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Partial modelling of the perennial crop cycle misleads LCA results in two contrasted case studies

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Abstract

Purpose As highlighted in recent reviews, there is a need to harmonise the way life cycle assessment (LCA) of perennial crops is conducted. In most published LCA on perennial crops, the modelling of the agricultural production is based on data sets for just one productive year. This may be misleading since performance and impacts of the system may greatly vary year by year. The purposes of this study are to analyse how partial modelling of the perennial cycle through non-holistic data collection may affect LCA results and to make recommendations.

Methods Three modelling 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. Modelling choices tested were as follows: (i) a chronological modelling over the complete crop cycle of orchards, (ii) a 3-year average from the productive phase, and (iii) various single years from the productive phase. In both case studies, the system boundary was a cradle-to-farm gate with a functional unit of 1 kg fresh fruits. LCA midpoint impacts were calculated with ReCiPe 2008 in Simapro©V.7. We first analysed how inputs, yields and potential impacts varied over time. We then analysed process contributions in the baseline model, i.e. the chronological modelling, and finally compared LCA results for the various perennial modelling choices.

Results and discussion Agricultural practices, yields and impacts varied over the years especially during the first 3–9 years depending on the case study. In both case studies, the modelling choices to account or not for the whole perennial cycle drastically influenced LCA results. The differences could be explained by the inclusion or not of the yearly variability and the accounting or not of the immature phase, which contributed to 7–40 or 6.5–29 % of all impact categories for oil palm fruit and citrus, respectively.

Conclusions The chosen approach to model the perennial cycle influenced the final LCA results for two contrasted case studies and deserved specific attention. Although data availability may remain the limiting factor in most cases, assumptions can be made to interpolate or extrapolate some data sets or to consolidate data sets from chronosequences (i.e. modular modelling). In all cases, we suggest that the approach chosen to model the perennial cycle and the representativeness of associated collected data should be made transparent and discussed. Further research work is needed to improve the understanding and modelling of perennial crop functioning and LCA assessment.

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1 Introduction

First life cycle assessments (LCAs) including perennial crops were mostly cradle-to-grave assessments of biosourced products from agricultural feedstock, e.g. biofuel or biomaterials. Despite the important contribution of the cropping system to the impact of the whole supply 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).

There exists a great variety of perennial cropping systems from homogeneous 5-year-long sugar cane plantation, for instance, up to century-old vineyards or very diverse cocoa agroforestry systems. Perennial cropping systems last for several years or decades, along which the crop stand goes through different development phases. During the stand establishment or immature phase, harvest may not be possible or profitable. Afterwards, the mature phase allows for more or less regular production up to a potential final declining or senescing phase depending on the crop and production conditions. These long and partitioned cycles imply specific management usually combining long-term management strategies and short or medium-term adjustments. Moreover, it also implies complex and evolving interactions with the ecosystem that affect the potential performance of the crop and the efficacy of the management. Indeed, management feedback on the production may be delayed due to the long-term development of the agroecosystem and may be more or less direct depending on the harvested product (i.e. biomass from *Miscanthus × giganteus* versus latex from rubber tree). Assessing perennial crops in the same way as annual ones may hence induce an important 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 harmonise 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 and quantify the potential bias due to varying choices in modelling the perennial crop cycle within cradle-to-gate LCAs. The baseline assumption is that a chronological modelling is the closest way to model the real perennial crop cycle since it uses a continuous data set for a single plantation plot followed up over its whole lifespan (Bessou et al. 2013). By essence, the chronological modelling integrates annual variations and cumulative effects that constitute a long-term perennial cycle, shall these punctual or chronic effects be compensated or not by the medium natural resilience or practice adaptation. We hence compared this chronological modelling with two other ways to model the cycle: (1) a 3-year average of three consecutive productive years; and (2) various single years from the productive phase randomly selected, which was assumed to be an approximation of a perennial crop by an annual crop in the year of the assessment. The influence of these modelling choices was tested in two contrasted case studies in different soil and climate conditions and with different crop management. The first case study concerned oil palm fruit production in Indonesia; the second one implied small citrus production in Morocco. We first present the data sets used for the life cycle inventory (LCI) and the life cycle impact assessment (LCIA) results; then, we present and discuss the effect of modelling choices for the perennial cycle and make some recommendations in terms of modelling strategy and data needs. Finally, we conclude with highlighting the 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 continuous agricultural land use. Studied systems were established after at least one generation of plantations; there was hence no direct land use change to account for. The approach is an attributional LCA without any assessment of rebound effect. There is therefore no consideration of any indirect land use change. The system boundary is a cradle-to-farm gate one. In the baseline model, which encompasses the whole perennial crop cycle, the system boundary includes nursery, tree planting, non-productive years and productive years. The land preparation for tree planting consists of the destruction of the previous crop (as for a re-planting procedure), digging and seedling planting. The system boundary includes all upstream processes to produce and transport inputs to the field, plus application of inputs to the field, field emissions and other field operations up to fruit collection at the edge of the orchard or plantation. At the field gate, there is no co-product production. Pruning residue leftovers in the field are considered as negligible in terms of emissions to the environment in the case of oil palm fruits but were accounted for in the nitrogen balance for citrus. In our oil palm case study, which was an experimental trial on mineral fertiliser treatments, there was no field application of palm oil mill residues (e.g. empty fruit bunches), which are commonly used as organic amendments and lead to further field emissions (Stichnothe and Schuchardt 2011). Such exclusive mineral fertiliser treatments are consistent with a complete mass balance at the mill supply area level. Produced quantities of palm oil mill residues are not sufficient to cover the whole supplying area; therefore, parts of the plantations

receive only mineral fertilisers. Excluding those organic amendments would however not be suitable if we wanted to have an average LCA of the whole mill supply area (which is usually done in palm oil LCA). Allocations or system expansion were not needed in these case studies. Downstream processes to protect or transport the fruits to storehouses are excluded (Fig. 1).

Three modelling choices for the perennial crop cycle were tested in parallel for the two contrasted LCA case studies. Modelling choices tested were as follows: (1) a chronological modelling over the complete crop cycle of orchards, (2) a 3-year average from the full production phase and (3) a selection of different single years from the full production phase for oil palm and the three last years recorded for small citrus. The first and baseline model is the chronological modelling that 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 modelling.

For individual years or the 3-year average model, nursery, tree planting and non-productive years were not included in the studied system. The selection of individual years was made randomly before conducting the LCA. This selection is meant to reproduce the random effect linked to the assessment of a perennial crop using only data from the year of the assessment, no matter when that year occurs within the crop cycle and whether it might be or not representative. The assessment over three consecutive years also aimed at reproducing the same random effect while checking whether a 3-year average might or not smooth out some distortion from the non-accounting of the full cycle. The way the perennial crop cycle is modelled in the LCA actually influences the delineation of the system boundaries. Although the production can be compared through the same functional unit, the comparison between models aims to investigate the distortion due to both varying system boundaries and varying data quality in terms of captured yearly variations and potential cumulative or compensation effects. According to ISO norms 14044, "The deletion of life cycle stages, processes, inputs or outputs is only permitted if it does not significantly change the overall conclusions of the study…". It is hence critical to check if and how the perennial crop modelling affects LCA results.

