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Aude Alaphilippe, Sylvaine Simon, Laurent Brun, Frank Hayer, Gérard Gaillard. Life cycle analysis reveals higher agroecological benefits of organic and low-input apple production. *Agronomy for Sustainable Development*, 2013, 33 (3), pp.581-592. 10.1007/S13593-012-0124-7 . hal-01201368

HAL Id: hal-01201368

<https://hal.science/hal-01201368>

Submitted on 17 Sep 2015

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Life cycle analysis reveals higher agroecological benefits of organic and low-input apple production

Aude Alaphilippe · Sylvaine Simon · Laurent Brun · Frank Hayer · Gérard Gaillard

Accepted: 19 November 2012 / Published online: 7 December 2012
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Abstract Conventional agricultural systems depend on high inputs of fertilizers and toxic pesticides that are a threat for human health and the environment. Such issues are rapidly changing agriculture in Europe. As a consequence sustainable production systems are currently developed as safer alternatives, for instance organic and low-input systems use of mechanical and biological methods versus toxic substances. However, there is a lack of knowledge on the overall impact of these alternative systems on toxicity, energy use, and global warming, notably for perennial crops such as apple orchards, which require the control of many pests. Here we present the first analysis of the environmental impacts of nine apple orchard systems using life cycle analysis. We used data from a survey of apple orchard systems located in Southern France, covering 2006–2009. Conventional, low-input, and organic orchards were planted with three apple cultivars differing in their disease susceptibility, hence designing nine apple systems, with the Golden Delicious conventional system being considered as the reference. Our results show that low-input systems planted with low disease susceptibility Melrose cultivar decreased environmental impacts by 6–99 %. Organic systems had one of the highest impacts per mass unit due to low yields, but showed low impacts per area unit planted with low-susceptibility cultivars generally. Potential toxicity was decreased by 2–40 % for human, 71–82 % for aquatic life, and 97–99 % for terrestrial life using mechanical control versus toxic pesticides to control weeds and diseases.

Keywords Apple orchard · Conventional · Organic · Low input · Life cycle assessment · Environmental performance

1 Introduction

Conventional apple orchard systems are intensively sprayed to control pests, diseases, and weeds. Pesticide use as measured by the mean Treatment Frequency Index exceeds 35 in France (Sauphanor et al. 2009). Although conventional production systems are most common, the organic farming systems and the low-input systems based on International Organisation for Biological Control (IOBC) guidelines of integrated fruit production (Malavolta and Cross 2009) are developing in European apple orchards. The alternative production systems differ in their allowances of synthetic chemicals, which are banned in organic farming (Letourneau and Bothwell 2008), whereas the low-input systems permit their use as a last resort or under certain conditions, according to the IOBC definition of integrated fruit production (Malavolta and Cross 2009). Both production systems are described as environmentally favorable compared with the conventional system, in particular for physical and chemical soil characteristics such as infiltration rate (Vogeler et al. 2006), soil biodiversity (Maluche-Baretta et al. 2007), and biodiversity (Letourneau and Bothwell 2008). In both organic and low-input production systems, there is an increased use of alternative methods, e.g., mechanical weed control and non-synthetic active ingredients aiming at improving the environmental efficiency of protection strategies. A methodology calculating the different impact categories is therefore necessary to compare the overall environmental impact of these production systems and to avoid the risk of pollution transfer from one impact category to another. Life cycle assessment (LCA),

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also named cradle-to-grave analysis, allows an objective and general comparison of the analyzed systems (Milà i Canals et al. 2006; Mouron et al. 2006) and is suitable for comparing production systems (Haas et al. 2001). This method was originally developed for industrial processes, but was adapted to agriculture several years ago (Cowell and Clift 1997), in particular to arable crops and animal production. In the last few years, adaptation of the LCA methodology has extended to specialized crops, such as apple or tomato productions (Anton et al. 2004; Boulard et al. 2011; Milà i Canals et al. 2006; Mouron et al. 2006). However, only one LCA study based on actual farm data compares the environmental impacts of the conventional apple production practices with integrated fruit production (Milà i Canals et al. 2006). Moreover, this study did not include an organic system and concluded that the farm organization was one of the major factors influencing the outcome. There is presently no standardized comparative environmental evaluation available for apple production systems, despite the prevalence of this fruit crop in temperate areas (FAO 2008).

