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ABSTRACT

Several papers highlight methodological challenges related to the lifecycle assessment (LCA) of fruit production systems. These concern both the limited number of impact categories assessed in current LCA literature and the narrow view on the full production phase of an orchard cycle. This article addresses these challenges and contributes to improving the scientific knowledge on impacts associated with less productive years within an orchard cycle, and how these affect the impact associated with an entire fruit growing cycle. Using apple as a case study, an LCA is performed to obtain the impacts associated with young and old low productive trees, alongside those associated with trees in full production. Using the ILCD impact assessment method, the LCA is based on a large dataset of apple orchards in Flanders (Belgium), covering three production systems (conventional, integrated and organic production) and accounting for input and yield variability. The annual median impact values are used to describe a “typical” orchard for each orchard phase and production system. In conventional farming, lowest annual median impacts are mostly found in the full production phase while highest impacts are observed in the old low productive orchards. In integrated and organic production on the other hand, the lowest annual median impacts mostly occur in the old low productive orchards while highest impacts are found for the young low productive trees. Results for organic farming must however be interpreted with care, following the small sample size of organic producers. To calculate the impacts associated with a full orchard cycle, an orchard model was built based on the annual median impact within each apple bearing orchard phase and production system and using weighting factors based on the yields obtained within each of the orchard phases. Across the three production systems, the two low production phases are responsible for 27 to 38% of the calculated orchard cycle impact. Calculated impacts for the entire orchard cycle are, on average across the impact categories, higher than full production impacts in conventional and integrated farming, while lower in the case of organic farming. A mere focus on high productive trees leads to an underestimation of, on average, 18% in conventional farming and 11% integrated farming, versus an overestimation of 11% for organic farming. Inclusion of non-productive phases such as nursery and planting and destruction of the orchard, would further alter the orchard cycle impacts.

1 Introduction

The Life Cycle Assessment (LCA) approach is widely used to evaluate environmental impacts of food products, and its use in agricultural systems has clearly risen in recent years (PréSustainability, 2014). However, in literature on LCAs of fruit production systems in particular, several authors highlight methodological challenges related to both the data inventory and the impact assessment: in a review on LCAs applied to perennial cropping systems, Bessou et al. (2013) conclude that the majority of LCAs only focus on energy and greenhouse gases, thus neglecting other potentially relevant impact categories such as eutrophication and acidification. In addition, many LCA studies tend to focus on full productive years of fruit orchards only, thereby neglecting impacts occurring in less productive years. In their review on LCA for perennial cropping systems, Bessou et al. (2013) found that in 70% of the reviewed studies, the inventory is based on one productive year only (with this percentage going up to 88% if palm oil studies are excluded). Bessou et al. (2013) and Cerutti et al. (2014, 2011) therefore stress the importance of taking into account the whole orchard lifetime. Cerutti et al. (2014) reviewed the application of LCA in the fruit sector, and looked at modelling approaches for orchard systems. According to the authors, the following two characteristics affect the complexity of modelling fruit systems: firstly, orchards are biological systems, and thus high variability and unpredictability in inputs and outputs can be expected. Secondly, orchards are perennial systems, meaning that certain processes only occur once in an orchard lifetime, while others are repeated annually. Additionally, orchards mostly have low (or no) yields in the first years of their lifetime. As such, a mere focus on the productive period may lead to underestimations of the environmental impact of the final product. The authors therefore suggest building an orchard model based on the following six stages: (1) nursery, (2) orchard planting and field preparation, (3) early low production phase due to system's immaturity, (4) full production phase, (5) low production phase due to plant senescence, and (6) removal and disposal of plants. In this model, the low and full production orchard stages are taken into account using weighting factors based on the yields obtained in these phases. Bessou et al. (2016) further applied three different modelling approaches for calculating the environmental impact for producing 1 kg of oil palm fruit and citrus: chronological modelling over the complete orchard cycle, a 3-year average from the full productive orchard phase, and consideration of various single full productive years. The range in obtained LCA results for each of the modelling choices illustrates the importance of including all phases of a perennial crop cycle and of accounting for highly variable annual inputs and outputs.

In 2012, fruit production in Belgium covered 17729 ha or 1.33% of the cultivated area. Almost 40% of the fruit production area in Belgium is used for apple production, with Jonagold and Jonagored occupying over 60%. As over 90% of the fruit production area is found in Flanders, it is not surprising that 91% of the apple area is located in Flanders. In 2012, 2.5% of the total fruit production area and 0.03% of the apple production area in Flanders was further occupied by organic fruit producers and fruit producers in conversion, with the total area used for organic production rising year after year (ADSEI, 2014, 2013a, 2013b, Samborski and Van Bellegem, 2015, 2013). Looking at production volumes, Belgium produced 220 Gt apples in 2012, representing 2% of the EU-28 production (European Commission, 2013; VLAM, 2015).

Using apple as a case study, this paper offers insight into the environmental impact of Flemish fruit production systems, including the lower production phases. The objective of this paper is twofold. Firstly, we provide a typology of the different apple bearing orchard phases by assessing a large sample of fruit orchards over a period of eight years to account for natural seasonal variability. The dataset contains orchards managed according to three different production systems (conventional, integrated and organic production) and, based on their age, belonging to three orchard production phases, similar to the three apple-bearing phases (phases 3-4-5) in Cerutti et al. (2014). The LCA includes a broad range of impact categories and provides an analysis of the contributing field operations and associated embodied impacts of products applied. We hereby note that, even though all three production systems are included in the assessment, our main goal was not to compare amongst these three production systems, but rather show the reader that there are in fact differences in production systems. Secondly, using the median impacts within each production system and each apple bearing orchard phase, we build an orchard model based on the yield contribution of each orchard phase to the total yield obtained throughout the orchard lifespan, and compare the resulting full orchard cycle impacts for a broad range of impact categories with those of the full production phase. Our hypothesis is that, for the case study, the inclusion of low productive apple bearing years leads to higher, yet more realistic, environmental impacts per tonne.

2 Materials and Methods

2.1 Goal and scope

The goal of this LCA is to assess the environmental impacts of the production of 1 tonne (t) of apples leaving the farmers' hands (including the last transport step by the farmer to the auction or sorting centre) for different production systems, and this for three orchard production phases. Additionally, we calculate the impacts associated with a full orchard cycle.

2.2 Life cycle inventory (LCI)

2.2.1 Data collection

The EU Farm Accountancy Data Network (FADN) gathers accountancy data of about 80000 holdings and is an instrument for evaluating the income of agricultural holdings and the impacts of the EU Common Agricultural Policy. To ensure representativeness of the farm sample, statistical stratification is applied, using region, economic size and type of farming as criteria (FADN, 2010). In Belgium, the sample includes 1200 agricultural holdings, of which 720 are located in Flanders (De Becker, 2007). The FADN dataset used for the purpose of this study, contains data from 79 commercial apple farmers in Flanders, covering a period of 8 years (2005-2012), applying the conventional, integrated, or organic production system. Integrated Production (IP) is based on Integrated Pest

Management (IPM) and was initially a voluntary scheme¹ with environmental requirements beyond conventional farming practices; as of 1 January 2014, IPM has become obligatory². Organic farming relies on stricter environmental requirements, such as limited and selective use of fertilisers and plant protection products. Criteria and standards are laid down in European legislation³ and are subsequently translated into regional legislation in Flanders⁴.

For each farm, data are available at orchard level, with each orchard containing trees from the same cultivar, but with possibly differing ages. A selection was made of those orchards cultivating Jonagold or its mutants, leaving us with in total 1030 annual orchard data records⁵. Next, for each orchard record, the orchard age was determined, categorizing each orchard record according to a production phase⁶. Based on Cerutti et al. (2014), Mouron et al. (2012, 2006b) and personal communication with Fruitteeltcentrum⁷ (2013), we distinguished between “young and low production trees” (orchard age ≤ 3 years), “mature and full production trees” (orchard age between 4 - 15 years), “old and low production trees” (orchard age ≥ 16 years), and “mixed production orchards” (trees of different production phases on one single orchard). In line with the objectives for this research, we only retained the two low production phase orchards and the full production phase orchards for each production system, and left out the mixed production sites. As a last step, we excluded those records that did not contain data on production yield. This left us with 512 orchard records, spread over in total 141 orchards on 70 farm holdings over the course of 8 years, as shown in Table 1. In this dataset, 13 farms apply conventional production, 50 integrated production and 2 organic production, while 5 holdings have both conventional and integrated production orchards. The area of the orchards ranges between 0.04 and 29.4 ha, with an average value of 2.5 ha and a median of 1.83 ha. All orchards are based on dwarf rootstocks. The average tree density is 2076 trees/ha, ranging from 1323 to 3392 trees/ha and with a median value of 2036 trees/ha. The majority of the farms is located on sandy loam (69%) or loam (21%) soils, and 6% on sandy soil and 4% on stony-loamy soils. Flanders has a temperate climate (category Cfb within the Köppen climate classification, (Peel et al., 2007)), with an average rainfall of 800 mm per year (KMI, 2016).

¹ Decision of the Flemish Government of 26 March 2004 to recognize the integrated production method for pome fruits and the producers applying this cultivation method

² Following Directive 2009/128/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for Community action to achieve the sustainable use of pesticides

³ Council Regulation (EC) No 834/2007 on organic production and labelling of organic products, and Implementing Commission Regulation (EC) No 889/2008, later amended by Commission regulation (EC) No 271/2010

⁴ More information on the legislation current applicable in Flanders, can be found the Supplementary Materials of Goossens et al. (2017).

⁵ An orchard refers to an area with trees from the same cultivar, therefore, one farm can have several orchards depending on the number of cultivars it produces. An orchard record is a data record containing information on inputs and yield for one specific orchard, for one specific year. As our dataset covers a period of 8 years, each orchard can have in total maximum 8 orchard records.

⁶ We hereby calculate the age of the orchard as of its planting date, thus leaving out the first year(s) of the apple tree in the nursery stage. The trees used for apple growing are generally 1 year old feathered trees. In case no feathered trees are obtained after one year, trees are cut in the nursery (the so-called Knip-boom technique), after which they stay there for another year before being sold to apple farmers. As such, the apple trees, upon arrival at the apple farm, have already received 1 or maximum 2 years of care (and thus inputs) in the nursery.

⁷ The Fruitteeltcentrum is a KU Leuven R&D division for applied research in fruit cultivation.

Table 1 Overview of the 512 orchard records included in the assessment with the “Column %” showing how the orchard records of each orchard production phase are distributed over the production systems, and the “Row %” showing how the orchard records of each production system are distributed over the orchard production phases.

Production system	Total	Orchard production phase								
		Low (young)			Full			Low (old)		
		N	Column %	Row %	N	Column %	Row %	N	Column %	Row %
Conventional production	64	14	24%	22%	48	11%	75%	2	6%	3%
Integrated production	424	40	68%	9%	364	86%	86%	20	63%	5%
Organic production	24	5	8%	21%	9	2%	38%	10	31%	42%

2.2.2 System boundaries

The field operations included in the assessment are: fertilization, plant protection and chemical sanitation measures, mechanical work, harvest and transport by the farmer. Irrigation and weather damage prevention measures are included to a limited extent as tap water use for irrigation and frost protection is included, but related electricity use is not as our data inventory did not allow us to differentiate between electricity used for irrigation, lighting, and cooling for those holdings with cold storage rooms on the farm premises. For all field operations, unless specified otherwise here below, we include manufacturing and transport of energy carriers, pesticides, fertilisers and water used. Excluded are the manufacturing and maintenance of machinery, equipment and materials used such as tractors, harvesting machines, wooden poles, hail nets, and housing for pheromone, as well as construction and maintenance of farm buildings and infrastructure. Field losses are indirectly taken into account as the inventory covers all inputs needed to cultivate both the harvested (= “yield”) and the non-harvested apples (= “field loss”). We do not differentiate between apples of various quality, and consider all apples harvested, whether for the purpose of direct human consumption or redirected to the processing industry.