2.2 Data source and LCI

Primary data were collected through field surveys and were recorded within the CIRAD LCA DATABASE ©-2014. These encompassed the following parameters characterising 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 encompassed: production of synthetic inputs (fertilisers, pesticides, material at the nursery) and energy carriers (fuels, electricity); machines and fuel consumptions for input transportation (oversea and road
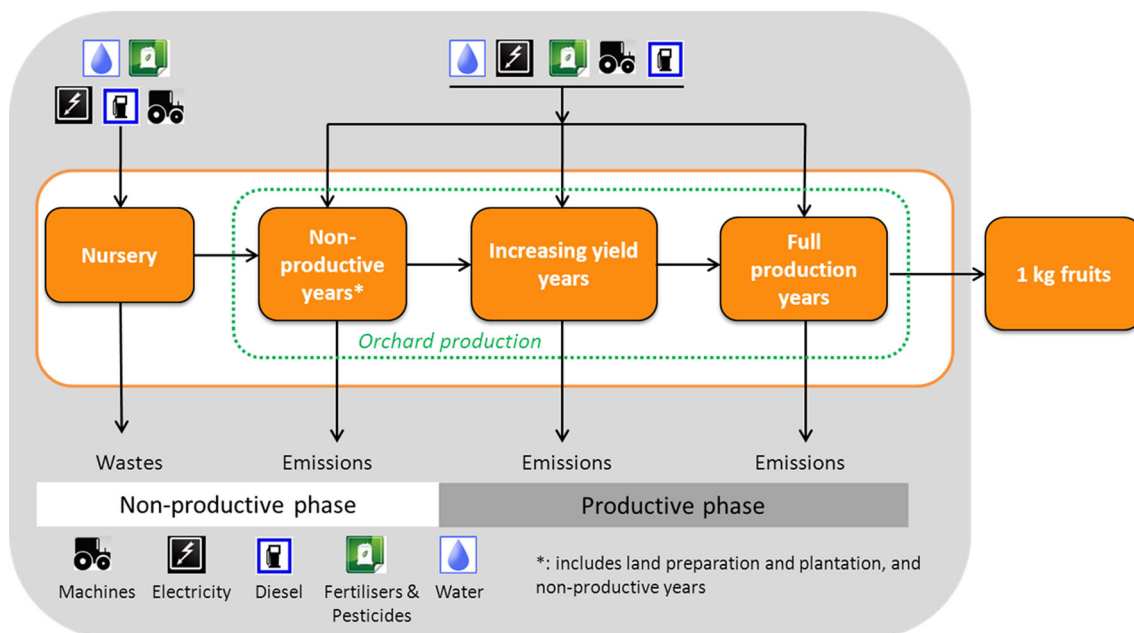

Fig. 1 Simplified flow diagram for studied systems for oil palm from Indonesia and small citrus from Morocco. Orchard refers here to both perennial crop stands although "orchard" is not a commonly used term for oil palm plantations

transports); machines for field operations, although fuel consumption was adapted to reflect primary data.

2.2.1 Oil palm fruit system

The studied oil palm production system consisted of industrial plantation blocks on mineral soil (Typic Dystropept, Acrisol) in Riau Province, Sumatra, Indonesia. These blocks were part of a long-term experimental trial on fertiliser treatments. The palms were planted in 1992 with a density of 136 palm trees/ha. Data on land preparation were based on company standard. Data on seed and seedling productions were based on both company standards and field interviews. The plantation was not irrigated, and water use took place only at seed and seedling production stages as well as for field input dilution. For the purpose of the present study, one data set from the trial was used consisting in the 3-replicate average for one given fertiliser treatment (Table 1). Primary data on fertiliser inputs were collected over the period 1992–2012. Yield records started after the three first non-productive years (no fruit harvested) and covered the period 1995–2012. Finally, pesticides and field maintenance operations were recorded only over the period 2008–2012. Applications of herbicides were organised based on the company standard operating procedure including three applications per year with both a selective approach, i.e. selected species were controlled (especially woody weeds and certain ferns such as *Dicranopteris linearis*), combined with a systematic application to maintain an access to the palms (weeded circles and harvesting path). Unlike at the nursery stage, insecticides and fungicides are not commonly used in plantations during productive years due to low pest pressure and efficient integrated pest management in the study area. In our case study, no pest or disease outbreak occurred over the 18 years of productive recorded years. There were hence no curative punctual chemical treatments applied on top of regular treatments, which consisted in standard applications of paraquat and glyphosate for weed control in palm circles

and harvest pathways. Consequently, the 5-year average for pesticide treatments and maintenance operations was assumed to be relevant for the whole cycle and to cover yearly variations of the rates applied, if any, based on the expert knowledge from the trial manager. Fertilisers were applied mechanically during the productive years, whereas pesticide application and harvest were done manually.

2.2.2 Small citrus system

A 9-year-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 yields were observed across the first 9 years. The orchard was assumed to last 25 years. From the 10th to the 25th year, for which data did not exist, we averaged data for all inputs and yields from the years 7, 8 and 9 as a proxy for this final phase called projection scenario. The average yield of 42 t/ha corresponded to the expected yield by the farmer. An important characteristic of citrus orchard is the alternating yield phenomenon. In theory, a biannual pattern could have been designed for this projection scenario. However, from an LCA perspective, the interest of such a biannual pattern lies in the combination between actual yield and variations over time of climate (rainy versus dry years) and pest pressure which could not be simulated for the projection scenario. 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 × 4 m, was fertigated. Several pumps were used to pump water in the groundwater (≥100 m depth). Water was stored in lagoons allowing 10 days of autonomy in water during the dryer season in case of pumps' failure.

Table 1 Key agronomic data for the oil palm fruit system in Indonesia; (min and max values encountered in specific years over the considered period)

	Units	Average for the non-productive years (1–3 years)	Average for the productive years (4–21 years)	Average for the whole cycle	Average for the last 3 years of the cycle	Year 4 1995	Year 5 1996	Year 10 2001	Year 15 2006	Year 21 2012
Fertilisers										
N	kg/ha/year	38 (32; 44)	112 (109.5; 156)	101	109.5	156	109.5	109.5	109.5	109.5
P_2O_5	kg/ha/year	44 (38; 51)	78 (76.5; 107)	73	76.5	107	76.5	76.5	76.5	76.5
K_2O	kg/ha/year	86 (13; 193)	206 (204; 245)	189	204	245	204	204	204	204
MgO	kg/ha/year	7 (6; 8)	32 (0; 46)	28	37	46	27.5	37	37	37
Borate (boric acid)	kg/ha/year	3 (0; 4)	4 (0; 6.5)	4	6.5	0	0	6.5	6.5	6.5
Fossil fuel	L/ha/year	0	4.7	4	4.7	4.7	4.7	4.7	4.7	4.7
Total pesticides[a]	kg/ha/year	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
	L/ha/year	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84
Yield	t/ha/year	0	27 (13; 36)	23	27	13	26	25	27	27