The aim of our work was to calculate and to compare the environmental impacts of different apple production systems with a LCA holistic approach including energy consumption and other relevant environmental impact categories beside ecotoxicity and human toxicity. To avoid differences related to farmers' practices, climatic conditions, soil heterogeneity, or other regional parameters, we used a pluri-annual dataset from a system experiment reproducing growers' practices. The dataset covered four seasons (2006–2009) for three production systems: conventional, low input, and organic. As planting date, abiotic conditions, and conservative design of orchards were similar among the experimental orchards, the comparison between production systems mainly focused on differences in plant protection and fertilization. This study also addressed the significance of the cultivar within each system, since the same three cultivars differing in disease susceptibility were planted in each production system.

2 Materials and methods

2.1 Experimental design and apple orchard management

2.1.1 Design of the orchard systems

The experimental orchard was created specifically to conduct multi-criteria assessments of three production systems representative of fruit grower practices, conventional, low-input, and organic systems. Experimental design and apple production systems are described in Simon et al.

(2011). Briefly, this experimental orchard named BioREco was planted in January 2005 on a surface area of 3.3 ha, in the Middle Rhone valley (France) at the INRA Gotheron experimental unit. It consisted of nine plots; each plot (0.37 ha), referred to as a 'production system', was a combination of one production system and one apple cultivar.

Production systems were:

- Conventional: chemical pesticides were mainly used to control pests, diseases, and weeds. Bulletin of extension services were used to schedule treatments.
- Organic farming: no synthetic inputs were applied, as defined by the European rules for organic production (EC 889/2008 and EEC 2092/91).
- Low input: preference was given to other protection methods than chemicals (mating disruption, sanitation practices...), according to IOBC European guidelines (Malavolta and Cross 2009).

Within each production system, the three planted cultivars were:

- Smoothee 2832T®: a 'Golden Delicious' type cultivar susceptible to scab, a major fungal disease of apple due to *Venturia inaequalis*. Smoothee 2832T® is referred to as 'Golden D.'
- Ariane: scab-resistant cultivar (*Vf*-gene, named Rvi6 following the nomenclature (Bowen et al. 2011; Agence BIO 2011).
- Melrose: low susceptibility to scab, based upon quantitative resistance.

Those cultivars were selected to represent the range of scab susceptibility of commercial orchards. Planting density was 1,000 trees/ha, with a grass cover between rows.

2.1.2 Cultural practices and activities within the apple production systems

All cultural operations of fertilization, plant protection, irrigation, within-row management, tree training, fruit load management, and harvest were monitored in the nine production systems. Detailed information on the machinery use and the input(s) are given in Table 1.

Fertilization differed between systems. Organic fertilizers, on-farm compost and feather manure, were applied in autumn and spring respectively in the organic farming systems. The compost consisted of a mixture of 1/5 of small tree branches and 4/5 of cow manure from a neighbor farm. Mineral fertilizers were applied in the other production systems in three applications from late winter to early summer. The mean total yearly available nitrogen was 45 kg ha⁻¹ and the mean K₂O supply was approximately 65 kg ha⁻¹ year⁻¹ in all plots. P₂O₅ supply was 30 kg ha⁻¹ year⁻¹ in organic farming orchards and 50 kg ha⁻¹ in the conventional and low-input

Table 1 Harvest, labor, machinery, and input use in the nine apple production systems: 4-year mean, for all data except for yield data from year 2009

Production system	Conventional			Low input			Organic		
	Golden D.	Melrose	Ariane	Golden D.	Melrose	Ariane	Golden D.	Melrose	Ariane
Number of applied compounds ^a	23.3	22.5	20.8	14.8	10.8	11.3	5.3	5.3	5.3
Total weight of chemical (kg) ^a	41.2	38.5	36.7	33.6	23.7	24.1	138.9	85.4	75.0
Number of passes for pesticide spraying	34.3	32.3	29.3	25.3	16.5	18.8	29.0	17.5	16.5
Total machinery use (h ha ⁻¹ year ⁻¹)	56.8	53.9	60.1	62.6	57.5	65.3	55.7	56.5	64.1
Platform use (h ha ⁻¹ year ⁻¹)	32.2	30.7	41.6	36.5	39.4	47.0	21.1	34.0	45.9
Yield (t ha ⁻¹) 2009 1 and 2 grade fruits	41.7	38.3	34.2	39.7	36.9	31.7	18.3	29.7	18.5

^a Excluding microbiological compounds

orchards (Simon et al. 2011). All fertilizers were applied with a tractor and a sprayer. In the organic farming orchards, the compost was ploughed into the soil just after application.