The inventory contains, for each orchard record, data on the yield obtained in the respective growing season and on inputs of energy, water, fertilisers, pesticides and land. The list below provides more detail on the inputs contained in the inventory. Embodied impacts related to production of the inputs were mainly taken from the ecoinvent v3.2 and Agri-footprint 2.0 databases available in SimaPro 8 (PRé Consultants, the Netherlands), using respectively “allocation, default” and “economic allocation”⁸, while direct field emissions were calculated using IPCC guidelines (IPCC, 2006a, 2006b) and methodologies described in the Agri-footprint manual (Blonk Agri-footprint, 2015a) or ecoinvent reports (Nemecek and Kagi, 2007; Nemecek and Schnetzer, 2011). Detailed emission calculations for the various input categories can be found in Part 1 of the Supplementary Materials.

- Energy: fossil energy used (incl. lubricants) for farm equipment and vehicles during field operations. Energy use for vehicles refers to transport on the orchard and farm premises, transport related to fetching agricultural inputs by farmers, and transport by farmers to bring the harvested apples to the auction or sorting centre. Unfortunately, our dataset only includes the cumulative amount of all energy sources used

⁸ Both models allocate reference products and by-products based on their market value (“economic allocation”)

for field operations and transport, and does not allow us to identify the amounts of energy used for each field operation or transport step.

- Water: use of tap water for for example irrigation and frost protection measures.
- Fertilisers: use of both organic and synthetic fertilisers. As a wide range of fertiliser products is used within the different production systems, the fertilisers were grouped into in total 36 fertiliser categories as listed in Part 2 of the Supplementary Materials (Table S1). Emissions resulting from fertiliser application were calculated based on the nitrogen, phosphorous and heavy metal content of each fertiliser applied, with the exception of micro-nutrient fertilisers for which no emissions were taken into account. A special case within the fertilisers applied, is the organic fertiliser blood meal, which is a slaughterhouse by-product based on blood from cattle, chickens and pigs, and which is applied as high-nitrogen fertiliser powder. Organic fertilisers based on waste products such as animal manure or compost are generally considered as residual products for which the embodied emissions are allocated to the systems these waste streams originate from (Blonk Agri-footprint, 2015b; Notarnicola et al., 2015). As such, in this paper, no impacts are considered for the production or on-farm storage of these waste products, while impacts associated with farmers transporting them to the field are included in the input category “energy use”. For blood meal however, which undergoes processing before being ready-to-use, the embodied impacts were taken into account and its production process was assumed to be similar to the one for “blood meal, spray dried, consumption mix, at feed compound plant” from the Agri-footprint database.
- Pesticides: use of fungicides, herbicides, insecticides, rodenticides, pheromones and plant growth regulators, covering in total 199 active ingredients (a.i.) as listed in Part 2 of the Supplementary Materials (Table S2). In 76% of the data records, no data on the production of the a.i. - or of similar substances - could be found. In order to avoid the use of “pesticide unspecified” from ecoinvent, which cannot be expected to be representative, the production phase of pesticide products was left out of the inventory (in line with the approach followed by Agri-Footprint, personal communication, 29.01.2016). The emissions of the a.i. applied were modelled based on Audsley et al. (2003) with 85% of the applied quantity being emitted to the soil, 10% to the air, and 5% staying on the leaves/fruits. The ecoinvent dataset for impacts of substances when released to soil and/or air covered 74% of the substances used, and up to 99% when including replacement of similar substances; the remainder 1% of substance impacts were modelled as “pesticide unspecified” as a last resort at the moment.
- Input of land: use of arable land for the apple orchards, expressed in ha. We assumed that all land occupied by the apple orchards had been used for agricultural purposes for a long time; as such, no land transformation needs to be taken into account (Stoessel et al., 2012).

2.3 Life Cycle Impact Assessment (LCIA)

The product environmental footprint and related ILCD (International reference Life Cycle Data system) impact assessment method was applied, resulting in impacts spread over 16 impact categories (EC-JRC, 2010). For the purpose of this paper, not all impact categories were analysed in depth. To facilitate selection of impact categories,

normalisation of the impact values is often performed: those impact categories for which the normalised values are relatively equal across the products under comparison, can then be assumed to be less interesting to analyse than those with a broad range of normalised values. In our dataset, no such “relatively equal normalised values” were found across the nine combinations of production systems and orchard production phases. We therefore based our selection of impact categories on literature (Alaphilippe et al., 2012; Bessou et al., 2016; Brentrup et al., 2004; Cerutti et al., 2011b; Milà i Canals et al., 2008; Mouron et al., 2006a; Olafsdóttir et al., 2014; Sessa et al., 2014), and focused our analysis on: climate change (kg CO₂ eq), acidification (molc H⁺ eq), terrestrial eutrophication (molc N eq), freshwater and marine eutrophication (kg P eq and kg N eq respectively), human toxicity - cancer effects (CTUh), freshwater ecotoxicity (CTUe), land use (kg C deficit), water resource depletion (m³ water eq) and mineral, fossil and renewable resource depletion (kg Sb eq). We hereby note that the quality of the characterization factors for the different impact categories used within the ILCD method may in some cases still be unsatisfactory. For example, the European Commission indicates that the impact categories related to toxicity and resource depletion are at the moment rather unreliable (EC-JRC, 2012). In the absence of clear guidance on which impact categories to include or exclude from the analysis, all impact categories selected above were retained.

Environmental impact calculations were performed for each of the 512 orchard records, based on the inputs each orchard received during one growing season and per tonne of apple produced. Due to the skewed distribution of the data, the annual median impact value was used to describe a typical orchard belonging to each of the three production systems and orchard production phases. Our dataset contains in total 512 orchard records, with for each record, information on over 250 different inputs (use of different energy carriers, use of different fertilisers, use of in total 199 different active ingredients, ...). SimaPro does not allow us to easily calculate the associated impacts for all 512 orchards in one single batch, nor does it allow us to calculate the median values. SimaPro was therefore used to calculate the per unit impact values, after which all other calculations were done using JMP Pro 12 (SAS Institute Inc, NC, USA). First, we created a file for each input in SimaPro, containing the applied product and its associated emissions. Next, we calculated the impacts of applying 1 kg of each input, resulting in impacts spread over 16 ILCD impact categories. These impacts were subsequently imported into JMP, and multiplied (as matrices) with data on the annual amounts of inputs per tonne apple used on each orchard. As such, we obtained – for each input category - the annual impacts in each of the impact categories for each one of the 512 orchard records, expressed per tonne of apple. We subsequently summed, for each impact category, the impacts caused by the various input categories to obtain the total annual impact for each of the 512 orchard records. Using boxplots, the median impact values were visualized, complemented with the range of values across the 512 orchard records. Additionally, sample variability was assessed for each production system and orchard production phase.

We traced back the contributing processes to the impact observed within each orchard phase and production system related to the field operations performed: annual use of energy, water, fertilisers, pesticides and land. The relative contribution of each input is obtained through the ratio of its calculated median impact to the sum of the median impact values for each input category. We hereby note that, as the distributive property does not apply to calculating median values, the sum of the median impact values for each agricultural input is not necessarily the same as the

median of the sum of the impacts across the various input categories which we calculated above to describe a typical orchard for each production system and orchard production phase.

2.4 Full orchard cycle impacts

The impacts of the entire orchard cycle were calculated, taking into account the low productive orchard phases next to full productive ones. For each production system, we propose extending the orchard model suggested by Cerutti et al. (2014), basing ourselves on our large dataset of orchard records and using weighting factors based on the median yields obtained within each of the orchard production phases. As mentioned in Section 2.2.1, the young and low production phase is assumed to last for 3 years, followed by 12 years of full production, and subsequently followed by an old and low production phase after which the orchard is destroyed and replanted. Based on the ages of the old orchards contained in our dataset, this phase lasts for 2 years in the case of conventional and integrated production, while it lasts for 6 years in the case of organic production. This approach is in line with the fact that fruits leaving the farm gate may come from both highly and less productive trees, with no indication from which orchard they come from. On a yearly basis, the volume of apples being sent into the post-harvest chain is linked to the volumes or yields obtained in each orchard. The chance for an apple to come from a specific orchard production phase, is therefore proportional to the yield accumulated throughout this phase.

The impact for the full orchard cycle is calculated as follows:

$$\text{Orchard cycle impact}_{j,k} = \sum_{i=1}^3 \text{impact}_{j,k,i} \times \text{yield contribution}_{k,i} \quad (\text{Eq. 1})$$

with the weighting factor “yield contribution” :

$$\text{yield contribution}_{k,i} = \frac{\text{lifespan}_{k,i} \times \text{yield}_{k,i}}{\sum_{i=1}^3 \text{lifespan}_{k,i} \times \text{yield}_{k,i}} \quad (\text{Eq. 2})$$

whereby:

- $\text{impact}_{j,k,i}$ = annual median impact per tonne apples for orchard production phase i, impact category j and production system k
- $\text{yield}_{k,i}$ = median yield obtained in orchard production phase i and production system k
- $\text{lifespan}_{k,i}$ = lifespan of orchard production phase i and production system k

3 Results

3.1 Sample characteristics: key agronomic data

Table 2 lists the annual median inputs applied and median yield obtained within each production system (conventional production “CONV”, integrated production “IP”, organic production “ORG”) and within each orchard production phase (young and low production trees “1”, mature and full production trees “2”, old and low production trees “3”). More statistical information on the annual inputs and outputs can be found in Part 3 of the Supplementary Materials (Table S3). The range in yield seems to be very large, and is overlapping between the three orchard production phases. We hereby note the limited number of organic low production phase orchards, and the low yield found in 4 out of 5 orchard records taken into account (only one record had a comparable yield to the median yields obtained in the other production systems). We therefore stress that this paper aims at providing a typology of the different production systems and production phases of the orchards within our sample. The findings are thus applicable to this specific case study and not necessarily to the broader range of all apple orchards in Flanders or beyond. Table 2 further also contains information for calculating the full orchard cycle impact in Section 3.4: lifespan and yield contribution (see Equation 2) of each orchard production phase.

Table 2 Characteristics of the different systems under investigation: annual median inputs needed to produce 1 tonne of apples and annual median output (yield) per ha for the conventional production system (CONV), the integrated production system (IP) and the organic production system (ORG), each system having young low productive years (denoted with 1), full productive years (denoted with 2) and old low productive years (denoted with 3). The typical lifespan of each phase as well as the resulting yield contribution (Equation 2) are indicated as well.

	CONV1	CONV2	CONV3	IP1	IP2	IP3	ORG1	ORG2	ORG3
INPUTS									
Energy (MJ/t)	308	347	478	464	272	280	5239	603	331
Drinking water (10^{-2} m ³ /t)	8.59	2.79	0	0	5.24	18.4	355	0	25
Synthetic fertilisers (kg/t)									
Total product use	18.8	15.1	18.5	57	14.7	13.9	197	64.3	27.3
N ($*10^{-1}$)	20.5	11.1	16.1	28.6	10.8	7.88	36.4	16.3	1.07
P ($*10^{-2}$)	21	5.72	33.4	47.8	16.6	7.17	0	14.2	0
K ($*10^{-1}$)	13.9	2.23	18.7	17	6.29	2.04	0	13.8	5.88
Organic fertilisers (kg/t)									
Total product use	0	0	220	0	0	0	3230	0	15.2
N	0	0	2.07	0	0	0	17.4	0	1.22
P ($*10^{-1}$)	0	0	3.96	0	0	0	51.3	0	0
K	0	0	1.61	0	0	0	1.65	0	0
Pesticides (kg a.i./t)									
Fungicides ($*10^{-1}$)	7.55	5.74	5.66	10	4.70	3.34	152	8.60	6.28
Herbicides ($*10^{-2}$)	12.0	9.81	12.2	14.6	9.55	7.05	0	0	0
Insecticides ($*10^{-2}$)	3.34	3.75	9.78	5.68	3.03	2.25	96.1	3.93e-2	14
Pheromones ($*10^{-2}$)	0	0	0	0	0	0	4.56	0	0
Plant growth regulators ($*10^{-4}$)	2.55	2.88	26.8	11.1	4.19	2.20	0	0	0
Rodenticides	0	0	0	0	0	0	0	0	0
OUTPUTS									
Yield (t/ha)	28.5	43.1	41.1	25.0	53.5	65.1	2.39	48.6	48.8
ORCHARD CYCLE									
Lifespan (years)	3	12	2	3	12	2	3	12	6
Yield contribution (%)	12	76	12	9	76	15	1	66	33

3.2 Environmental burdens associated with each production system and orchard production phase

Table 3 lists the annual median impacts per tonne apples within each production system and orchard phase for the ILCD impact categories under investigation (please refer to Part 3 of the Supplementary Materials, Table S4, for statistical details). The next sections will further analyse the impacts, including how the use of each agricultural input contributed to this. As many studies tend to focus on the full production phase only, as also noticed by Bessou et al. (2013) and Cerutti et al. (2014, 2011b), the values between brackets in Table 3 show how the less productive phases perform compared to the full productive phase. Table 3 further also lists the impact of the full orchard cycle, as calculated and analysed in Section 3.4.