[a] Pesticides are herbicides used on a routine basis to clean circles and harvest pathways

Table 2   Key agronomic data for the three phases and three individual years of a 9-year-old small citrus orchard in Morocco

	Units	Non-productive years (1–3 years)	Increasing-yield years (4–9 years)	Full production years (10–25 years)	Year 7 2006	Year 8 2007	Year 9 2008
Fertilisers							
N	kg/ha/year	55.1 (46.1; 69.4)	155.2 (65.7; 224.5)	213.9	213.1	204.0	224.5
P_2O_5	kg/ha/year	24.4 (8.5; 43.2)	48.3 (24; 66.8)	64.9	66.8	63.1	64.7
K_2O	kg/ha/year	1.6 (0; 4.6)	140.4 (57; 221.4)	186.3	122.8	221.4	214.8
Irrigation							
Water (groundwater)	m^3/ha/year	6111.7 (5835.1; 6496.4)	7982.4 (6632.7; 11,054)	8906	11,054	9032.7	6632.7
Fossil energy	L/ha/year	1305 (1157.7; 1427.9)	1550.1 (1090.5; 1722.8)	0	1722.8	1687	1661
Electrical energy	kWh/ha/year	0	0	7661.2	0	0	0
Insecticide treatments							
Acetamiprid	kg/ha/year	0.05 (0.03; 0.08)	0	0	0	0	0
Imidacloprid	kg/ha/year	0.04	0.04 (0.01;0.06)	0	0	0	0
Metomyl	kg/ha/year	0.43 (0.35; 0.51)	0.23 (0.17;0.29)	0	0	0	0
Thiocyclam hydrogen oxalate	kg/ha/year	0	0.05 (0.003; 0.10)	0	0	0	0
Abamectin	kg/ha/year	0	0.00005	0	0	0	0
Malathion	kg/ha/year	0	0.45 (0.26; 0.65)	0.38	0.26	0.44	0.44
Deltamethrin	kg/ha/year	0	0.004 (0.0009; 0.011)	0.005	0.0009	0.011	0
Lambda-cyhalothrin	kg/ha/year	0	0.003 (0.0005; 0.008)	0	0.0025	0.0020	0.0073
Spinosad	kg/ha/year	0	0.0003 (0.0001; 0.0003)	0	0.00015	0.00030	0
Fenthion	kg/ha/year	0	0.25	0	0	0.25	0
Methidathion	kg/ha/year	0	0.06	0	0	0	0
Chlorpyriphos-Ethyl	kg/ha/year	0	2.26 (0.12; 4.4)	4.4	0.12	4.4	0
Total insecticides	kg/ha/year	0.52	3.35	4.79	0.38	5.1	0.45
Herbicide treatments							
Glyphosat	kg/ha/year	2.14 (0.12; 3.83)	1.92 (0.13; 4.35)	2.25	1.07	2.29	3.37
Paraquat	kg/ha/year	0.08	0	0	0	0	0
S-metolachlore	kg/ha/year	0.36	0	0	0	0	0
Total herbicides	kg/ha/year	2.58	1.92	2.25	1.07	2.29	3.37
Total pesticides	kg/ha/year	3.1	5.27	7.04	1.45	7.39	3.82
Yield	t/ha/year	0	29 (5.5; 66.2)	42	39.6	66.2	20.5

Data for the full production phase from year 10 to 25 are extrapolated from the average data for the 3 last recorded years (years 7–9); (min and max values)

2.2.3 Field emissions

For oil palm system, field emissions were calculated as follows. Emissions due to fertiliser field application were estimated according to IPCC 2006 Tier 1 guidelines for both N- and C-compounds. In the studied system, only synthetic fertilisers were applied. Indeed, within the studied system boundary (edge of the plantation block), we did not consider the mill stage and hence did not include any palm oil co-product field application and emissions (i.e. no production neither application of empty fruit bunch or palm oil mill effluent). Potential emissions related to the recycling of palm fronds cut at harvest were considered negligible. In particular, biogenic carbon emissions were supposed to be neutral in terms of climate change impact due to the fast decomposing rate (roughly 1 year for a complete decomposition of palm fronds *In* (Khalid et al. 2000). P-compounds emissions were estimated based on the SALCA-P model (Prasuhn 2006) considering only run-off and leaching risks. The risk of erosion was considered null in our case studies of perennial plantation with permanent soil cover on zero-slope land area (0–3 %). Heavy metal contents were recorded for synthetic fertilisers only (Freiermuth 2006; Audsley E Coord. et al. 1997). The final reception compartment of all pesticides and heavy metals was assumed to be the soil (Nemecek and Kägi, 2007).

For small citrus, ammonia, NO_x, phosphate and pesticides emissions were estimated following recommendations from Nemecek and Kägi (2007). Following Brentrup et al. (2000), 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. Direct nitrous oxide emissions were based on the IPCC emission factor (2006), while indirect nitrous oxide emissions due to leaching and ammonia volatilisation were not accounted for. In the nitrogen budget approach proposed by Brentrup et al (2000), nitrate leaching is deduced from all other nitrogen inputs and outputs; therefore, the calculation of indirect nitrous oxide emissions would distort the nitrogen budget and would lead to infinite circular corrections of the nitrate leached. Given the small amount of indirect nitrous oxide emissions and the low impact expected of such omission on final results, we preferred to neglect those emissions. As part of the N budget, N export in fruits was based on Vannière (1992), and N sequestered in trees (roots, stand, branches) was modelled using expertise from H. Vannière.

2.3 Impact characterisation method

The impact assessment was performed using the ReCiPe Midpoint life cycle impact assessment method (Goedkoop et al. 2013), 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), water depletion (m^3-eq.), human toxicity (kg 1,4-DBeq) and fossil depletion (kg oil-eq.). All ReCiPe midpoint impacts are given in the Electronic Supplementary Material (S1a).

3 Results

3.1 Assessing the agronomic and environmental performance over the whole cycle

In the case of oil palm fruits, fertilisation management varied mostly during the first 4 years of the perennial cycle (Fig. 2a). The immature or non-productive phase consisted of the first 3 years when no fruit bunches were harvested. During this phase, fertiliser doses increased progressively with slightly more nitrogen and phosphate compared to potassium at the right beginning. Potassium doses were increased later on, as it is a critical limiting factor for fruit production. In the studied experimental trial, N and P_2O_5 fertiliser doses were close to the current company routine practices in similar plot conditions, whereas potassium doses were higher (~+25 %). In the fourth year,