Tree training, fruit load management, and harvest could vary according to the cultivar (Table 1). Most of the activities related to this work category were manual, but required a self-driven platform. Fruit thinning was manual only in the organic farming systems. Chemical thinning was used in combination with manual work in the other production systems.

Protection against weeds, pests, and diseases was defined by sets of decision rules which were related to the production system and the associated guidelines or framework. Within a production system, decision rules could vary according to the cultivar, especially for disease management constrained by cultivar susceptibility. Plant protection practices differed between systems in the type and the frequency of use of pesticides, and also in the use alternative methods (Table 1). A treatment is one application process, independently of the number of dose equivalents of each pesticide compound. The yearly number of treatments (4-year mean value) varied from 16.5 (organic farming Ariane) to 34.3 (conventional Golden D.). The conventional systems displayed the highest number of applications (Table 1).

Understorey management was defined according to production systems. Within rows, weeds were controlled by herbicides in the conventional systems, by mechanical and/or manual work in the organic farming systems, whereas a combination of both chemical and mechanical practices was used in the low-input systems. Between rows, mechanical work was used in all systems, mostly mulching and sanitation practices such as leaf litter shredding or removal as a management of winter scab inoculum.

These orchards entered full production in year 2009; first- and second-grade fruits yield varied in year 2009 from

18.5 up to 41.7 t per ha for organic farming Golden D. and conventional Golden D., respectively. The organic farming systems had the lowest yields.

2.2 Life cycle assessment

The design of a LCA study is described in ISO 14044 (ISO 2006). First the goal and scope of the study have to be defined as well as the system boundaries. In a second step, production data are collected and the life cycle inventory is set up, which was then used to calculate the ecoinventory and the different environmental impacts. The final step is the interpretation of the results. In this section the authors will give a short overview of the decisions concerning the LCA analysis made during the study.

2.2.1 Goal and scope

The goal of this LCA study was to compare the environmental impacts of nine apple production systems in their first years using the data from the experimental orchard BioREco, which combines three production systems with three cultivars. The comparison between production systems mainly focused on differences in plant protection and fertilization, since planting date, abiotic conditions, and conservative design of orchards were similar among the experimental systems.

2.2.2 Functional units, system definition, and boundaries

The system boundary was set at the field gate. The considered system included all inputs and processes required to deliver apples for storage.

The analysis included the following processes:

- Infrastructure: manufacturing and maintenance of machinery and sheds.

- All field processes such as fertilization, plant protection, sanitation practices, mechanical work, tree training, and harvest including fuel delivery and combustion.
- Production of mineral and organic fertilizers, and pesticides.
- Direct field emissions: nitrate, ammonia, nitrous oxide, phosphorus, heavy metals, and pesticides.

The temporal system started after the harvest in the previous year and ended with the beginning of the harvest in the current production year. The post harvest activities in autumn were related to the next harvest.

Two functional units, a mass-based and a surface-based unit, are appropriate when studying only the production systems. These functional units reflect (1) the social perspective of preserving landscape and sustaining land use and (2) the production (Nemecek and Gaillard 2010). Our LCA results were therefore expressed in hectares (ha year) and kilograms of first- and second-grade fruits (kg year). This study included the four first years of production corresponding to the harvest of years 2006, 2007, 2008, and 2009. As full production was reached in 2009, only that results related to yield 2009 were presented. Since no difference was observed between the experimented systems for irrigation, orchard planting, and removal, these aspects were not integrated in the calculations. Data collected in the experimental orchard BioREco (Simon et al. 2011) from 2006 to 2009 were used to describe the production systems. The input characteristics and associated emission flows were defined with inventories from the Ecoinvent database v2.01. and the Swiss Agricultural Life Cycle Assessment (SALCA) database (Nemecek et al. 2004) adapted when necessary in a joint INRA/ART collaboration.

2.2.3 Specificities of LCA for apple production

The direct field emissions (NH_4^+ , N_2O , phosphorus, NO_3^- , heavy metals, and pesticides) were estimated according to SALCA methodology described in Gaillard and Nemecek (2009). We used the LCA calculation tools SALCA-crop v3.1 of ART. The tool consists of modules programmed in Microsoft EXCEL® and a system implemented in the TEAM™ software (Version 4.0) from PriceWaterHouse Coopers/Ecobilan (Paris, France). To estimate these field emissions, local parameters that influence emission flows were set in the SALCA-crop tool: the experimental orchard had no drainage and slope. The local weather is relatively dry during the summer period due to Mediterranean influences and the yearly total rainfall is around 850 L m^{-2} . The soil contains 2 % organic matter, 15 % clay, and the rooting depth was around 40 cm.