Table 3 Annual median impacts per tonne apples within each production system and orchard production phase for (a) the conventional system (CONV), (b) the integrated production system (IP) and (c) the organic production system (ORG), each system having young low productive years (denoted with 1), full productive years (denoted with 2) and old low productive years (denoted with 3). The values between brackets for the low productive phases indicate how these phases perform compared to the full productive phase: positive values refer to the lower productive phase having a higher environmental impact than the full production phase, while negative values refer to a lower environmental impact for the low productive phase. The last column lists the impacts associated with a full orchard cycle. The values in bold indicate that the full orchard cycle impact is higher than that of the full production phase (denoted with 2 in the table). In these cases, a mere focus on the full production phase would be an underestimation of the full orchard cycle impact.

a) CONVENTIONAL PRODUCTION						
Impact category		Unit	1 Low (young)	2 Full	3 Low (old)	Entire Orchard cycle
Climate change	CC	kg CO ₂ eq/t	75.1 (+24%)	60.4	106 (+75%)	67.7
Human toxicity, cancer effects	HTC	10 ⁻⁶ CTUh/t	6.51 (+102%)	3.22	16.5 (+413%)	5.22
Acidification	AC	10 ⁻¹ molc H ⁺ eq/t	15.7 (+38%)	11.4	27.5 (+142%)	13.8
Terrestrial eutrophication	TEU	molc N eq/t	6.63 (+52%)	4.36	11.8 (+171%)	5.53
Freshwater eutrophication	FEU	10 ⁻³ kg P eq/t	31.5 (+137%)	13.3	45 (+239%)	19.3
Marine eutrophication	MEU	10 ⁻¹ kg N eq/t	10.5 (+62%)	6.48	26 (+301%)	9.33
Freshwater ecotoxicity	FET	10 ³ CTUe/t	6.44 (+1%)	6.39	3.49 (-45%)	6.05
Land use	LU	kg C deficit/t	77.8 (-19%)	96.1	160 (+67%)	102
Water resource depletion	WD	10 ⁻² m ³ water eq/t	9.39 (+14%)	8.22	15 (+82%)	9.18
Mineral, fossil & renewable resource depletion	MD	10 ⁻⁴ kg Sb eq/t	7.26 (-52%)	15.0	46.3 (+208%)	17.8

b) INTEGRATED PRODUCTION						
Impact category		Unit	1 Low (young)	2 Full	3 Low (old)	Entire Orchard cycle
Climate change	CC	kg CO2 eq/t	144 (+146%)	58.6	56.8 (-3%)	65.9
Human toxicity, cancer effects	HTC	10 ⁻⁶ CTUh/t	8.62 (+179%)	3.09	2.13 (-31%)	3.43
Acidification	AC	10 ⁻¹ molc H+ eq/t	21.8 (+126%)	9.62	7.70 (-20%)	10.4
Terrestrial eutrophication	TEU	molc N eq/t	8.38 (+113%)	3.93	2.81 (-29%)	4.15
Freshwater eutrophication	FEU	10 ⁻³ kg P eq/t	38.8 (+128%)	17	9.14 (-46%)	17.8
Marine eutrophication	MEU	10 ⁻¹ kg N eq/t	18.6 (+218%)	5.85	3.98 (-32%)	6.69
Freshwater ecotoxicity	FET	10 ³ CTUe/t	9.30 (+101%)	4.62	3.01 (-35%)	4.79
Land use	LU	kg C deficit/t	200 (+119%)	91.3	96.5 (+6%)	102
Water resource depletion	WD	10 ⁻² m3 water eq/t	26.8 (+235%)	8	13.5 (+69%)	10.5
Mineral, fossil & renewable resource depletion	MD	10 ⁻⁴ kg Sb eq/t	95.3 (+389%)	19.5	9.21 (-53%)	24.6

c) ORGANIC PRODUCTION						
Impact category		Unit	1 Low (young)	2 Full	3 Low (old)	Entire Orchard cycle
Climate change	CC	kg CO2 eq/t	835 (+378%)	175	94.9 (-46%)	154
Human toxicity, cancer effects	HTC	10 ⁻⁶ CTUh/t	64.5 (+307%)	15.9	4.22 (-73%)	12.4
Acidification	AC	10 ⁻¹ molc H+ eq/t	239 (+929%)	23.2	18.7 (-20%)	23.4
Terrestrial eutrophication	TEU	molc N eq/t	106 (+1290%)	7.60	6.86 (-10%)	8.15
Freshwater eutrophication	FEU	10 ⁻³ kg P eq/t	484 (+843%)	51.3	17.9 (-65%)	43.7
Marine eutrophication	MEU	10 ⁻¹ kg N eq/t	103 (+912%)	10.2	7.77 (-24%)	10.1
Freshwater ecotoxicity	FET	10 ³ CTUe/t	30.4 (+999%)	2.77	1.58 (-43%)	2.60
Land use	LU	kg C deficit/t	2141 (+519%)	346	249 (-28%)	328
Water resource depletion	WD	10 ⁻² m3 water eq/t	225 (+462%)	40.1	24.7 (-38%)	36.5
Mineral, fossil & renewable resource depletion	MD	10 ⁻⁴ kg Sb eq/t	582 (+87%)	311	66 (-79%)	232

Figure 1 shows the variability of the impacts within each impact category and for each production system and orchard production phase.

Figure 1 Impacts per tonne of apples for each production system and orchard production phase, for the conventional system (CONV), the integrated production system (IP) and the organic production system (ORG), each system having young low productive years (denoted with 1), full productive years (denoted with 2) and old low productive years (denoted with 3): boxplots showing median value, range and outliers. The following outliers for IP1 were removed for those impact categories marked with an * to enhance readability: FEU at 9,28 kg P eq/t, HTC at $5,44 \times 10^{-4}$ CTUh/t, and MD at 0,30 and 0,52 kg Sb eq/t.

The most extreme outliers are observed for IP1, even to the extent that they were left out of the graphs for three impact categories to allow decent visualisation of the boxplots. This is remarkable since the median impact for IP1 is in most impact categories close to that of the best performing production system in that orchard phase, being CONV1. Looking closer at these IP1 outliers, we find that they can be traced back to three individual orchard

records: two of them have outlier impacts in all ten impact categories, while the third one has outliers in eight impact categories. A detailed look at the agronomic data associated with these orchard records, shows a very low yield of about 2 tonnes per ha for each one of them, which is obviously a lot lower than the median yield obtained in IP1 and which explains the high impacts per tonne. A relatively low yield compared to the median yield, is also observed for many outliers in the other production systems and/or orchard production phases. Nevertheless, some outliers have yields comparable to that of the median yield in their respective production system and orchard production phase, and one IP2 outlier orchard record even has a yield twice as high as the median IP2 yield. On the other hand, we observe many orchard records with a low impact score in all impact categories assessed, and this within each combination of production systems and orchard production phases.

3.3 Contribution analysis

Figure 2 gives an overall visualization of the contributing processes to the impact categories, and this for each combination of production system and orchard production phase. The trends visual in this figure are further detailed by deciphering the underlying data, as described below per impact category.

Figure 2 Contributing processes (%) to the median impacts per tonne apples for the conventional system (CONV), the integrated production system (IP) and the organic production system (ORG), each system having young low productive years (denoted with 1), full productive years (denoted with 2) and old low productive years (denoted with 3).

Looking at the contributing input processes to the **climate change (CC) impact**, we find high contributions by energy use and synthetic fertilisers. Energy use impacts mainly relate to diesel use and its associated emissions, notably to diesel for transport by tractors (used both for farming activities on the orchard or farm premises and for transport of agricultural inputs and harvested apples). High volumes of organic fertilisers such as compost and manure used in CONV3 and in particular in ORG1 (Table 2) may have contributed to energy usage in these orchards, as their transport is very fuel consuming. Next to diesel for transport, we observe a high contribution by diesel used for equipment in ORG1. A possible explanation is the high competition between young trees and other vegetation and the prohibition to use herbicides in organic farming, which requires farmers to apply a lot of mechanical (fuel consuming) field operations such as weeding, mowing, and mulching (Milà i Canals, 2003).

Additionally, and this relates to all organic orchards, in order to avoid using chemical thinning agents, organic farmers often prune as a pre-thinning measure, followed by mulching of prunings, which again leads to high energy use (Milà i Canals, 2003).

The impact of the synthetic fertilisers originates mainly from embodied impacts associated with producing the big volumes of micronutrient fertilisers applied and from nitrous oxide emissions as a result of the application of nitrogen-containing fertilisers. In three cases, we also see contributions from organic fertilisers due to nitrous oxide emissions stemming from the application of compost (CONV3, ORG1 and ORG3), manure (ORG1) and blood meal which has a high nitrogen content (ORG1 and ORG3). Next to emissions following its high nitrogen content, blood meal also greatly contributed to the CC impact through its embodied production impacts, with about half of the impact due to the animal origin of the product and half of the impact resulting from the transformation of the by-products to ready-to-use products. For the former, the use of soybean-based feed is responsible for 23% of the CC impact caused by the blood meal consumption mix, while for the latter, the main contributing processes are use of electricity and process steam from natural gas.

In all cases but ORG2 and ORG3, **human toxicity cancer effects (HTC) impacts** are mainly caused by heavy metal emissions stemming from fertiliser use, in particular by chromium emissions to water and soil. In ORG2 and ORG3 on the other hand, the main contributor is production of micronutrient (synthetic) fertilisers. In some cases, small contributions are observed for energy and fungicide use, and to a minimal extent, of water and organic fertiliser use. In the latter case, this refers using green manure and more specifically, to impacts resulting from producing tractors and machinery for its cultivation. In contrast to what may be expected, hardly any impacts were due to using other plant protection products besides fungicides; only for CONV3 a very small contribution of 0.02% by insecticide usage was observed.

Acidification (AC) impacts are mainly caused by using fertilisers, complemented by energy use. AC impacts from fertilisers refer to impacts caused by ammonia emissions stemming from organic and synthetic fertiliser use, and to impacts from micronutrient fertiliser production in the case of ORG1, ORG2 and ORG3 and from blood meal production in ORG3. AC impacts from energy use result from nitrous oxide emissions.

The **terrestrial, freshwater and marine eutrophication (TEU, FEU and MEU) impacts** are driven by fertiliser use, complemented to a lower extent with energy use. Fertilisers contribute to TEU through their ammonia emissions, to FEU through phosphorous emissions and through the production of micronutrient fertilisers (in particular for ORG) and blood meal (ORG3), and to MEU through nitrate emissions and through the production of potassium fertiliser (for CONV3), blood meal (ORG3) and micronutrient fertilisers (ORG). Energy contributions are caused by nitrous oxide emissions in the case of TEU and MEU, and by the embodied impact for producing diesel for FEU.

Fungicide usage is the main cause of **freshwater ecotoxicity (FET) impacts**, mainly caused by emissions to soil and air of the a.i. Captan and Thiram used in IP and CONV, and of copper hydroxide and copper oxychlorid used in

ORG. An exception is ORG1, where heavy metal emissions stemming from fertiliser usage, in particular copper and zinc emissions to soil, are the main contributors. Additionally, a relatively high share of the impact in ORG2 and ORG3 is caused by synthetic fertilisers, namely the production of micronutrient fertilisers. Furthermore, in CONV and IP, a small share of the impacts is due to herbicide and insecticide usage.