1995, harvest of fruit bunches started and yield steeply increased up to 1997. There was a slight delay between the increases in fertiliser doses and yields, which may be correlated with the physiological palm development. A delay between uptake and production response may be due to the high maintenance costs for the plant during the first years, the physiological delay between floral initiation and fruit maturity, and potential stresses. This delay also had repercussion on the environmental indicators. In 1995, when the yield was still low compared to the optimum and fertiliser doses actually higher than the final routine ones, environmental indicators showed higher potential impacts across all categories compared to the other years. On the contrary, in the following years 1996–1997, when the yields reached their maximum (36 tFFB/ha), and fertiliser doses had fallen to the routine levels, the environmental indicators dropped and reached their lowest levels over the whole cycle. During these 2 years, we could again observe a delay in the yield response which influenced the environmental indicators. In the following years, yield stabilised at the average level of 27 tFFB/ha. This yield was slightly higher than the reference average in Indonesian industrial plantations, i.e. 18–21 tFFB/ha (Zulkifli et al. 2009; Stichnothe and Schuchardt 2011), albeit the exact weighting due to the proportion of immature and mature plantations is not systematically clarified. It fell in the upper end of the potential yield range at maturity, i.e. 20–30 tFFB/ha (Corley and Tinker 2003). Given that data were taken from an experimental block where the fertilisation management was tested, fertiliser doses remained fixed after 1996, which can explain no major variations in yields and environmental indicators during the rest of the cycle. No major disease or deficiency occurred that could have induced further fluctuations in the stand performance along its cycle. Nevertheless, there was still a slight annual fluctuation in yield along the years during the mature phase. These variations were likely related to variations in climate conditions, notably rainfalls, and most certainly in relation to the physiological cycle of the palm themselves. It was established that oil palm performance is highly depending on water balance, with a decline of yield reaching 8–10 % for each 100 mm of water stress (Dufour et al. 1988; Caliman 1992). Moreover, yield variation is in large part due to variation in the number of harvested bunches. Bunch productivity is determined by several physiological parameters (e.g. sex and abortion probability), and water deficit, solar radiation, temperature and day length are considered key external factors driving variation. Hence, there may be up to 4 years delay between floret meristem individualisation and bunch harvest (Combres et al. 2013; Pallas et al. 2013). These complex interactions underpin the physiological logic supporting the full accounting of the perennial cycle when assessing a crop lifecycle performance.

In the case of small citrus from the Moroccan orchard, we observed four agronomic phases (Fig. 2b). The first non-productive phase lasted 3 years during which fertilisers, water and pesticides were applied to allow the growing of young

trees, but no fruits were harvested. During the second phase of also roughly 3 years, both input applications and yield increased. In the third phase, trees reached maturity and input application tended to stabilise, while yields strongly alternated. Finally, in our case study, a projection scenario phase with constant inputs and outputs was added to complete the full cycle. In this real orchard situation (the first 10 years), the farmer adapted inputs to the different phases of the trees. For fertiliser inputs, a baseline fertilisation was provided to the orchard via the fertigation system and possibly completed through foliar treatments based on soil and leaf analyses over the season. During the alternating yield phase, the farmer did not really adjust the fertilisation to the actual yield year by year because citrus follow a 2-year cycle in which the fertilisation will feed either the fruits on a good yield year or the tree growth the following year. Most importantly and given the complexity of regulating the alternating yield phenomenon, the farmer preferred to make sure the trees would not suffer from any nutrient deficiency be it for reaching a good yield or for ensuring tree growth. The climate demand on a daily basis was used by the farmers to estimate water requirements over the tree phases. Environmental indicators varied with the different phases and actual variations of inputs and outputs (Fig. 2b). For the last 3 years with recorded data (years 7–9),
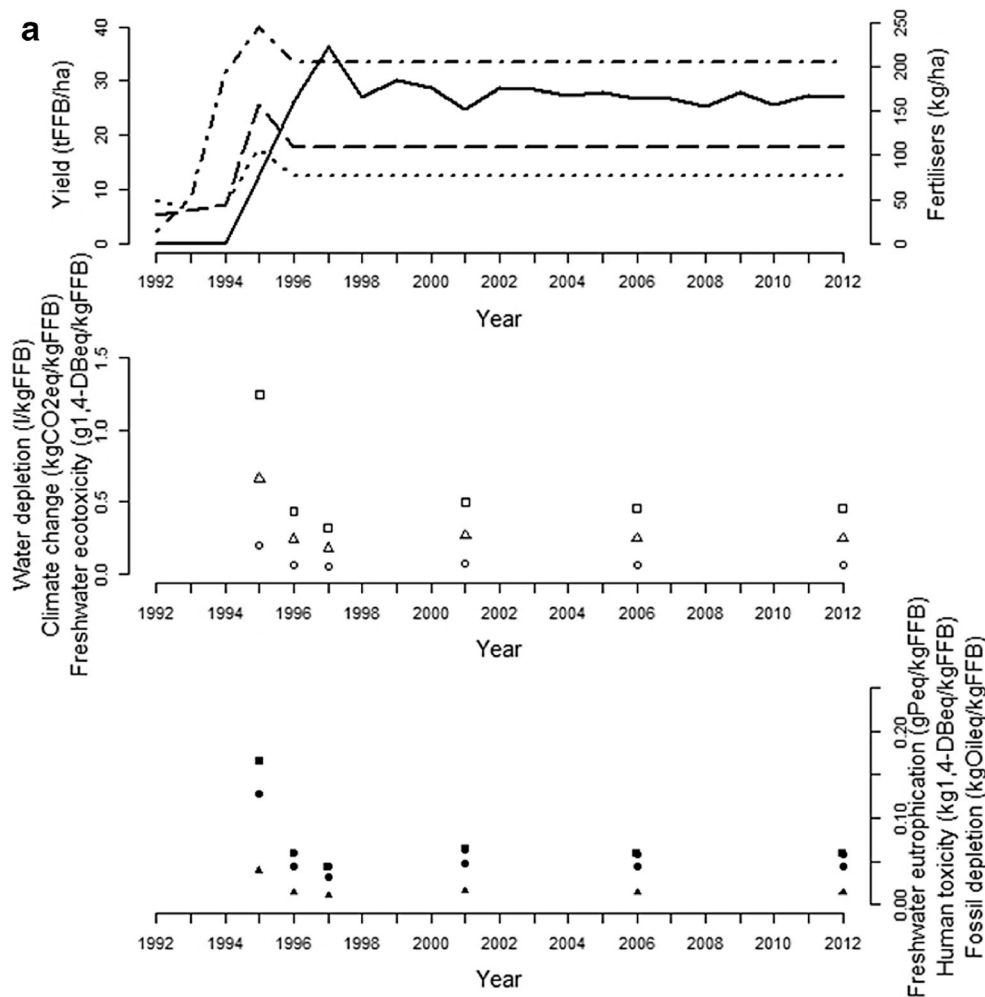

Fig. 2 a Evolution of the fertilisation management, yields and midpoint indicators (ReCiPe-Midpoint (H)) along the perennial cycle for the oil palm case study. Agronomical indicators are given per hectare: "yield" = *solid line*; "N doses" = *longdash line*; "P2O5 doses" = *dotted line*; "K2O doses" = *dotdash line*. Environmental indicators are expressed per kilogram of oil palm fresh fruit bunches: *empty symbols* refer to indicators read on the left-hand axis (water depletion = *empty square*; climate change = *empty circle*; freshwater ecotoxicity = *empty triangle*), *filled symbols* refer to indicators read on the right-hand axis (freshwater eutrophication = *filled square*; human toxicity = *filled circle*; fossil depletion = *filled triangle*). Circles and triangles tend to overlap. **b**