Among field processes, allocation rules were used when the same machinery was shared by two different field

processes. For example, the same equipment was used to plough in the compost (field process: fertilization) and the leaf litter (field process: sanitation). To calculate the impacts, 50 % of the “environmental cost” of the machinery use was associated with the fertilization activity and 50 % with the sanitation practice, which is part of plant protection.

2.2.4 Impact assessment

The SALCA method developed within the life cycle group of ART (Gaillard and Nemecek 2009) includes relevant impact categories and the assessment methodologies EDIP97 (Hauschild and Wenzel 1998) and CML01 (Guinée et al. 2001). All these methodologies use the mid-point approach, which translates the category impact into real phenomenon such as ozone formation or terrestrial toxicity. The following environmental impacts were considered:

- Demand for non-renewable energy resources, expressed in MegaJoule-equivalent (MJ-eq), included direct resources, i.e., diesel and electricity and indirect ones, i.e., coal, oil gas, and uranium non-renewable energy (Hischier et al. 2009).
- Global warming potential over 100 years, expressed in kg CO_2 -equivalent included main emissions considered in agriculture, i.e., carbon dioxide, methane, and nitrous oxides in the air compartment at a global scale, stemming from the use of energy resources and nitrogen fertilizers (IPCC 2007).
- Ozone formation potential, expressed in kg ethylene-equivalent, considered the production of ozone from volatile organic compounds according to their ability to produce ozone (EDIP97).
- Eutrophication potential or nutrient-enrichment potential, expressed in kg N-eq $\text{ha}^{-1} \text{ year}^{-1}$, considered the enrichment of phosphorus and nitrogen nutrients in aquatic and terrestrial ecosystems (EDIP97).
- Acidification potential, expressed in kg SO_2 -eq $\text{ha}^{-1} \text{ year}^{-1}$, included aerial emissions of acidifying substances, among which SO_2 , NH_3 , and nitrous oxides (EDIP97).
- Terrestrial and aquatic ecotoxicity potential, expressed in kg 1,4-Dichlorobenzene-equivalent (kg 1,4-DCB-eq.) was mainly caused by pesticides and heavy metals (CML01).
- Human toxicity potential, expressed in 1,4-DCB kg-eq, considered impact of toxic pollutants on human health, through aerial emissions (CML01).

The equipment used for spraying was a self-propelled machine. The CML01 characterization factors were used to calculate the human toxicity, and the aquatic and terrestrial ecotoxicity of applied pesticides. The missing characterization factors for active ingredients were calculated using the SYNOPSIS database (Gutsche and Rossberg 1997) as a

reference, and FOOTPRINT PPDB (2007) for data gaps or active ingredients missing in SYNOPS (Hayer and Gaillard 2010). Both databases are actively managed and continuously updated. For both databases the European review monographs were used as preferential data source. If European monographs were not available, alternative sources were used, such as documents from national legislation processes, pesticide manuals, IVA-datasheets, or publications. The pesticide emissions were assumed as emissions to soil.

3 Results and discussion

We will here detail the following impact categories: (1) non-renewable energy resources, (2) global warming potential, and (3) environmental and human toxicity, as well as an overview of all eight impact categories. As plant protection was a main focus in this study, the contribution of the different processes related to plant protection activities,

i.e., manufacture and application of pesticides, sanitation practices, and mechanical work, was detailed and presented.

3.1 Non-renewable energy resources

Figure 1 shows the energy demand of the nine production systems and the sources of energy consumption. Results per kilogram (year 2009) and per hectare (4-year mean) gave opposite trends. Organic farming systems were generally less energy consuming compared with low-input and conventional systems when results are expressed per ha year, but the opposite was displayed, when expressed per kg year commercial fruits. Organic farming system yields were the lowest. The low-input and conventional systems displayed similar values for energy demand and yields.