Despite its name, the **land use (LU) impact** is not caused by land use in the literal sense of the word as this impact category, expressed in kg carbon deficit, refers to the mass of carbon lost from the soil during land transformation and occupation (Brandão et al., 2011; Milà i Canals et al., 2007). Such changes of soil organic matter are in our apple orchards mainly caused by the embodied impacts of diesel (namely petroleum production) and of micronutrient fertilisers. In the case of ORG3, the organic fertilisers also contributed to the LU impact, through the production process of blood meal, whereby 51% of the impact comes from soybean-based feed given to the animals whose slaughterhouse by-products were afterwards used for producing blood meal. Although by-products of broilers, pigs and cows are used in equal volumes to produce blood meal, over 80% of this LU impact caused by soybean-based feed is attributable to compound feed for broilers.

As can be expected, a big share of the **water depletion (WD) impact** is caused by using tap water. Nevertheless, the production of micronutrient fertilisers and, to a lesser extent, energy use (diesel) also contributed to this impact.

The **mineral, fossil and renewable resource depletion (MD) impact** is caused almost entirely by using synthetic fertilisers, in particular the production of micronutrient fertilisers.

3.4 Full orchard cycle impacts

Table 2 lists the yields and lifespan associated with each orchard production phase and the associated yield contributions, as calculated using Equation 2. For each production system, the full production phase has the highest yield contribution while the young trees have the lowest yield contribution, down to only 1% in the case of organic farming. Based on these yield contributions, and on the annual median impact values, the full orchard cycle impacts were calculated for each production system, as shown in Table 3.

Based on its duration, the full production phase accounts for 71% (12 out of 17 years) of the ORG and IP orchard life cycles, and for 57% (12 out of 21 years) of an ORG orchard life cycle. Figure 3 on the other hand, shows how the three orchard phases have contributed to the orchard cycle impacts, concluding that the contribution of the full production phase to the orchard cycle impact is, on average across the impact categories, lower for CONV and IP (respectively 62 and 68%) and higher for ORG (73%). A minimum contribution of 47% is found for HTC impacts in CONV, while the maximum contribution of 89% occurs in the MD category for ORG. The contribution of the two low production phases is, on average, highest for CONV whereby the young trees are, on average, responsible for 13% of the orchard cycle impact and the old trees for 24%. In IP, the young and old low productive phases account on average for 21 and 11% respectively, while in ORG, these shares are 7 and 20% .

Figure 3 Orchard cycle impacts for producing 1 tonne of apples: relative contributions of the three orchard production phases for each production system.

The bold values in Table 3 indicate if the impact of the full orchard cycle is higher than that of full production phase. For CONV, with the exception of FET, the orchard cycle impacts are higher than the full production impact with a maximum increase of 62% for HTC. For IP, all orchard cycle impacts are higher than those in the full production phase, with a maximum increase of 31% observed for WD. For ORG on the other hand, the orchard cycle impacts are mostly lower than the full production impacts, with the largest impact decrease observed for MD (-25%). Focussing on the productive phase only, rather than using the full orchard cycle impact, would thus lead to an underestimation of up to 38% in CONV (for HTC), with an average underestimation of 18% across the impact categories, and up to 24% in IP (for WD) with an average underestimation of 11%. On the other hand, in ORG, focusing on the full production phase is an overestimation of 11% on average, and up to 34% in MD. Compared with the low productive phases, the orchard cycle impact is lower than that of the young trees in all impact categories for IP and ORG, and in all but two cases (LU and MD) for CONV. It is also lower than that of the old trees in all but one impact category (FET) for CONV, and in the case of WD for IP; in all other cases the orchard cycle impact is higher than the impact of the old low productive orchards.

4 Discussion

Similar to the research of Alaphilippe et al. (2012), who looked into the benefits of organic and low-input apple production in Southern France, we found high energy use per tonne of organic apples produced compared to the other production systems. Nevertheless, the maximum median energy use observed in our organic plots (5 MJ/kg apple) is a lot higher than the maximum value of 0.9 MJ/kg as reported by Alaphilippe et al. (2012), and this despite the fact that their system boundaries are broader: the authors also include energy consumption related to machinery production and maintenance. It however seems that the authors did not include transport of the harvested apples to

for example the auction or a sorting centre, which is included in our dataset; same for transport related to fetching voluminous organic fertilisers such as compost and manure. Analysing how each of our field processes contributed to energy use was unfortunately not possible as our dataset only reported total energy use, with no distinction between for example use for transport, mechanical thinning or plant protection, tillage, or use of self-driven platforms for harvest.

For conventional farming, the majority of high impact scores is found in the last orchard production phase while, within integrated production and organic farming, highest median impacts for all impact categories are observed in the first orchard phase. In particular for organic farming, we find that the impacts associated with the first orchard phase are remarkably higher than in the other two phases which is attributable to the low yield obtained in the first orchard phase for organic production. Possibly, the limited use of fertilisers and the prohibition to use plant growth regulators in organic farming have led to less vigorous young trees and thus to lower yields. Low impacts are mainly found in the full production phase in the case of conventional farming (in 7 out of 10 categories), and in the old production phase for integrated and organic production (respectively in 8 and 10 categories). Comparison between the different production systems was out of the scope of this paper, as mentioned in the objectives, as this would require more detailed knowledge on field operations performed on the orchards.

Using a dataset of 445 apple orchards from 12 farms in Switzerland, Mouron et al. (2006a) investigated the management influence within the integrated farming system, concluding that good environmental performance of a farm relies on good management such as effective and timely use of technologies, and a realistic distributional thinking when it comes to allocating inputs. Our variability analysis of the impacts occurring in each production system and orchard production phase shows that the outliers observed were most of the times related to orchard records for which the yield was very low compared to the median yield obtained in the respective production system and orchard production phase, leading to relatively high impacts per tonne of apples produced in most, if not all, impact categories. Without knowledge of the climatological circumstances, such as the occurrence of hail storms, it is not possible to say whether these farmers were just unlucky that year or whether this is a clear case of bad management. Other outlier orchard records however, had a yield similar to – or in one case even remarkably higher than – the median yield. These orchards clearly did not suffer from low yields; the high impacts per tonne were thus due to the volume or nature of agricultural inputs applied to the orchards in the respective growing season and these orchard records can be considered as bad performers. On the other hand, our analysis also showed that it is possible to produce “low-impact apples” with low impacts per tonne of apple in *all* impact categories. Our analysis thus confirms the importance of management practices as concluded by Mouron et al. (2006a), despite the different functional unit chosen in that study (impacts per ha).

Looking at the contributions to each impact category for each of the inputs used, we find that synthetic fertiliser use is the main contributor to the impacts in 54% of the cases, mainly in CONV and IP. In second place comes energy use in 12% of the cases, closely followed by organic fertilisers (11%). Next are the heavy metal emission from fertiliser use and the fungicide emissions (both 9%), and lastly water use (4%). Overall, the production process and

the great volumes of micronutrient fertilisers had a great share in the impacts caused, as well as the production process of diesel and of blood meal (in the case of ORG3 and – for the climate change impact – also ORG1). Currently, organic farmers apply blood meal from conventionally grown cattle, chickens and pigs, as there are no restrictions on the origins of its components and as there is currently no organic blood meal available for sale. Following the restrictions on using phosphorous in agriculture, organic farmers use blood meal as a last resort to provide sufficient amounts of nitrogen while avoiding using phosphorous containing fertilisers such as manure (personal communication with CCBT⁹, 2016).

Comparing the median impacts and their contributing processes with literature, we find that for climate change, our median impacts are below or in the lowest part of the range of 0.1-0.4 kg CO₂ eq/kg given by Nemecek et al. (2012), who assessed crop variability in a global context; except for ORG1 which has an impact twice the upper value of this range. Compared with the range of 0.03-0.08 kg CO₂ eq/kg of Alaphilippe et al. (2012) for different apple production systems in France, our climate change impacts are relatively high. Here again, this may be attributable to differing system boundaries. Similar to Milà i Canals et al. (2006), who focussed on apple production in New Zealand, energy and fertiliser use were found as the greatest contributors to the climate change impact, and to the impact categories of acidification and eutrophication. For toxicity impacts, Alaphilippe et al. (2012) found the highest aquatic toxicity impacts occurring in the organic orchards, while in our study, the organic farms have the lowest median freshwater ecotoxicity impact, except for the first orchard phase (due to its low yield). The main contributing processes to these impacts are however the same, namely pesticides emissions, and in particular for our study, fungicide emissions. Additionally, for ORG1, there is a high contribution by heavy metal emissions, which corresponds to findings from Nemecek et al. (2012). These heavy metal emissions stemming from fertiliser use were the greatest cause of human toxicity impacts, complemented with impacts related to the production of synthetic fertilisers, which is in line with findings from Nemecek et al. (2012) and Alaphilippe et al. (2012), although these authors also observed high contributions by the production of machinery and buildings, which was excluded from our system boundaries.

Some critical reflections concerning the methodology applied for this research can be formulated as follows. Firstly, as mentioned in Section 2.2, impacts related to the production and storage of waste products such as compost and manure are not taken into consideration as they are allocated to the system they were created in, which is a common approach in the LCA study field (Blonk Agri-footprint, 2015b). One exception to this is the production of blood meal, for which data was available in the Agri-footprint database as this product is commonly used for feeding purposes as well, and which, due to the required processing phase, could almost be regarded as a “synthetic fertiliser”. As such, there is a discrepancy in the way the impacts for fertiliser production are assessed: embodied impacts are taken into account for synthetic fertilisers and for blood meal, but not for other organic fertilisers such as manure or compost. Therefore, farmers using waste-based fertilisers have an apparent advantage over those that use synthetic fertilisers when it comes to the production impacts of these fertilisers, although it is widely known that

⁹ The CCBT is the coordination centre for applied research and extension on organic agriculture and is part of the Strategic Action Plan for Organic Farming of the Flemish Government.

both manure and compost emit a lot of greenhouse gases during their production or storage. The issue of how to allocate the burdens for waste products was also addressed by Audsley et al., (2003); in the end, it was decided to follow the approach taken in the Agri-footprint 2.0 database. Secondly, our inventory excludes the production process of pesticides, as explained in Section 2.2. Additionally, for the micro nutrient fertilisers, we included their production process using a generalised data record which may lead to over- or underestimations of the production process. Furthermore, due to lack of data, no emissions were taken into account for these micronutrient fertilisers although some micronutrient fertilisers definitely contribute to heavy metal emissions and thus to toxicity impacts. Regarding the heavy metal emissions to soil and water, we further note that, to calculate the final flows, the balance was made from heavy metal inputs and heavy metal outputs, with the outputs referring to the heavy metal content of the apple biomass which is removed from the field. However, for this we had to revert to literature (See supplementary section, Part 2.B.6) as no data could be found for the heavy metal content in apple biomass in Flanders, except for cadmium and lead for which EU thresholds were set up (European Commission, 2001). Knowledge on the actual heavy metal content of apples for the other elements would definitely improve the analysis as these values can be very site-specific. Thirdly, although internationally recognised sources such as IPCC (2006b) were used, the emissions factors for nitrogen-based emissions may be an over- or underestimation of reality as the emissions and thus the effectiveness of fertilisation greatly depend on climatological circumstances. Furthermore, and this is particularly true for organic farming, nutrient supply through organic fertilisation is often not fine-tuned to the plants' needs, resulting in additional emissions. Fourthly, due to lack of data, our study does not take into account carbon sequestration following the use of organic fertilisers, which is believed to be quite substantial (Aguilera et al., 2015), nor does it consider impacts related to CO₂ emissions following tillage, which is required when manure or compost are used, in contrast to using synthetic fertilisers. On the other hand, (reduced) tillage may be beneficial to soil fertility and soil biodiversity, which is also not taken up by the LCA impact categories, nor does an LCA incorporate the effects of landscape or biodiversity enhancing measures whereas studies have shown differences in soil quality (Glover et al., 2000; Reganold et al., 2001) and in soil fertility and biodiversity (Mäder et al., 2002) amongst different production systems. For Belgian soils specifically, analysis of a large number of soil samples in the period 2008-2011 has shown that a larger share of organic soils has a good organic carbon content than the non-organic soils, while a smaller share suffers from phosphorous saturation (Maes et al., 2012). Information on these processes may thus also affect the results.