Evolution of the fertilisation management, yields and midpoint indicators (ReCiPe-Midpoint (H)) along the perennial cycle for the small citrus case study. Agronomical indicators are given per hectare: "yield" = *solid line*; "N doses" = *longdash line*; "P2O5 doses" = *dotted line*; "K2O doses" = *dotdash line*; "Irrigation water" = *dashed line*. Environmental indicators are expressed per kilogram of raw fruit: *empty symbols* refer to indicators read on the left-hand axis (water depletion = *empty square*; climate change = *empty circle*; freshwater ecotoxicity = *empty triangle*), *filled symbols* refer to indicators read on the right-hand axis (freshwater eutrophication = *filled square*; human toxicity = *filled circle*; fossil depletion = *filled triangle*). Empty circles and squares tend to overlap
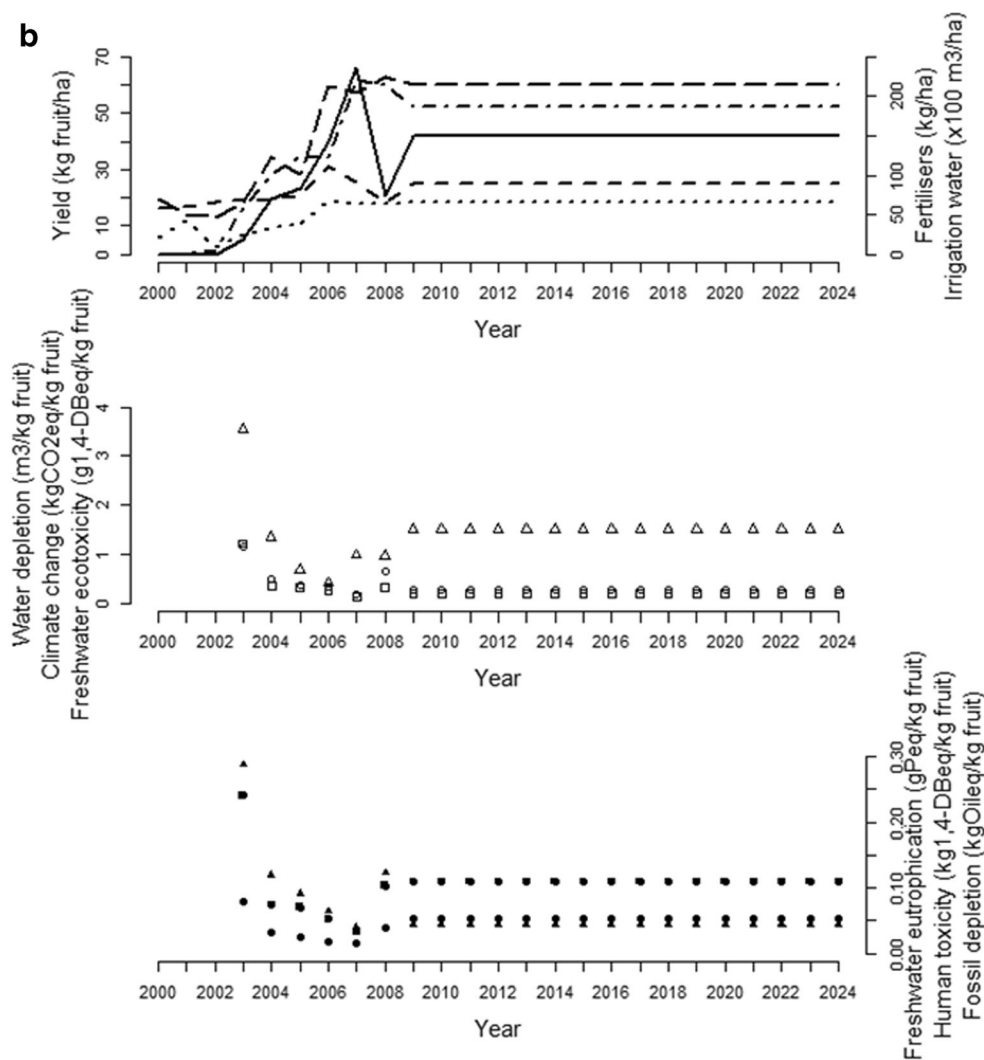
Fig. 2 continued.

the observed alternating yield phenomenon (20.5 to 66 kg/ha) affected all environmental impacts, which highly fluctuated. Beyond this phase, no further variation could be observed due to the projection scenario (see Section 2.2.2). Freshwater ecotoxicity and eutrophication and fossil depletion impacts were the more sensitive impacts during the increasing-yield phase (phase with the largest variation in indicators across the cycle), while Climate change was quite sensitive during both the increasing and alternating yield phases. In addition to the yield variations, the variations of environmental indicators might have been also accentuated by seasonal variations of climate and pest pressure. For instance, year 2008 cumulated the lowest yield of the mature phase and high rainfalls responsible for important leaching of nitrate. In that year, excess of fertilisers compared to the actual yield could not be anticipated by the farmer. A similar pattern was also observed for toxicological impacts because disease and pest attacks would also be strongly dependent on climate conditions.

3.2 Contribution analysis for the chronological model

Across the cradle-to-farm-gate life cycle of oil palm fruit (Fig. 3a), the productive phase accounting for 18/21 (86 %) of the whole cycle contributed to the largest share of most impact categories (75–95 %) except for freshwater eutrophication and water depletion. Although the non-productive phase only accounted for 14 % of the cycle length, it contributed to 7–40 % of all impact categories. Since the palm plantations were not irrigated, the water depletion category, which only considered 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 and fertiliser dilution along the whole cycle. Across the other impact categories, fertilisers (production, transport from manufacture site to storage point, and field emissions) contributed greatly to climate change, terrestrial acidification, marine eutrophication, and fossil depletion (70–90 %). Other interventions (including mostly pesticide