The plant protection activities, i.e., sanitation practices, pesticides and herbicide applications, or within-row mechanical weeding in organic farming and low-input systems, were the most energy consuming. The diesel consumption of machineries and also the energy needed for their construction

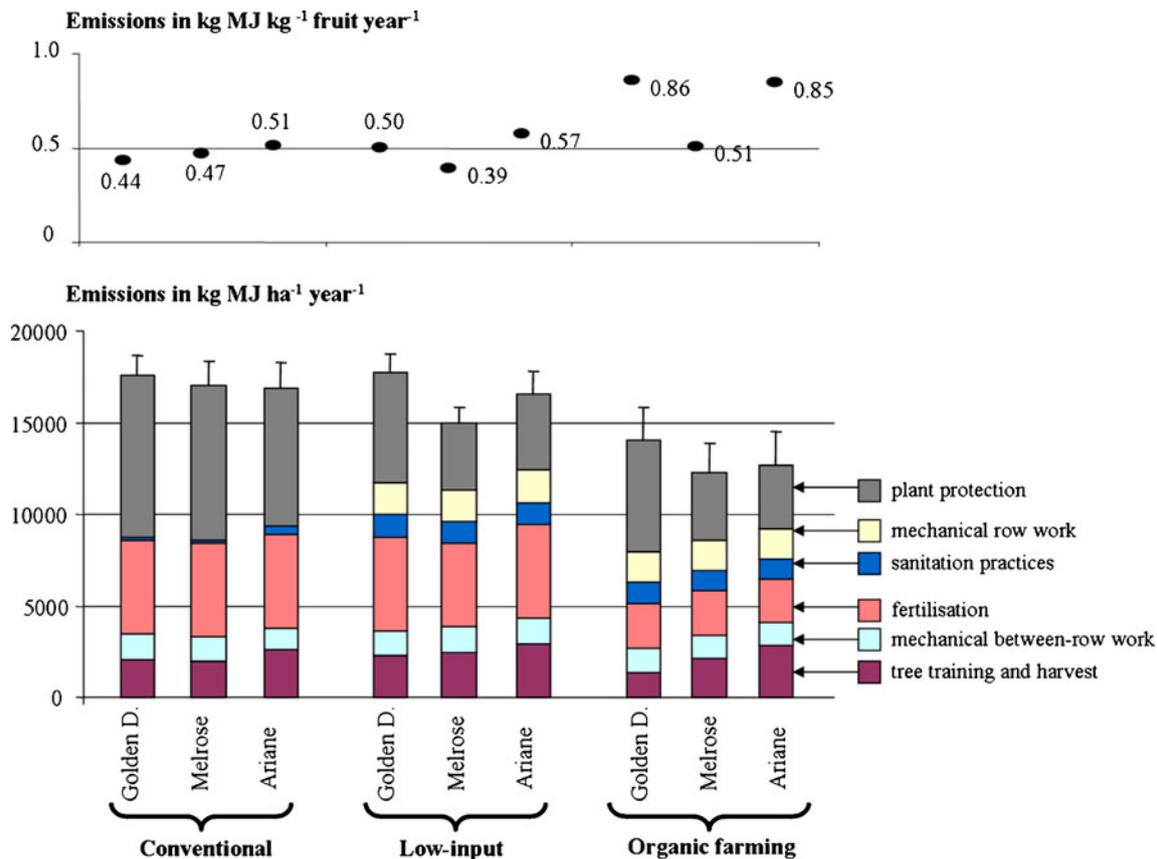


Fig. 1 Processes and their demand for non-renewable energy in the nine apple production systems MJ kg⁻¹ year⁻¹ in 2009 (plain line) and 4-year mean MJ ha⁻¹ year⁻¹ (columns) and the error bars indicate the standard deviations. See Table 1 for definitions of plant protection. Note that organic farming systems were generally less energy consuming compared with low-input and conventional systems when results are expressed per ha year, but the opposite was displayed, when expressed

per kg year commercial fruits. This difference is due to the fact that organic farming system yields were the lowest. In contrast, the low-input and conventional systems displayed similar values for energy demand and yields. The plant protection activities, i.e., sanitation practices, pesticides, and herbicide applications or within-row mechanical weeding in organic farming and low-input systems, were the most energy consuming

(data not shown) were mainly responsible for this energy consumption. Although of lower importance, fertilization including fertilizer production and application was the field process that differentiated most the organic from other production systems. Indeed mineral fertilizers were more energy consuming than organic ones to produce (data not shown). Thus, the organic farming systems had a lower total energy demand for fertilization than the other two systems.

The level of energy use for plant protection activities was also highly related to the cultivar in addition to the production system whatever the functional unit. For both Ariane and Melrose cultivars the energy consumption in the low-input and the organic farming systems was respectively slightly to highly reduced compared with the conventional systems. This effect was caused by a lower number of fungicide applications for low-susceptibility cultivars and the nature of applied active ingredients according to the production system. Indeed the scab-susceptible Golden D. cultivar required more pesticide applications and consumed more energy whatever the production system.