Regarding the full orchard cycle impact, our study found that, as an average across the production systems, the two low production phases account for 27 to 38% to the orchard cycle impact, with a maximum contribution of 53% in the case of human toxicity cancer effects in conventional production. This is higher than the Alaphilippe et al. (2014) findings, who compared a semi-extensive and an intensive apple fruit production system in France: they calculated the contribution of the establishment stage of the orchard and the orchard's nursery, creation, and destruction phases to the total impacts and found that these low and non-productive stages contributed up to 21% and 28% in a semi-extensive and intensive production system respectively. These differences can be explained as follows: Alaphilippe et al. (2014) consider both the low productive and non-productive years which together take up 4% and 13% of the orchard lifespan in the semi-extensive and intensive orchards respectively. Our study, however,

could not consider the non-productive phases. Instead, we took into account the low productive years during the orchard establishment phase and at the end of the orchard lifespan. These low productive years together cover 29% of our orchard lifespan in conventional and integrated orchards, and 43% of the lifespan of organic orchards. It is exactly this lifespan that influences the yield contribution of each orchard production phase that was used to calculate the orchard cycle impact. In addition, Alaphilippe et al. (2014) have calculated the impacts cumulatively, based on the sum of all inputs used during the entire orchard cycle, with a lifespan of 15 years for the intensive system and 26 years for the semi-extensive system. Our model on the contrary, is built on a weighted sum of the median impacts occurring in each orchard phase, with a total lifespan of 17 or 21 apple-bearing years, depending on production system. In another study, Cerutti et al. (2014, 2011a) calculated the environmental impacts associated with the production of 1 kg of apples taking into account the whole lifetime of the orchard cycle, based on six stages which also include non-productive phases, as listed in Section 1. The authors found that the full productive phase accounted for about 64% of the impacts of the entire orchard cycle; the contribution of the lower production phases combined with the unproductive phases thus being 36%. Here as well, results are hard to compare as we excluded the non-productive phases such as nursery and planting and destroying the orchard.

The wide range in resulting impacts found in literature, however, show the complexity and variability in assessing environmental impacts for non-productive years of an orchard cycle: Vinyes et al. (2015) assessed different growth scenarios for peach orchards, taking into account the impacts of the soil preparation and planting of the orchard and distributing these evenly over the 15 years lifespan of the orchard. The soil preparation and planting stage was found to be responsible for only 0 to 2.42% of the impact per kg peach produced, depending on the production scenario chosen and impact category assessed. Regarding the nursery, Beccaro et al. (2014) found that for chestnut, the nursery stage accounts for almost 17% of the entire environmental impact, with 80% of nursery impact stemming from plastic use. The high share of impacts within the nursery stage caused by use of plastics was also confirmed in the study of Cambria and Pierangeli (2011) on walnut tree seedlings. By contrast, in the study by Alaphilippe et al. (2014), the nursery phase was found to contribute only to a very limited extent. Bessou et al. (2016) further concluded that the non-productive years, which include both the nursery and the non-fruit bearing years, contributed to 7-40 or 6.5-29% of all impact categories for oil palm fruit and citrus, respectively.

Cerutti et al. (2014, 2011a) further found that consideration of the full productive years only, would probably lead to an *underestimation* of about 27% of the impacts. Our results show that, for conventional and integrated production, a mere focus on the full production phase leads to an underestimation of the full orchard cycle impact in respectively 90 and 100% of the impact categories assessed. This underestimation can be as big as 38% in conventional farming (for human toxicity cancer effects), and 24% in integrated farming (for water depletion). These numbers would even be higher if we were to include the nursery phase and the orchard creation and destruction phases as Cerutti et al. (2014, 2011a) did. Similarly, in their study on the environmental impact of different peach orchard production periods, Vinyes et al. (2015) found that focussing on one highly productive year only, leads to a lower impact in all impact categories than when applying a multiyear approach which takes into account the entire orchard cycle; on

average across the impact categories assessed, an underestimation of 49% is observed¹⁰. Along the same lines, Bessou et al. (2016), who applied different modelling approaches for oil palm fruit and citrus, found that a mere focus on the highly productive years rather than taking into account the entire orchard cycle, including nursery and planting, leads to an average underestimation of 13% and 10% for palm oil fruit and citrus respectively¹¹. Nevertheless, in a third of the impact categories assessed for citrus, focussing on high productive years seems to be an *overestimation* of the full orchard cycle impact. In the case of organic farming, our study also showed that a focus on the full production phase leads to an overestimation, and this in 8 out of 10 impact categories assessed, with a maximum overestimation of 34% (for mineral, fossil and renewable resource depletion). As such, our hypothesis is confirmed in conventional and integrated farming, but does not add up in organic farming. For all production methods, we can expect the orchard cycle impacts to increase when including the non-productive orchard phases. For conventional and integrated production, a narrow focus on high productive trees rather than the entire orchard cycle would thus lead to an even bigger underestimation. For organic farming however, it cannot be predicted whether such changes to the system boundaries of the assessment would still lead to orchard cycle impacts being lower than the full productive orchard impacts as now is the case, or not.

Next to looking at the broader picture of what can contribute to an orchard's impact, a next step could be to look at potential other outputs from the orchard and on how to allocate the impacts. Boschiero et al. (2015) for example looked at how to allocate impacts related to biomass production in an apple orchard to on the one hand the apples itself and on the other hand to the woody residues resulting from trimming and renewal of the orchard which can subsequently be used for bioelectricity production. Based on the allocation factors suggested by Boschiero and co-workers, the impact associated with apple production would be lower than our figures as only 79% (in case of mass allocation) or 99.7% (in case of economic allocation) of the calculated impacts would be allocated to apple, while the remainder is allocated to woody residues production.

5 Conclusions

Using the ILCD impact assessment method, the present LCA is based on a large dataset of apple orchards, covering three production systems and three orchard production phases, and accounting for yield and input variability. In the majority of the impact categories assessed for conventional farming, the old orchards are associated with the highest median impacts while, for integrated production and organic farming, highest median impacts for all impact categories are observed in the young orchards. In particular for organic farming, we find that the impacts associated with the young trees are remarkably higher than the other two phases following the low yield obtained for these trees and the functional unit chosen for the LCA (namely 1 tonne apples). Lowest median impacts on the other hand are

¹⁰ To obtain this value, we compared the total impacts listed in Table 3 of Vinyes et al. (2015) for the “high” and “multiyear” scenario.

¹¹ To obtain this value, we compared the impacts for the three-year average, which is assumed to be representative for a full production year, with the full cycle modelling scenario as found in the supplementary materials of Bessou et al. (2016).

found in the full productive orchards in the case of conventional farming (in 7 out of 10 categories), and in the old orchards for integrated and organic production (respectively in 8 and 10 categories).

Looking at the contributions to the impacts for each of the inputs used (based on median values), we find that synthetic fertiliser use is the main contributor to the impacts in 54% of the cases, followed by energy use (12%), organic fertilisers (11%), heavy metal emission from fertiliser use (9%), fungicide emissions (9%), and water use (4%). Overall, the production process and the great volumes of micronutrient fertilisers had a great share in the impacts caused, as well as the production processes of diesel and blood meal.

Our variability analysis of the impacts occurring in each production system and orchard production phase shows outliers with high impacts per tonne in most, if not all, impact categories. This is the result of the low yields obtained in these orchards which is most probably due to climatological circumstances rather than bad management. However, our analysis also showed outlier orchard records with relatively high yields which means that for these orchards, the nature and/or volume of inputs applied to the field lead to a high impact in this specific growing season. Next to these bad performing orchard records, we also observed good performing orchard records with low impacts per tonne of apple in all impact categories.

Looking at the composition of the full orchard cycle impact, we find that, as an average across the production systems, the low productive phases account for 27 to 38% to the orchard cycle impact, with a maximum contribution of 53% in the case of human toxicity cancer effects in conventional production. Comparing the impacts associated with the full orchard cycle model with the median impacts obtained in the full production phase, we find that a mere focus on highly productive orchards leads to an underestimation of, on average across the impact categories, 18% in conventional farming and 11% integrated farming, thus confirming our hypothesis. For organic farming however, focussing on the full productive phase leads to overestimation of 11% on average. Our orchard model currently takes into account the less productive apple bearing phases, but omits non-productive phases such as nursery and planting and destruction of the orchard. For all production methods, we can expect the orchard cycle impacts to increase when including those non-productive orchard phases. For conventional and integrated production, a narrow focus on high productive trees rather than the entire orchard cycle would thus lead to an even bigger underestimation. For organic farming however, it cannot be predicted whether or not this would still be an underestimation of the orchard cycle impact or not.

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ELECTRONIC SUPPLEMENTARY MATERIAL

Life cycle assessment for apple orchard production systems including low and high productive years in conventional, integrated and organic farms

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6 Contents

- 7 – Part 1: Inventory, Field emissions – detailed formula applied and sources used
- 8 – Part 2: Inventory, Listing of fertilisers and pesticide products used
- 9 – Part 3: Results, Statistical details

10

11

ELECTRONIC SUPPLEMENTARY MATERIAL

Part 1: Inventory, Field emissions – detailed formula applied and sources used

Part 1 lists the formulae applied and the sources used for calculating the field emissions for the following input categories: energy use, fertiliser use, and pesticide use.

A. Input: Energy use

1. CO₂, N₂O, CH₄ emissions to air from use of fossil fuels

$$\text{Fuel_CO2} = \sum \text{FF_fuel} \times \text{EF_CO2_fuel}$$

$$\text{Fuel_N2O} = \sum \text{FF_fuel} \times \text{EF_N2O_fuel}$$

$$\text{Fuel_CH4} = \sum \text{FF_fuel} \times \text{EF_CH4_fuel}$$

Parameter	Description	Unit	Source
FF_fuel	Annual use of each fossil fuel source	MJ	FADN database
EF_CO2_fuel	CO ₂ emission factor	kg CO ₂ /MJ	(IPCC, 2006a): Ch.2, Table 2.5
EF_N2O_fuel	N ₂ O emission factor	kg N ₂ O/MJ	(IPCC, 2006a): Ch.2, Table 2.5
EF_CH4_fuel	CH ₄ emission factor	kg CH ₄ /MJ	(IPCC, 2006a): Ch.2, Table 2.5

Average emission factors:

Energy source	EF_CO2 (kg CO ₂ /MJ)	EF_CH4 (*10 ⁻⁶ kg CH ₄ /MJ)	EF_N2O (*10 ⁻⁶ kg N ₂ O/MJ)
Diesel	0.0741	10	0.6
Natural gas	0.0561	5	0.1
LPG	0.0631	5	0.1
Charcoal	0.112	200	1
Gasoline	0.0693	10	0.6
Lubricants	0.0733	10	0.6
Methane	0.0546	5	0.1
Petroleum/crude oil	0.0733	10	0.6

2. NO_x emissions to air from use of diesel

$$\text{NOx}_{\text{diesel}} = (\text{FF}_{\text{diesel_on-road}} \times \text{EF}_{\text{NOx_on-road}}) + (\text{FF}_{\text{diesel_off-road}} \times \text{EF}_{\text{NOx_off-road}})$$

Parameter	Description	Unit	Average	Std	Source
FF_diesel_on-road	Annual use of mazout/diesel for on-road purposes	MJ	-	-	FADN database
FF_diesel_off-road	Annual use of mazout/diesel for off-road purposes (farm equipment)	MJ	-	-	FADN database
EF_NOx_on-road	NOx Emission factor for diesel (on-road trucks)	kg NOx/MJ	0.000777		(Ntziachristos and Samaras, 2014), table 3-6
EF_NOx_off-road	NOx Emission factor for diesel (off-road farm equipment)	kg NOx/MJ	0.000809		(Winther et al., 2014), table 3-1