Fig. 3 **a** Contribution analysis from cradle-to-farm gate for environmental impacts (ReCiPe-Midpoint (H)) of palm oil fruit from Indonesia modelling the full cycle. Results are expressed per kilogram of fresh fruit bunches. All ReCiPe midpoint impacts are given in the Electronic Supplementary Material (S1a). **b** Contribution analysis from cradle-to-farm gate for environmental impacts (ReCiPe-Midpoint (H)) of small citrus from Morocco modelling the full cycle. Results are expressed per kilogram of raw fruit. All ReCiPe midpoint impacts are given in the Electronic Supplementary Material (S1b)
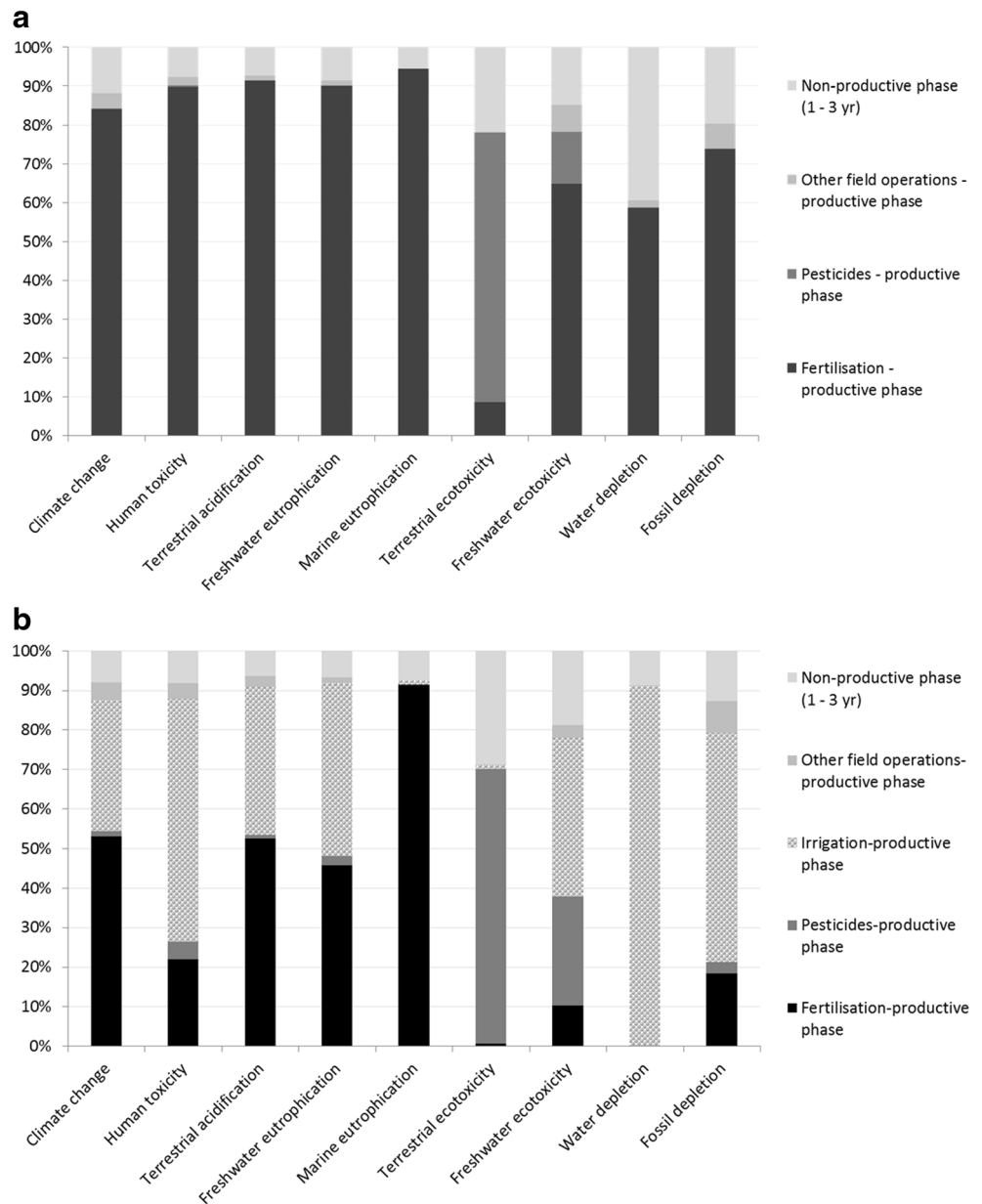
application) contributed more to the toxicity impact categories (~75 %), freshwater eutrophication (25 %), water depletion (28 %), and fossil depletion including fuel use (22 %). Fossil depletion was mostly related to fossil fuel used for field operations such as annual plantation maintenance and fertiliser broadcasting; the latter being included in "other field operations" and not "fertilisation". The overall great contribution of fertilisers to the various environmental impacts explained the high sensitivity of indicators to changes in fertiliser management and yields along the first plantation years (Fig. 2a).

Across the cradle-to-farm-gate life cycle of small citrus, the tree planting and non-productive years (non-productive phase) contributed between 6.5 % for terrestrial acidification and 29 % for terrestrial ecotoxicity (Fig. 3b). For categories other than

toxicity impacts, fertilisation and irrigation represented the two main contributors. This was due to the production and field emissions of fertilisers and fossil fuel use (for irrigation). For terrestrial ecotoxicity, the on-field emission of pesticides was the almost exclusive contributor shared between the non-productive (29 %) and the productive phases (70 %). The share of the non-productive phase 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 for pumping) 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 %).

3.3 Sensitivity analysis to modelling approach for perennial crop cycle

In Fig. 4a, b, modelling approaches are compared to the baseline modelling of the whole cycles. In both cases, the results were highly sensitive to the modelling 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, all models apart from the year 4 (1995) proved lower impacts than the baseline full cycle accounting. The lower impacts are partly due to the non-accounting for the non-productive phase. Hence, the discrepancies are slightly more severe for the last impact categories to which the non-productive phase contributed more (terrestrial ecotoxicity, freshwater ecotoxicity, water and fossil

