-mobilising mechanisms;
(iii) the inclusion of impacts due to water use.

5. Acknowledgement

The authors would like to thank the French National Research Agency (ANR) for its support to field work in Indonesia, within the frame of the SPOP project (http://spop.cirad.fr/) Agrobiosphere program. They are also very grateful to their local partners in Morocco and Indonesia who provided all the data used in these studies. Most authors of this paper are members of the ELSA research group (Environmental Life-cycle and Sustainability Assessment www.elsa–lca.org), and wish to thank the French Region Languedoc–Roussillon for its support to ELSA.

6. References

Bessou C, Basset-Mens C, Tran T, Benoist A (2013) LCA applied to perennial cropping systems: a review focused on the farm stage. Int J Life Cycle Assess 18:340–361. doi: 10.1007/s11367-012-0502-z

Bouwman AF, Boumans LJM, Batjes NH (2002) Modeling global annual N2O and NO emissions from fertilized fields. Glob Biogeochem Cycles 16:11. doi: 10.1029/2001GB001812

Cerutti AK, Beccaro GL, Bruun S, et al. (2013) LCA application in the fruit sector: state of the art and recommendations for environmental declarations of fruit products. J Clean Prod. doi: 10.1016/j.jclepro.2013.09.017

Cerutti AK, Bruun S, Beccaro GL, Bounous G (2011) A review of studies applying environmental impact assessment methods on fruit production systems. J Environ Manage 92:2277–2286. doi: 10.1016/j.jenvman.2011.04.018

Fazio S, Barbanti L (2014) Energy and economic assessments of bio-energy systems based on annual and perennial crops for temperate and tropical areas. Renew Energy 69:233–241. doi: 10.1016/j.renene.2014.03.045

Mithraratne N, McLaren S, Barber A (2008) Carbon Footprinting for the Kiwifruit Supply Chain – Report on Methodology and Scoping Study. 63.

Monti A, Fazio S, Venturi G (2009) Cradle-to-farm gate life cycle assessment in perennial energy crops. Eur J Agron 31:77–84. doi: 10.1016/j.eja.2009.04.001

Stehfest E, Bouwman L (2006) N2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutr Cycl Agroecosystems 74:207–228. doi: 10.1007/s10705-006-9000-7

Nemecek T, Kägi T (2007) Life Cycle Inventories of Swiss and European Agricultural Production Systems. Final report ecoinvent V2.0 No. 15a. Agroscope Reckenholz-Taenikon Research Station ART, Swiss Centre for Life Cycle Inventories, Zürich and Dübendorf, Switzerland, retrieved from: www.econivent.ch

Prasuhn V (2006) Erfassung der PO4- Austräge für die Ökobilanzierung SALCA Phosphor. Agroscope Reckanholz-Tänikon ART. 20 p.

Vannière (1992) Essai porte-greffe nutrition du clémentinier en Corse (Station de Recherches Agronomiques de San Giuliano INRA CIRAD – IRFA). Fruits 47(1)

Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector

LCA Food 2014

8-10 October 2014 - San Francisco

Rita Schenck and Douglas Huizenga, Editors
American Center for Life Cycle Assessment

The full proceedings document can be found here:
http://lcacenter.org/lcafood2014/proceedings/LCA_Food_2014_Proceedings.pdf

It should be cited as:

Schenck, R., Huizenga, D. (Eds.), 2014. Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (LCA Food 2014), 8-10 October 2014, San Francisco, USA. ACLCA, Vashon, WA, USA.

Questions and comments can be addressed to: staff@lcacenter.org

ISBN: 978-0-9882145-7-6