B. Input: Fertiliser use

1. Nitrous oxide (N₂O) emissions to air from application of fertiliser

According to Blonk Agri-footprint (2015), nitrous oxide emissions from fertiliser use are can be divided into direct (release of N₂O directly from fertiliser) and indirect emissions (N₂O emissions through a more intricate mechanism). Other nitrous oxide emissions (e.g. changes in organic soil management or emissions resulting from urine/dung of grazing animals) are not taken into account.

$$\text{N2O}_{\text{total}} = \text{N2O}_{\text{N_total}} \times 44/28$$

$$\text{N2O}_{\text{N_total}} = \text{N2O}_{\text{N_direct}} + \text{N2O}_{\text{N_indirect}}$$

$$\text{N2O}_{\text{N_direct}} = (\text{F}_{\text{SN}} + \text{F}_{\text{ON}}) \times \text{EF}_1$$

$$\text{N2O}_{\text{N_indirect}} = \text{N2O}_{\text{N_atm_dep}} + \text{N2O}_{\text{N_LEACH}}$$

$$= [(\text{F}_{\text{SN}} \times \text{Frac}_{\text{GASF}}) + (\text{F}_{\text{ON}} \times \text{Frac}_{\text{GASM}})] \times \text{EF}_4 + (\text{F}_{\text{SN}} + \text{F}_{\text{ON}}) \times \text{Frac}_{\text{LEACH}} \times \text{EF}_5$$

Parameter	Description	Unit	Average	Std	Source
F_SN	Annual application of synthetic fertiliser N	kg N			FADN database
F_ON	Annual application of organic fertiliser N	kg N			FADN database
EF_1	Emission factor for N additions from mineral fertilisers, organic amendments and crop residues, and N mineralised from mineral soil as a result of loss of soil carbon	kg N ₂ O-N/kg N	0.01	0.003-0.03	(IPCC, 2006b), Ch11, Table 11.1
Frac_GASF	Fraction of synthetic fertiliser that volatilizes as NH ₃ and NO _x	kg (NH ₃ -N + NO _x -N)/ kg N applied	0.1	0.03-0.3	(IPCC, 2006b), Ch11, Table 11.3
Frac_GASM	Fraction of applied organic N fertiliser materials that volatilizes as NH ₃ and NO _x	kg (NH ₃ -N + NO _x -N)/ kg N applied	0.2	0.05 - 0.5	(IPCC, 2006b), Ch11, Table 11.3
EF_4	Emission factor for N ₂ O emissions from volatilization and re-deposition of N on soils and water surfaces	kg N ₂ O-N / kg (NH ₃ -N + NO _x -N) volatilised	0.01	0.002-0.05	(IPCC, 2006b), Ch11, Table 11.3
FRAC_LEACH	Fraction of organic and inorganic fertiliser N lost through leaching or runoff as NO ₃	kg N / kg N applied	0.3	0.1-0.8	(IPCC, 2006b), Ch11, Table 11.3
EF_5	Emission factor for N ₂ O emissions from N leaching and runoff	kg N ₂ O-N / kg N leaching/runoff	0.0075	0.0005-0.025	(IPCC, 2006b), Ch11, Table 11.3

2. Ammonia (NH₃) emissions to air from application of fertiliser

All nitrogen that volatilizes is assumed to convert to ammonia (Blonk Agri-footprint, 2015).

$$\text{NH}_3 = 17/14 \times \text{NH}_3\text{-N}$$

$$\text{NH}_3\text{-N} = (\text{F_SN} \times \text{Frac_GASF}) + (\text{F_ON} \times \text{Frac_GASM})$$

Parameter	Description	Unit	Average	Std	Source
F_SN	Annual application of synthetic fertiliser N	kg N			FADN database
F_ON	Annual application of organic fertiliser N	kg N			FADN database
Frac_GASF	Fraction of synthetic fertiliser that volatilizes as NH ₃ and NO _x	-	0.1	0.03-0.3	(IPCC, 2006b), Ch11, Table 11.3
Frac_GASM	Fraction of applied organic N fertiliser materials that volatilizes as NH ₃ and NO _x	kg (NH ₃ -N + NO _x -N)/ kg N applied	0.2	0.05 - 0.5	(IPCC, 2006b), Ch11, Table 11.3

3. Carbon dioxide (CO₂) emissions to air from application of urea fertiliser

This is to compensate for the CO₂ that was fixed during the industrial production process of urea (Blonk Agri-footprint, 2015).

$$\text{CO2_urea} = 44/12 * \text{EF_urea} * \text{F_urea}$$

Parameter	Description	Unit	Average	Std	Source
F_urea	Annual application of synthetic fertiliser under the form of urea	kg urea			FADN database
EF_urea	Emission factor for CO ₂ -C emissions from urea application	kg CO ₂ -C/kg urea	0.2		(IPCC, 2006b)

4. Nitrate (NO₃⁻) emissions to water from application of fertiliser

We assume that all nitrogen that leaches is emitted as nitrate (Blonk Agri-footprint, 2015).

$$\text{NO3-} = 62/14 \times \text{NO3-N}$$

$$\text{NO3-N} = (\text{F_SN} + \text{F_ON}) \times \text{Frac_LEACH}$$

Parameter	Description	Unit	Average	Std	Source
F_SN	Annual application of synthetic fertiliser N	kg N			FADN database
F_ON	Annual application of organic fertiliser N	kg N			FADN database
FracLEACH	Fraction of synthetic fertiliser lost through leaching or runoff as NO ₃	-	0.3	0.1-0.8	(IPCC, 2006b), Ch11, Table 11.3

5. Phosphorous emissions to water from application of fertiliser

$$\text{P_emission} = \text{Frac_P-loss} \times \text{F_P}$$

Parameter	Description	Unit	Average	Std	Source
F_P	Annual application of fertiliser P	kg P			FADN database
Frac_P-loss	Fraction of phosphorus emission that actually reaches freshwater	-	0.05		(Blonk Agri-footprint, 2015)

6. Heavy metal emissions to soil and water from fertiliser use

The emissions are the result of inputs of heavy metals due to fertilizer and manure application and of deposition and outputs of heavy metals due to leaching and removal of biomass (Blonk Agri-footprint, 2015). According to (Nemecek and Schnetzer, 2011), the emissions to the soil may result in negative values when more heavy metals are exported than imported. In this case, the heavy metals are transferred either to the water bodies or to the products harvested from the field (food, feed and straw).

$$M_{\text{soil}_i} = (\sum \text{inputs}_i - \sum \text{outputs}_i) * A_i$$

$$\sum \text{inputs}_i = A * A_{\text{content}_i} + B * B_{\text{content}_i} + C_i$$

$$\sum \text{outputs}_i = D * D_{\text{content}_i} + m_{\text{leach}_i}$$

$$M_{\text{leach}_i} = m_{\text{leach}_i} * A_i$$

With

$$A_i = \frac{A * A_{\text{content}_i} + B * B_{\text{content}_i}}{A * A_{\text{content}_i} + B * B_{\text{content}_i} + C_i}$$

Parameter	Description	Unit
M_{soil_i}	heavy metal accumulation in the soil for heavy metal i attributable to agricultural activities	
A_i	allocation factor for the share of agricultural inputs in the total inputs for heavy metal i	
A	Mineral fertilizer application	kg/ha/yr
A_{content_i}	heavy metal content i for mineral fertilizer applied, see table below	mg/(kg N or P or ...)
B	organic fertilizer application	kg DM/ha/yr
B_{content_i}	heavy metal content i for manure or other organic fertilisers applied, see table below	mg/kg DM
C_i	Deposition for heavy metal i , see table below	mg/ha/yr
D	yield	tonne FM/ha/yr
D_{content_i}	heavy metal content i for apple, see table below	mg/kg FM
M_{leach_i}	leaching of heavy metal i to the ground and surface water attributable to agricultural activities	mg/kg FM or DM
m_{leach_i}	average amount of heavy metal leaching, see table below	

Heavy metal content of mineral fertilizers (A_content_i) ¹									Source
	Unit	Cd	Cu	Zn	Pb	Ni	Cr	Hg	
N-fertilizer	mg/kg N	6	26	203	54.9	20.9	77.9	0.1	(Blonk Agri-footprint, 2015)
P- fertilizer	mg/kg P	90.5	207	1923	154	202	1245	0.7	(Blonk Agri-footprint, 2015)
K- fertilizer	mg/kg K	0.2	8.7	11.3	1.5	4.5	10.5	0.1	(Blonk Agri-footprint, 2015)
Lime	mg/kg Ca	0.7	20.4	93.6	13.6	14.7	20.6	0.1	(Blonk Agri-footprint, 2015)
Heavy metal content of organic fertilisers (B_content_i)									
	Unit	Cd mg/kg Fertili zer	Cu mg/kg Fertili zer	Zn mg/kg Fertili zer	Pb mg/kg Fertili zer	Ni mg/kg Fertili zer	Cr mg/kg Fertili zer	Hg mg/kg Fertili zer	
Biogas digestate (average for pig and cow manure)	mg/kg DM	0.545	251.8 75	616.3 75	13.9	18.08 75	16.93 75	0.137 5	Based on (Blonk Agri-footprint, 2015); digestate is assumed to originate from fermentation of animal manure
Blood meal	mg/kg	0	0	0	0	0	0	0	No data found; levels set to 0
Champost	mg/kg DM	0.13	9.9	48	4.2	1.0	4.8	0.016	(Mels et al., 2008)
Compost	mg/kg DM	0.7	25	75	65	10	50	0.2	(Mels et al., 2008)
Green manure/agricultural residues	mg/kg DM	0.4	28.5	70	18	9.5	26	0	(Amlinger et al., 2004), Table 4.5
Pigs	mg/kg DM	0.45	51.5	214.7 5	14.25	18.75	20.65	0.197 5	(Blonk Agri-footprint, 2015)
Cow	mg/kg DM	0.64	452.2 5	1018	13.55	17.42 5	13.22 5	0.077 5	(Blonk Agri-footprint, 2015)
Poultry	mg/kg DM	1.52	99	469	16.2	19.05	8.7	0.085	(Blonk Agri-footprint, 2015)
Peat	mg/kg	0	0	0	0	0	0	0	No data found; levels set to 0
Rabbit	mg/kg DM	0.6	61	453	2.4	2.6	12.5	0.3	(Moreno-Caselles et al., 2002)
Sewage sludge	mg/kg DM	1.5	389.4	993.8	134.2	29.7	42.8	1.1	(Mels et al., 2008), Table 2
Substrate	mg/kg	0	0	0	0	0	0	0	No data found; levels set to 0
Deposition of heavy metals (C_i)									
	Unit	Cd	Cu	Zn	Pb	Ni	Cr	Hg	
Deposition	mg/ha /yr	700	2400	90400	18700	5475	3650	50	

¹ As micronutrient fertilisers do not contain nitrogen, phosphorous or potassium, the calculations for heavy metal emissions resulted in zero even though in reality, they may lead to heavy metal emissions.

Heavy metal content of apple (D_content_i)								
	Unit	Cd	Cu	Zn	Pb	Ni	Cr	Hg
Apple	mg/kg FM	0.01	0.3	1.11	0.02	0.002	0.14	0.14
Sources: Data for Cd and Pb obtained through personal communication with the auction; (Stefanut et al., 2007) for Cu, Zn and Cr; (Delahaye et al., 2003) for Ni and Hg								
Heavy metal leaching to groundwater (m_leach_i)								
	Unit	Cd	Cu	Zn	Pb	Ni	Cr	Hg
Leaching	mg/h a/yr	50	3600	3300 0	600	n.a.	2120 0	1.3

C. Input: Pesticide use

For each a.i. applied, we calculate the associated emissions using the emission fractions from Audsley et al. (2003) whereby 10% is emitted to the air, 85% to the soil, and 5% stays on the leaves/plant.

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ELECTRONIC SUPPLEMENTARY MATERIAL

Part 2: Inventory, Listing of fertilisers and pesticide products used

Part 2 provides for a listing of the fertilisers (Table S1) and pesticides (Table S2) used within the 512 orchard records.