Tree training and harvest required a self-driven platform, and therefore energy consumption. The main differences among cultivars were related to tree growth and behavior. Particularly, trees had lower growth and fruit load in organic farming than in other systems, and manual fruit thinning was much more time consuming in Ariane than in the other two cultivars.

Compared with the potential impacts per mass unit calculated by Mila i Canals et al. (2006), harvesting appears as the main contributor. Although mechanization was the main contributor for this impact category, direct energy consumption by field operations prevailed in Mila i Canals et al. (2006), whereas machinery production also highly contributed in our study.

In the organic farming and low-input systems, herbicide applications were replaced by a mechanical understorey management with an inter-row disk with four tilling and three earthing up disks (Ommas, Italy). The inter-row disk machinery was also used for sanitation practices in the organic farming and low-input systems to plough in the leaf litter to decrease scab development in the next spring and also to plough in compost in the organic farming systems. In the organic and low-input systems, the use of machinery was scheduled to combine all these field activities into one operation in order to decrease impacts and to optimize machinery use. The Ommas machinery was used up to eight times per year and consumed an important amount of energy. However, the reduction in herbicide applications and its related reduction in energy use in organic and low-input systems generally balanced this machinery and energy use. The organic farming and low-input systems therefore ranked better than the conventional systems in this category.

Here the LCA results clearly demonstrated that replacing phytosanitary applications with mechanical work and/or sanitation activities did not increase the total system energy consumption.

3.2 Global warming potential

All production systems had a similar global warming potential per surface unit (Fig. 2). When expressed per kilogram per year of commercial fruits in 2009, the global warming emissions varied from 0.028 to 0.084 kg CO₂-eq kg⁻¹ fruit year⁻¹ for low-input Melrose and organic farming Golden D., respectively.

In all production systems, fertilization had the strongest impact on global warming potential, followed by plant protection activities. Considering plant protection, the use in some systems of sanitation practices such as leaf litter ploughing in and/or leaf removal to decrease scab inoculum was counterbalanced by lower emissions due to a decrease in pesticide use. The impact was the highest for Golden D. cultivar regardless of the production system.

The main source of emissions is CO₂ from machinery use in the different cultural operations whatever the production system and the cultivar (see Table 1 for details on machinery use). All the other emissions were mostly due to fertilizer production, which accounted for 37 to 45 % of the total global warming potential (data not shown). The production processes of mineral fertilizers emit a large amount of CO₂, as well as nitrous oxides. In the organic farming systems, there was a specific methane emission related to the use of compost. The contribution of fertilizer production was consistent with their values range of Mila i Canals et al. (2006).

The global warming potential impact category is closely related to the energy consumption impact category, since the emissions produced during energy consumption potentially caused global warming. However, studying these impact categories provides additional information and shows the contribution of different processes, since for global warming potential other sources are responsible for impacts such as methane emissions.

Although the LCA methodology has been adapted specifically to apple production, there is a lack of knowledge on specific topics, and in particular a lack of inventories to estimate carbon sequestration. Perennial crops especially under organic management exhibit higher soil carbon sequestration than annual crops (Kramer et al. 2006; Macrae et al. 2010), but the importance of this phenomenon to mitigate this impact category is still highly discussed among the research community and requires more knowledge (Powlson et al. 2011). In our work, since the soil carbon content remained constant in each system over the 4 years of the study, we did not consider any specific carbon sequestration in the organic farming systems. Such missing information