Fig. 4 **a** Environmental impacts (ReCiPe-Midpoint (H)) for different modelling approaches of the perennial crop cycle for oil palm fruits from Indonesia: full cycle modelling (21 years, reference baseline 100 %), 3-year average, years 7, 8 and 9. Results are compared per kilogram of fresh fruit bunches. All ReCiPe midpoint impacts are given in the Electronic Supplementary Material (S1a). **b** Environmental impacts (ReCiPe-Midpoint (H)) for different modelling approaches of the perennial crop cycle for small citrus from Morocco: full cycle modelling, 3-year average, years 7, 8 and 9. Results are expressed per kilogram of raw fruit. All ReCiPe midpoint impacts are given in the Electronic Supplementary Material (S1b)
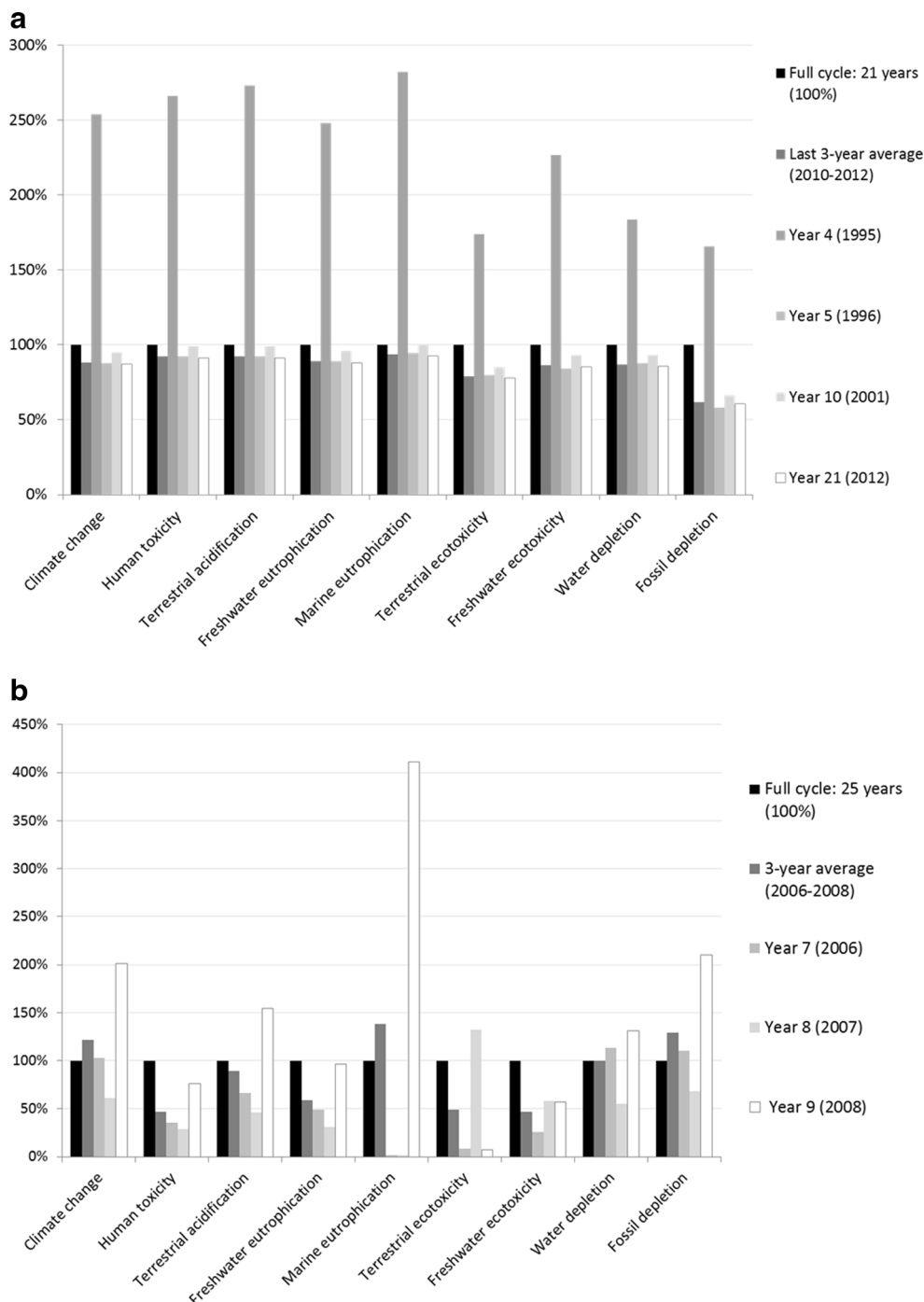
depletions). However, the exclusion of non-productive phase did not allow for explaining the whole range of discrepancies across models. The year 4 showed a very specific pattern with lower yields and more inputs that the average productive years. The resulting impact indicators ended up much higher than for all other models (1.7–2.8 times the baseline model). On the contrary, the year 6 showed overall lower impacts than the other models across all impact categories (0.4–0.75 times the baseline model). These results could be explained by the switch observed over the cycle evolution from highly increasing fertiliser doses and low yields to slightly lower fertiliser doses and high yields. This phenomenon may have also been accentuated by climatic conditions. Should the plantation be assessed at its early development stage, the environmental impact indicators would convey short-term contradictory messages. Results from years 10 and 21, as well as for the last 3-year average model (years 19–21) were similar. Agronomical practices and performance were quite stable after the first 6 years, and variations were due to yearly variations in climate and plantation stand conditions. The last 3-year average covered 60–95 % of the baseline model across all impact categories and did not provide any added value compared to the year-21 model.

In the case of small citrus, compared to the full cycle model, the 3-year average model showed results between 47 % for freshwater ecotoxicity 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 3 years over 25 and did not reflect the whole orchard cycle properly. The single year models 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 model 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.

4 Discussion

4.1 Representativeness and related data collection issues

As recommended by several authors (Bessou et al. 2013; Cerutti et al. 2011; Cerutti et al. 2013), perennials show important specificities that should be accounted for in LCA studies. Based on two contrasted case studies, our study demonstrated and quantified the highly variable agronomic performance and environmental impacts over the perennial stand's life cycle. It highlighted the significant contributions of non-productive and increasing-yield phases and the consequences of alternating yield phenomenon such as in citrus orchards. We also demonstrated the great sensitivity of LCA results to

the modelling choices for the perennial cropping systems. Overall, modelling perennial cropping systems as annual ones can lead to totally misleading conclusions. The choice of the modelling approach depends on the objective of the study and the data availability. In all cases, data sets should at least cover all important phases and include part of the inter-annual variability through representative averages.

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. For toxicity impacts, variations across models were also due to the use of different active molecules from 1 year to the other in relation to farmers' practices and evolution of regulations. In the case of oil palm fruit, the ranges of explored treatments and yields over the randomly selected single years were similar and smaller than the overall recorded data, respectively. In particular, in year 1997 that was not modelled in the study (see the Electronic Supplementary Material, S1a), the yield was much higher (+34 %) than the average of 26.94 kgFFB/ha ±16 % over the productive phase (to be also compared with the average over the individual assessed years of 23.49 kgFFB/ha ±26 %). Considering that the agricultural treatments did not much vary in the experimental conditions (±5–9 % depending on the fertiliser), assessing year 1997 alone would have accentuated the bias illustrated by selecting single year instead of the whole cycle.

The data set on the oil palm fruit production was related to a field trial that started in 1992. Due to the experimental conditions (the tested parameter was the fertiliser treatment), almost no variation on fertiliser doses occurred during the productive years. Hence, the captured inter-annual variability in this study, mostly traducing climatic variability, alternating and long-term processes, was very likely lower than what would occur in a commercial plantation. In commercial plantations, despite standard baseline practices, adjustments can be done year by year especially for the fertilisation based on regular diagnoses of the stand nutritional state (i.e. foliar analyses). Moreover, application of organic fertilisers, which are commonly produced from oil mill residues, may induce long-term changes in soil fertility (Carron et al. 2015). Finally, plantations older than 22 years usually do not receive any longer fertilisation (Choo et al. 2011). Accounting for these elements would probably further increase the discrepancies across the various models tested.

In the citrus case, data were only available for the first 9 years of the theoretical complete cycle of 25 years. The chronological modelling was hence not exactly an ideal chronological modelling but rather a hybrid with the modular one. This hybrid modelling still allowed for highlighting bias due to partial modelling. It also represented a very common

situation for LCA practitioners who most often aim at evaluating modern or current technology and will not sample too old orchards that were planted under outdated technologies (with low tree density, gravity irrigation for instance). In our case study, most of the mature phase was modelled as a module based on an average of representative mature years and extrapolated to cover the whole duration of this phase. Hence, the modelled cycle is based partly on historical data and partly on extrapolated data. In such cases, prospective analyses could be useful to anticipate on changes in practices or climate. A chronological modelling based on a retrospective data set over 25 years is highly relevant to evaluate a complete system a posteriori, but a modular modelling may be more suitable to evaluate a system with state-of-the-art technologies or to test the sensitivity of the system to changes in technologies. This may be particularly true in the case of changes of applied pesticide substances. Given the sensitivity of ecotoxicity impact categories to substance toxicities, changes in applied substances may drastically influence the results. If substances become prohibited by law along a perennial crop cycle, the use of a modular modelling with a cut-off year at the moment of practice change will allow for testing the sensitivity of results to this change.