Table S1 Listing of the synthetic and organic fertilisers used within the 512 orchard records, divided into two categories.

Synthetic	Organic
Ammonium nitrate (NPK 35-0-0)	Biogas digestate
Ammonium sulphate (NPK 21-0-0)	Blood meal
Calcium chloride	Champost
Calcium nitrate	Compost
Copper sulfate	Green manure
Di ammonium phosphate	Manure - liquid - cow
Hydrogen cyanide	Manure - liquid - swine
K fertiliser	Manure - rabbit
Lime fertiliser	Manure - solid - chicken
Liquid urea-ammonium nitrate solution NPK 30-0-0	Manure - solid - cow
Magnesium sulfate	Manure - solid - swine
N fertiliser	Sludge
Nitric acid	
NPK compound (15-15-15)	
P fertiliser	
PK compound	
Potassium chlorid	
Potassium fertiliser (as K ₂ O)	
Potassium nitrate	
Single superphosphate	
Triple superphosphate	
Urea	
Other industrial fertilisers & micronutrients (*)	

* The ecoinvent database does not contain fertilisers containing micronutrients (Nemecek and Kagi, 2007) and “chemical, inorganic” from the ecoinvent database was used instead to account for the associated embodied impact.

135 **Table S2** Listing of the pesticides used within the 512 orchard records, divided into six categories

Fungicides	Myclobutanil	Clopyralid	Phenmedipham	Etoxazole	Pheromones
Azaconazol	Nuarimol	Dicamba	Prohexadion	Endosulfan	(Z)-11-tetradecenylacetate
Azoxystrobin	Penconazool	Dichlobenil or 2,6	Propachlor	Ethiofencarb	(Z)-9- tetradecenylacetate
Bitertanol	Potassium bicarbonate	dichloobenzonitrile	Propaquizafop	Fenbutatin-oxide	1-Dodecanol
Boscalid	Prochloraz	Dichlorprop-p or 2,4-DP-p	Propyzamid	Fenpyroximate	1-tetradodecanol
Captan	Propamocarb	Diiflufenican	Pyridate	Fipronil	Codlemone or 8,10-
Carbendazim	Propiconazole	Dimethanamid	Quinmerac	Flonicamid	dodecadien-1-ol
Chlorothalonil	Prothioconazole	Diquat	Simazine	Flufenoxuron	Tetradecaan-1-ol
Copper hydroxide	Pyraclostrobin	Diuron	Sulcotrion	Furathiocarb	
Copper oxychlorid	Pyrimethanil	Flazasulfuron	Tepraloxymid	Hexythiazox	Plant growth regulators
Cyflufenamid	Quinoxifen	Fluazifop-p-butyl	Terbutylazin	Imidacloprid	2-(1-Naphthyl)Acetamide
Cyproconazol	Spiroxamine	Fluroxypyr	Triclopyr	Indoxacarb	6-Benzyladenine
Cyprodinil	Sulphur	Flurtamone	Triflusalufuron-Methyl	Kaoline	1-Naphthaleneacetic acid
Diethofencarb	Tebuconazole	Glufosinate	Trinexapac-Ethyl	Lambda-Cyhalothrin	Amidosulfuron
Difenoconazole	Tetraconazole	Glyphosate		Metaldehyde	Aminopyralide
Dimethomorf	Thiophanate-methyl	Iodosulfuron	Insecticides	Methiocarb	Chlormequat
Dithianone	Thiram	Iodosulfuron-methyl-	1,3 dichloropropene	Methoxyfenozide	Delta amino valeric acid
Dodine	Tolyfluamide	sodium	Abamectine	Oxamyl	Etephon
Epoxiconazole	Triadimenol	Isoxaben	Acetamiprid	Paraffin	Gamma amino butyric acid
Fenamidone	Trifloxystrobin	Linuron	Amitraz	Permethrin	Gibberellic acid A3
Fenarimol	Unknown a.i.	Mcpa	Azadirachtine	Phenoxycarb	Gibberellic acid A4-A7
Fenhexamid	Vinclozolin	Mecoprop	Azocyclotin	Phosalone	Glycinebetaine
Fenpropidin	Ziram	Mecoprop-P	Bifenthrin	Piperonyl butoxide	Laminarine
Fenpropimorph	Zoxamide	Mefenpyr-Diethyl	Bioallethrine	Pirimicarb	
Fentin hydroxide		Metamitron	Bromopropylate	Pymetrozine	Rodenticides
Fludioxonil	Herbicides	Metazachlor or	Carbaryl	Pyrethrin	Bromadiolone
Fluoxastrobin	Amitrol	Metolachlor	Chlorantraniliprole	Pyridaben	Chlorophacinone
Fluquinconazool	2,4 D	Methabenzthiazuron	Chlorpyrifos	Pyriproxyfen	Coumatetralyl
Fosethyl	Ammonium glufosinate	Metribuzin	Clofentezine	Spinosad	Difenacoum
Imazalil	Ammoniumthiocyanat	Metsulfuron-Methyl	Cyfluthrin	Spirodiclofen	Difethialone
Iprodione	Asulam	Napropamide	Dazomet	Spirotetramat	Flocoumafen
Kresoxim-methyl	Atrazin	Nicosulfuron	Deltamethrin	Tebufenozide	
Mancozeb	Bifenox	Nonylphenol-	Diazinon	Tebufenpyrad	
Maneb	Carfentrazone-ethyl	Polyglycoether	Dichlorvos	Thiacloprid	
Mepanipyrim	Chloridazon	Oxydiazon	Diflubenzuron	Thiamethoxam	
Metalaxil	Chlorpropham	Paraquat	Dimethoate	Unknown a.i.	
Metiram	Chlortoluron	Pendimethalin		Vamidothion	

136

137

ELECTRONIC SUPPLEMENTARY MATERIAL

Part 3: Results, Statistical details

Part 3 provides for the statistical details related to the annual inputs per tonne apples and outputs of the systems under investigation (Table S3), and the annual impacts per tonne apples in the various impact categories (Table S4).

Table S3 Characteristics of the different systems under investigation: Mean, median, minimum and maximum annual input per tonne apples and output

Low production (young)					Full production				Low production (young)			
	Median	Min	Mean	Max	Median	Min	Mean	Max	Median	Min	Mean	Max
CONVENTIONAL PRODUCTION												
Energy (GJ/t)	3.08e-1	1.31e-1	1.02	8.96	3.47e-1	3.01e-2	4.42e-1	2.25	4.78e-1	3.76e-1	4.78e-1	5.80e-1
Drinking water (m3/t)	8.59e-2	0	1.10	7.75	2.79e-2	0	1.12e-1	1.19	0	0	0	0
Synthetic fertilisers (kg/t)	1.88e1	4.55e-2	2.91e1	2.07e2	1.51e1	1.49	2.11e1	1.63e2	1.85e1	1.35e1	1.85e1	2.34e1
N	2.05	0	3.69	2.86e1	1.11	1.31e-2	1.57	1.08e1	1.61	1.44	1.61	1.77
P	2.10e-1	0	4.94e-1	2.88	5.72e-2	0	2.47e-1	1.99	3.34e-1	9.47e-2	3.34e-1	5.73e-1
K	1.39	0	2.82	1.60e1	2.23e-1	0	7.48e-1	6.94	1.87	1.38	1.87	2.37
Organic fertilisers (kg/t)	0	0	1.55e2	9.28e2	0	0	8.18e1	5.32e2	2.20e2	0	2.20e2	4.40e2
N	0	0	8.02e-1	6.80	0	0	2.29e-1	3.30	2.07	0	2.07	4.14
P	0	0	1.91e-1	1.70	0	0	5.69e-2	6.04e-1	3.96e-1	0	3.96e-1	7.93e-1
K	0	0	4.08e-1	2.96	0	0	1.63e-1	2.79	1.61	0	1.61	3.22
Pesticides (kg a.i./t)												
Fungicides	7.55e-1	2.61e-1	1.13	6.91	5.74e-1	3.06e-2	6.90e-1	1.93	5.66e-1	4.60e-1	5.66e-1	6.72e-1
Herbicides	1.20e-1	2.83e-2	2.61e-1	1.83	9.81e-2	7.09e-3	1.15e-1	5.42e-1	1.22e-1	1.09e-1	1.22e-1	1.35e-1
Insecticides	3.34e-2	1.02e-2	2.97e-1	3.53	3.75e-2	1.54e-3	1.12e-1	1.01	9.78e-2	2.18e-2	9.78e-2	1.74e-1
Pheromones	0	0	6.22e-4	3.54e-3	0	0	8.18e-3	4.93e-2	0	0	0	0
Plant growth regulators	2.55e-4	0	2.39e-2	3.17e-1	2.88e-4	0	1.19e-2	5.35e-1	2.68e-3	7.53e-4	2.68e-3	4.61e-3
Rodenticides	0	0	2.92e-5	4.08e-4	0	0	1.08e-5	2.34e-4	0	0	0	0
Yield (t/ha)	2.85e1	3.13	3.01e1	5.35e1	4.31e1	1.33e1	4.32e1	7.19e1	4.11e1	3.98e1	4.11e1	4.23e1

	Low production (young)				Full production				Low production (young)			
	Median	Min	Mean	Max	Median	Min	Mean	Max	Median	Min	Mean	Max
INTEGRATED PRODUCTION												
Energy (GJ/t)	4.64e-1	1.12e-1	1.15	8.76	2.72e-1	0	3.77e-1	1.04e1	2.80e-1	1.29e-1	4.95e-1	2.03
Drinking water (m3/t)	0	0	4.77e-1	5.55	5.24e-2	0	1.56e-1	2.70	1.84e-1	0	4.46e-1	2.32
Synthetic fertilisers (kg/t)	5.70e1	4.51	1.13e2	9.01e2	1.47e1	1.47e-1	2.64e1	2.33e2	1.39e1	0	2.00e1	7.33e1
N	2.86	4.85e-1	6.22	3.48e1	1.08	0	1.53	3.30e1	7.88e-1	0	9.29e-1	3.39
P	4.78e-1	0	5.17	1.66e2	1.66e-1	0	2.88e-1	7.34	7.17e-2	0	1.66e-1	8.97e-1
K	1.70	0	9.96	2.56e2	6.29e-1	0	1.10	2.11e1	2.04e-1	0	5.17e-1	2.04
Organic fertilisers (kg/t)	0	0	1.22e2	2.95e3	0	0	5.49e1	9.51e2	0	0	1.10e1	1.16e2
N	0	0	9.46e-1	2.50e1	0	0	5.46e-1	3.94e1	0	0	4.94e-2	5.22e-1
P	0	0	2.37e-1	5.98	0	0	1.45e-1	1.06e1	0	0	1.82e-2	1.93e-1
K	0	0	4.35e-1	6.23	0	0	2.65e-1	6.58	0	0	2.79e-2	2.95e-1
Pesticides (kg a.i./t)												
Fungicides	1.00	1.79e-1	2.13	1.83e1	4.70e-1	9.26e-2	5.92e-1	4.18	3.34e-1	0	4.53e-1	1.19
Herbicides	1.46e-1	3.63e-2	3.92e-1	2.98	9.55e-2	1.68e-2	1.17e-1	9.78e-1	7.05e-2	2.87e-2	8.84e-2	3.40e-1
Insecticides	5.68e-2	8.71e-3	1.07	2.55e1	3.03e-2	2.06e-3	7.55e-2	1.47	2.25e-2	0	2.93e-2	1.28e-1
Pheromones	0	0	3.27e-1	8.08	0	0	2.85e-1	1.78e1	0	0	9.93e-4	8.58e-3
Plant growth regulators	1.11e-3	0	3.41e-3	7.52e-2	4.19e-4	0	2.64e-3	4.65e-1	2.20e-4	0	4.97e-4	2.11e-3
Rodenticides	0	0	7.51e-5	1.31e-3	0	0	1.16e-5	6.06e-4	0	0	2.59e-6	5.17e-5
Yield (t/ha)	2.50e1	1.06	3.23e1	9.35e1	5.35e1	7.64	5.57e1	1.02e2	6.51e1	1.38e1	5.78e1	9.20e1