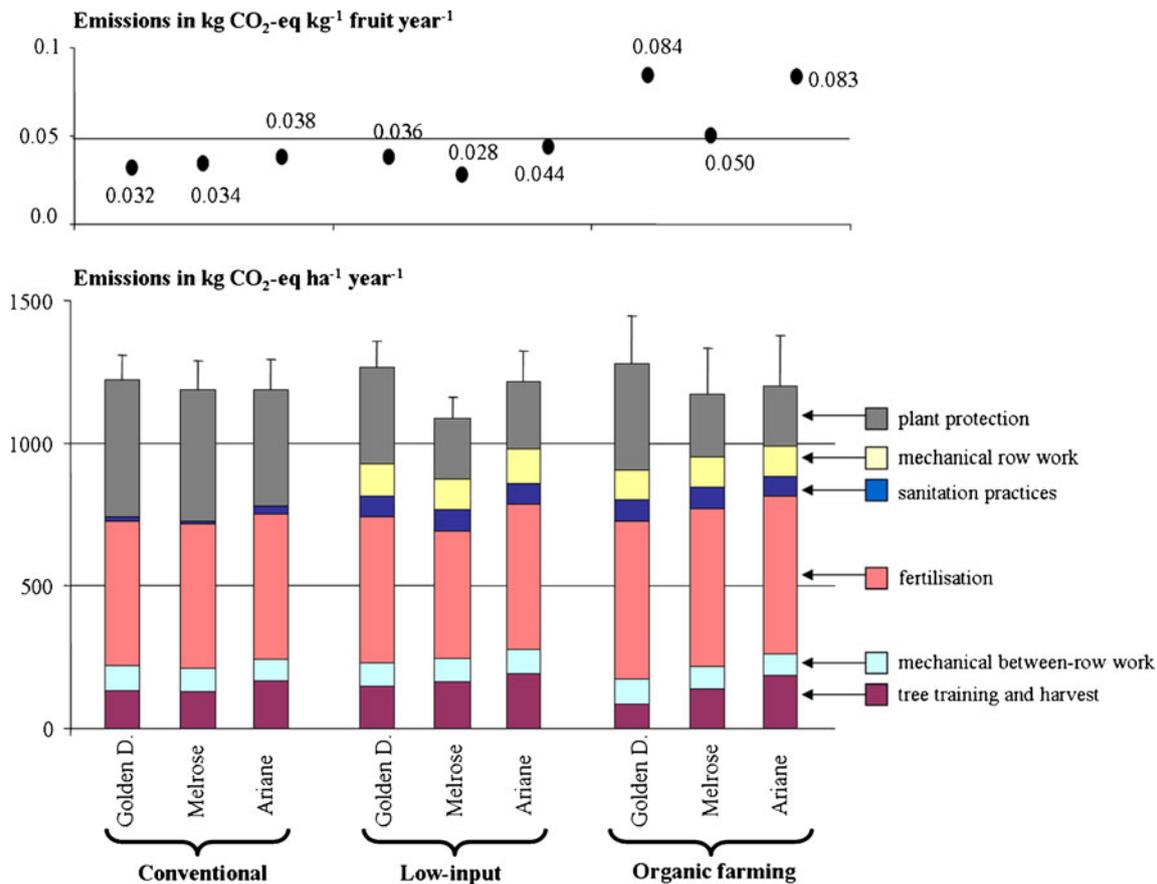


Fig. 2 Processes and their global warming potential in the nine apple production systems kg CO₂-eq kg⁻¹ year⁻¹ commercial fruits in 2009 (plain line) and 4-year mean in kg CO₂-eq ha⁻¹ year⁻¹ (columns). The error bars indicate the standard deviations. See Table 1 for definitions of plant protection. Note that all production systems had a similar

global warming potential per surface unit, but the opposite was displayed when results are expressed per kg year of commercial fruits. In all production systems, fertilization had the strongest impact on global warming potential, followed by plant protection activities

raises scientific questions to answer these specific needs, and might also open potential optimization of the production systems, through work on these gaps of knowledge.

3.3 Toxicity and ecotoxicity

The aquatic ecotoxicity (Table 2) was lowest in the low-input systems whatever the functional unit. The conventional systems were highly impacting due to the application of numerous very toxic active ingredients such as pyrimethanil (fungicide), ammonium thiocyanate (herbicide), pyridaben (miticide), and chlorpyrifos methyl (insecticide). In the organic farming systems, the use of mineral fungicides such as sulfur and copper was also highly impacting depending on the amount applied. The scab-susceptible Golden D. cultivar, which received around 100 kg year⁻¹ of sulfur vs. 38 kg year⁻¹ (4-year mean value) in the low-susceptible Melrose cultivar, displayed the highest impact of all systems. These results are inconsistent with the study of Mila i Canals (2006). In this study, aquatic ecotoxicity was dominated by emissions of

heavy metals related to direct energy consumption in the fields and to the input production. These differences might be explained by the difference in pesticide use and in the context of the study, i.e., the orchard proximity of surface and groundwater, as well as in the assessment methodology chosen.

For terrestrial ecotoxicity, the conventional systems were the most impacting, because of organophosphate insecticides (chlorpyrifos and azinphos methyl) followed by the application of herbicides (i.e., glyphosate) replaced by mechanical weeding in the low-input and organic farming systems. For the organic and to some extent low-input systems, mineral fungicides were responsible for most emissions, especially copper contamination of the soil of the orchard.

For scab-susceptible cultivars such as Golden D., emissions were higher than for both other cultivars in all three production systems, due to more treatments against scab.