Although the chronological modelling appears to be the unique way to avoid hidden bias, in most cases, available datasets do not cover the full plantation lifespan. It is important in those cases to identify the various phases over the whole plantation cycle that are critical in terms of physiological development and input/output flows. The number and relative importance of the various development stages and studied phases highly depend on the studied cropping system. Immature (non-productive) and mature (productive) phases are generally the two basic phases of all perennial crops, but further refinement may be suitable when data is available. In particular, the mature phase may be sub-divided with an initial "increasing yield" phase as well as a "decreasing yield" phase when the stand gets older and its performance declines. The final number of phases and their durations may be constrained by both inherent properties of the agroecosystem and technical or economic constraints. For instance, the end of the oil palm plantation cycle is more related to technical constraints to harvest the high fruit bunches in a cost-effective way than to the potential productivity of the palm trees, which remains high. On the contrary, a decreasing-yield phase may be more critical to assess in the vineyard case for instance, where qualitative objectives may take over quantitative ones towards the end of the crop cycle. The relative duration of the different phases should not be an a priori selection criterion. The immature phase has proven influential in our case studies despite its short duration within the whole cycle. The duration of the immature phase may greatly vary across systems, and its impact may be more or less diluted when amortised over the whole cycle. However, it may be important to capture the

impact of this phase, no matter its duration, in order to integrate potential impacts linked to the disequilibrium created by the transition due to land use change (LUC) or land preparation and planting. The relative duration of each potential phase depends eventually on the actual crop cycle length which may end up different from the theoretical cycle length. We generally recommend defining the crop cycle and the phases to be assessed in close connection with field experts and the study objective. The chronological modelling should be selected when the study objective is to investigate precisely the comprehensive influence of a field management without smoothing out its effects by combining plantation blocks or orchards. This would also imply the concomitant use of relevant models to properly model the management effects. In other cases, other approaches may be applicable (Bessou et al. 2013). Once critical phases are identified, it is then advised to collect representative data sets allowing for the characterisation of each of these phases based potentially on composite data sets from several years and plots (combining synchronic and diachronic sequences). The selected plots must be subject to similar soil and climate conditions in order to minimise potential bias. The perennial cycle is finally modelled as a weighted average of each contributing phase (or module) in relative proportions to their durations in the theoretical or practical plantation lifespan. It has been described as the modular modelling (Bessou et al. 2013).

4.2 Specific models for field emissions

In this study, default emission factors were used to estimate field emissions (e.g. Brentrup et al. 2000; IPCC 2006; Prasuhn 2006, etc.). However, perennial crops especially in the Southern countries are under-represented in current statistical models to estimate field emissions (Bouwman et al. 2002; Stehfest and Bouwman 2006). Similarly, operational models developed for annual crops in temperate regions such as those used in the Ecoinvent database are not valid for perennials in Southern countries, and more adapted ones are yet to be developed (Bessou et al. 2013; Perrin et al. 2014; Payen 2015). The modelling of field emissions in perennial cropping systems needs further research and improvement. It should combine parameters of soil, climate and practices and long-term recycling and remobilising mechanisms. Indeed, the evolution of a perennial stand over its cycle induces long-term exposure to climate hazards, specific development and feedback mechanisms as well as subsequent adaptations in agricultural practices that should be accounted for in the assessment. Some of these potential long-term effects were illustrated in our case studies. Without complete mechanistic models to simulate the agroecosystem functioning over the whole crop cycle, the only way to account intrinsically for such phenomena is to widen the data sets to at least account for each development stage of the stand development and, if possible, all years of the crop cycle. Developing

knowledge on the functioning of the perennial agroecosystems is needed to better model long-term effects such as buffer capacity, resilience or adaptation pathways, root propagation, etc. In the case of oil palm for instance, research work is ongoing to better assess and model the roles of crop residues as organic fertilisers, notably empty fruit bunches back from the mill, and long-term effects on soil quality beyond the net nutrient inputs. The effects of organic fertilisers on soil biodiversity (Carron et al. 2015), on soil moisture (Carr 2011), or on palm root propagation (Kheong et al. 2010), etc. are notably investigated. In light of this new knowledge and subsequent engineering models allowing for more accurate estimates of production factors and field emissions, data collection to represent the full perennial cycle and associated emission processes may be eased. By including expert-based retrospective or prospective analyses of critical conditions in terms of stand evolution and input/output fluxes, strategies may be also developed to optimise data collection across chronosequences and minimise bias in modular modelling compared to the chronological one.

Finally, for irrigated systems such as citrus cropping systems, impacts due to water use should be modelled based on a proper inventory of input and output water fluxes accounting again for soil, climate and practices. This constitutes another key research perspective if one wishes to apply most recent LCIA methods for water deprivation such as Boulay et al. (2011) and Berger et al. (2014). Although FAO has been proposing several generations of water budget models: CROPWAT (Allen et al. 1998) replaced by AQUACROP (Steduto et al. 2012) with increasing scientific relevance for herbaceous crops, these models are still not available for perennials especially for Southern perennials such as citrus showing highly specific transpiration patterns (Payen 2015).

Beyond the development needs intrinsically linked to the long-term dynamic nature of perennial cropping systems, further harmonisation is also needed to account for related phenomena such as land use change and carbon sequestration that are particularly critical in the case of perennial crops. The long-term dimension may imply specific complications such as tracking back LUC decades ago, ensuring LUC amortisation consistency in the future, or tracing the long-term fate of co-products in order, for instance, to assess carbon storage in exported woody parts. Despite some consensus (e.g. 20-year amortisation of LUC from IPCC) and recent work on guideline harmonisation (PAS2050-1 BSI 2012; Milà i Canals et al. 2012; Newell and Vos 2012), assessments still vary and knowledge still lacks to properly account for all involved mechanisms.

5 Conclusions

In two contrasted perennial case studies, one on palm oil from Indonesia, the other on small citrus from Morocco, different modelling approaches were tested to account for the perennial crop cycle. The baseline model included a complete modelling of the crop cycle while a 3-year average model and three single year models were also tested. Despite very different features, the two case studies contributed to draw consistent conclusions on the modelling of perennial crops in LCA:

1. Non-productive years have a non-negligible share in the environmental impacts of perennial crops 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 model is not sufficient to capture properly the full perennial crop cycle and can be misleading.

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.

Analysing two contrasted LCA case studies, we highlighted the specific character of perennial crops in LCA and how important the inclusion of all their phases is to account for their variable inputs and outputs over years. Other crucial and specific aspects of perennial crops especially in the Southern countries still warrant further research and better modelling notably regarding:

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

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