Low production (young)					Full production				Low production (young)			
Median	Min	Mean	Max		Median	Min	Mean	Max	Median	Min	Mean	Max
ORGANIC PRODUCTION												
Energy (GJ/t)	5.24	1.39	6.32	1.26e1	6.03e-1	2.96e-1	1.04	2.26	3.31e-1	1.82e-1	4.21e-1	7.64e-1
Drinking water (m3/t)	3.55	0	2.81	5.04	0	0	2.78e-2	2.50e-1	2.50e-1	0	2.42e-1	5.67e-1
Synthetic fertilisers (kg/t)	1.97e2	7.25e1	2.91e2	5.70e2	6.43e1	2.47	7.45e1	1.66e2	2.73e1	2.14	4.97e1	1.75e2
N	3.64	1.12e-1	4.07	1.15e1	1.63	9.38e-2	1.65	4.11	1.07e-1	2.87e-3	3.90e-1	1.86
P	0	0	2.68	1.30e1	1.42e-1	0	1.42e-1	3.54e-1	0	0	2.84e-2	1.62e-1
K	0	0	8.07e-1	4.04	1.38	0	2.46	7.73	5.88e-1	0	1.25	4.30
Organic fertilisers (kg/t)	3.23e3	0	2.33e3	3.90e3	0	0	1.93	1.74e1	1.52e1	0	4.60e1	2.05e2
N	1.74e1	0	1.43e1	2.42e1	0	0	2.51e-1	2.26	1.22	0	1.65	5.19
P	5.13	0	4.63	8.65	0	0	0	0	0	0	7.04e-2	3.78e-1
K	1.65	0	4.51	1.43e1	0	0	0	0	0	0	7.10e-2	6.24e-1
Pesticides (kg a.i./t)												
Fungicides	1.52e1	8.08e-1	1.55e1	3.57e1	8.60e-1	1.03e-1	7.17e-1	1.14	6.28e-1	1.48e-1	6.68e-1	1.51
Herbicides	0	0	0	0	0	0	0	0	0	0	0	0
Insecticides	9.61e-1	0	4.20	1.13e1	3.93e-4	0	3.55e-1	2.10	1.40e-1	0	2.83e-1	1.09
Pheromones	4.56e-2	0	3.92e-2	9.53e-2	0	0	0	0	0	0	1.53e-2	7.72e-2
Plant growth regulators	0	0	0	0	0	0	9.05e-5	8.13e-4	0	0	0	0
Rodenticides	0	0	0	0	0	0	0	0	0	0	0	0
Yield (t/ha)	2.39	1.78	7.46	2.66e1	4.86e1	2.29e1	4.96e1	1.18e2	4.88e1	2.28e1	5.16e1	9.02e1

Table S4 Impacts within each impact category: median, minimum, 25% quartile, mean, 75% quartile and maximum annual impacts per tonne apples

CONVENTIONAL PRODUCTION						
	Median	Min	Q25	Mean	Q75	Max
Low production (young)						
CC	7.51e1	1.24e1	4.95e1	1.71e2	1.13e2	1.41e3
HTC	6.51e-6	2.60e-7	2.28e-6	1.06e-5	1.04e-5	5.88e-5
AC	1.57	1.03e-1	9.88e-1	3.12	2.57	2.08e1
TEU	6.63	4.86e-1	4.40	1.36e1	1.14e1	8.93e1
FEU	3.15e-2	3.63e-4	3.30e-3	4.38e-2	6.07e-2	2.30e-1
MEU	1.05	4.76e-2	5.36e-1	1.99	2.15	1.37e1
FET	6.44e3	2.71e3	3.79e3	1.14e4	1.21e4	6.36e4
LU	7.78e1	2.83e1	3.98e1	2.58e2	1.89e2	2.28e3
WD	9.39e-2	3.35e-3	5.68e-3	6.22e-1	2.01e-1	3.88
MD	7.26e-4	2.74e-5	1.34e-4	5.26e-3	4.49e-3	5.15e-2
Full production						
CC	6.04e1	1.01e1	4.32e1	7.62e1	8.83e1	2.45e2
HTC	3.22e-6	4.68e-7	2.28e-6	5.82e-6	8.76e-6	2.27e-5
AC	1.14	1.50e-1	6.93e-1	1.29	1.64	5.46
TEU	4.36	6.34e-1	2.83	5.50	6.85	2.43e1
FEU	1.33e-2	6.11e-4	6.08e-3	2.07e-2	2.88e-2	1.04e-1
MEU	6.48e-1	8.00e-2	3.69e-1	7.78e-1	9.57e-1	3.68
FET	6.39e3	2.95e2	4.68e3	7.46e3	9.49e3	2.33e4
LU	9.61e1	1.07e1	7.08e1	1.21e2	1.47e2	5.20e2
WD	8.22e-2	1.06e-2	3.24e-2	1.04e-1	1.23e-1	5.94e-1
MD	1.50e-3	4.60e-5	7.12e-4	3.36e-3	4.23e-3	2.90e-2
Low production (old)						
CC	1.06e2	8.43e1	8.43e1	1.06e2	1.28e2	1.28e2
HTC	1.65e-5	5.82e-6	5.82e-6	1.65e-5	2.72e-5	2.72e-5
AC	2.75	1.26	1.26	2.75	4.24	4.24
TEU	1.18e1	5.04	5.04	1.18e1	1.86e1	1.86e1
FEU	4.50e-2	3.89e-2	3.89e-2	4.50e-2	5.11e-2	5.11e-2
MEU	2.60	1.73	1.73	2.60	3.47	3.47
FET	3.49e3	2.35e3	2.35e3	3.49e3	4.63e3	4.63e3
LU	1.60e2	1.40e2	1.40e2	1.60e2	1.80e2	1.80e2
WD	1.50e-1	1.43e-1	1.43e-1	1.50e-1	1.57e-1	1.57e-1
MD	4.63e-3	2.93e-3	2.93e-3	4.63e-3	6.33e-3	6.33e-3
INTEGRATED PRODUCTION						
	Median	Min	Q25	Mean	Q75	Max
Low production (young)						
CC	1.44e2	2.70e1	7.87e1	3.15e2	3.14e2	2.74e3
HTC	8.62e-6	1.17e-6	5.00e-6	3.15e-5	1.90e-5	5.45e-4
AC	2.18	3.70e-1	1.22	5.32	5.08	5.26e1
TEU	8.38	1.62	4.94	2.04e1	2.12e1	1.81e2
FEU	3.88e-2	1.36e-3	1.98e-2	3.20e-1	1.23e-1	9.28
MEU	1.86	2.18e-1	7.04e-1	3.67	4.61	2.42e1
FET	9.30e3	2.31e3	4.42e3	2.18e4	2.17e4	1.74e5
LU	2.00e2	3.04e1	9.64e1	4.96e2	4.58e2	4.35e3
WD	2.68e-1	9.18e-3	1.02e-1	7.01e-1	8.07e-1	6.23
MD	9.53e-3	5.49e-4	4.19e-3	3.35e-2	1.50e-2	5.20e-1

Full production						
CC	5.86e1	1.96e1	3.91e1	7.54e1	9.05e1	7.25e2
HTC	3.09e-6	2.48e-7	1.91e-6	4.66e-6	5.64e-6	2.79e-5
AC	9.62e-1	2.15e-1	6.12e-1	1.46	1.53	2.94e1
TEU	3.93	9.70e-1	2.50	6.13	6.20	1.31e2
FEU	1.70e-2	5.63e-4	7.91e-3	2.85e-2	3.10e-2	5.37e-1
MEU	5.85e-1	1.07e-1	3.72e-1	9.17e-1	9.62e-1	1.30e1
FET	4.62e3	7.76e2	3.09e3	5.86e3	7.02e3	3.80e4
LU	9.13e1	1.07e1	5.85e1	1.11e2	1.37e2	1.07e3
WD	8.00e-2	-2.94e-2	3.00e-2	1.41e-1	1.97e-1	1.40
MD	1.95e-3	7.44e-5	7.69e-4	4.33e-3	5.17e-3	3.79e-2
Low production (old)						
CC	5.68e1	1.89e1	2.98e1	6.87e1	7.99e1	1.93e2
HTC	2.13e-6	6.59e-7	1.24e-6	3.11e-6	5.00e-6	8.57e-6
AC	7.70e-1	2.58e-1	4.06e-1	8.98e-1	1.19	2.63
TEU	2.81	1.17	1.78	3.80	5.26	1.16e1
FEU	9.14e-3	2.29e-3	3.54e-3	1.43e-2	2.03e-2	5.76e-2
MEU	3.98e-1	1.25e-1	2.46e-1	5.02e-1	6.32e-1	1.65
FET	3.01e3	1.41e2	2.30e3	3.71e3	5.34e3	7.92e3
LU	9.65e1	3.13e1	4.43e1	1.31e2	1.28e2	4.28e2
WD	1.35e-1	1.39e-2	3.89e-2	2.60e-1	3.12e-1	1.16
MD	9.21e-4	7.25e-5	4.84e-4	2.99e-3	4.76e-3	1.37e-2
ORGANIC PRODUCTION						
	Median	Min	Q25	Mean	Q75	Max
Low production (young)						
CC	8.35e2	3.25e2	3.49e2	1.01e3	1.77e3	2.02e3
HTC	6.45e-5	2.67e-5	2.84e-5	1.22e-4	2.44e-4	2.57e-4
AC	2.39e1	4.83	6.89	1.96e1	3.01e1	3.24e1
TEU	1.06e2	1.58e1	2.77e1	8.17e1	1.24e2	1.30e2
FEU	4.84e-1	1.01e-1	1.40e-1	4.73e-1	8.01e-1	1.04
MEU	1.03e1	2.37	3.12	8.65	1.33e1	1.34e1
FET	3.04e4	6.74e3	9.01e3	4.96e4	9.97e4	1.05e5
LU	2.14e3	6.46e2	7.39e2	2.01e3	3.22e3	3.80e3
WD	2.25	7.21e-1	7.76e-1	2.35	3.96	4.72
MD	5.82e-2	7.49e-3	1.39e-2	6.80e-2	1.27e-1	1.71e-1
Full production						
CC	1.75e2	6.96e1	1.27e2	2.26e2	3.63e2	4.44e2
HTC	1.59e-5	8.86e-7	7.85e-6	1.55e-5	2.22e-5	3.12e-5
AC	2.32	7.11e-1	1.76	2.69	4.01	5.23
TEU	7.60	2.63	4.07	8.99	1.40e1	1.75e1
FEU	5.13e-2	6.55e-3	2.72e-2	5.09e-2	7.23e-2	1.03e-1
MEU	1.02	3.15e-1	6.09e-1	1.18	1.82	2.42
FET	2.77e3	7.08e2	2.60e3	4.35e3	7.59e3	9.01e3
LU	3.46e2	1.42e2	2.90e2	4.37e2	6.95e2	8.04e2
WD	4.01e-1	8.29e-2	2.67e-1	4.08e-1	5.58e-1	7.61e-1
MD	3.11e-2	9.42e-4	1.65e-2	3.12e-2	4.56e-2	6.12e-2
Low production (old)						
CC	9.49e1	3.55e1	5.88e1	1.08e2	1.49e2	2.48e2
HTC	4.22e-6	6.29e-7	2.09e-6	6.13e-6	1.18e-5	1.31e-5
AC	1.87	6.97e-1	1.32	2.24	2.61	5.96
TEU	6.86	2.06	4.61	9.25	1.16e1	2.53e1
FEU	1.79e-2	4.26e-3	9.35e-3	1.94e-2	2.94e-2	3.90e-2
MEU	7.77e-1	2.17e-1	5.56e-1	9.41e-1	1.15	2.39
FET	1.58e3	4.34e2	9.68e2	2.90e3	4.04e3	1.15e4
LU	2.49e2	9.12e1	1.74e2	3.10e2	3.68e2	8.39e2
WD	2.47e-1	9.82e-2	1.94e-1	2.72e-1	3.05e-1	6.35e-1
MD	6.60e-3	8.38e-4	8.78e-4	7.92e-3	1.36e-2	2.23e-2