The choice of the active ingredients in the low-input systems was largely influenced by their potential environmental impacts, which certainly decreased their impacts in the toxicity

Table 2 Potential aquatic and terrestrial ecotoxicity and human toxicity expressed in 1,4-dichlorobenzene-equivalent (1,4-DCB kg-eq ha⁻¹ year⁻¹) from non-pesticide origin^a and pesticide origin^b according to the target pest in the nine apple production systems (4-year mean ± standard deviation); potential aquatic and terrestrial ecotoxicity and human toxicity (kg 1,4-DCB-eq kg⁻¹ fruit year⁻¹) for 2009

Production system	Conventional			Low-input			Organic		
	Golden D.	Melrose	Ariane	Golden D.	Melrose	Ariane	Golden D.	Melrose	Ariane
Origin of water ecotoxicity per area unit (1,4-DCB kg-eq ha ⁻¹ year ⁻¹)									
Non-pesticide	26.4	26.3	25.7	25.6	24.1	25.3	74.1	70.2	33.8
Herbicides	42.1	42.1	42.1	24.9	0.0	12.5	0.0	0.0	0.0
Fungicides	73.5	78.4	91.2	84.1	79.2	68.5	218.1	143.0	142.0
Insecticides	216.1	162.0	164.5	3.4	0.0	4.6	0.1	0.1	0.1
Total	358±160	309±81	324±38	138±106	103±91	111±83	292±78	213±72	176±3
Water ecotoxicity per mass unit (1,4-DCB kg-eq kg ⁻¹ fruit year ⁻¹)									
Total	0.010	0.005	0.009	0.001	0.001	0.001	0.018	0.006	0.010
Origin of terrestrial ecotoxicity per area unit (1,4-DCB kg-eq ha ⁻¹ year ⁻¹)									
Non-pesticide	1.0	1.0	0.9	0.9	0.9	0.9	4.1	4.0	3.0
Herbicides	33.2	33.2	33.2	1.6	0.0	0.8	0.0	0.0	0.0
Fungicides	3.0	3.2	3.2	3.5	3.0	2.6	7.8	4.7	4.4
Insecticides	76.6	74.3	74.6	6.4	0.0	6.6	0.1	0.1	0.1
Total	113.8±44	111±40	111±40	12.4±3	3.9±13	10.9±15	12.1±3	8.8±2	7.6±1
Terrestrial ecotoxicity per mass unit (1,4-DCB kg-eq kg ⁻¹ fruit year ⁻¹)									
Total	0.002	0.002	0.002	0.000	0.000	0.000	0.001	0.000	0.000
Origin of human toxicity (1,4-DCB kg-eq ha ⁻¹ year ⁻¹)									
Non-pesticide	515.3	498.0	503.0	577.0	509.2	553.0	724.9	594.2	561.4
Herbicides	169.1	169.1	169.1	34.7	0.1	17.2	0.0	0.0	0.0
Fungicides	14.4	14.9	16.9	13.6	13.0	12.8	36.0	24.0	24.0
Insecticides	172.1	157.4	308.9	4.5	0.6	69.3	1.4	1.4	1.4
Other pesticides	0.1	0.1	0.2	0.1	0.1	0.1	0	0	0
Total	871±467	840±433	998±534	630±108	523±96	652±196	762±184	620±148	587±99
Human toxicity per mass unit (1,4-DCB kg-eq kg ⁻¹ fruit year ⁻¹)									
Total	0.012	0.013	0.014	0.015	0.013	0.018	0.047	0.022	0.037

^a e.g., production of inputs, buildings, and machinery use

^b Active ingredients applied in the nine apple production systems causing either aquatic, terrestrial ecotoxicity, or human toxicity

categories compared to the conventional systems. Moreover, the number of treatments was decreased in the low-input systems by combining methods such as pest prediction models, or visual controls in orchards, and treatment thresholds to assess the risk of fruit damages and/or avoid unnecessary treatments.

Human toxicity was highest per surface unit in the conventional systems, but highest per kilogram commercial fruits in the organic farming systems on the basis of the functional unit (Table 2), due to lower yields in organic farming compared to the other two production systems. Unlike aquatic and terrestrial ecotoxicity, the toxicity from non-pesticide origins, i.e., due to buildings and machineries and not to direct pesticide field emissions, was the most important cause of human toxicity (Table 2 and Fig. 3). The human toxicity was relatively high in all systems, because

of non-pesticide air emissions of chromium, arsenic, nickel, and copper associated with the production of machineries, buildings, and chemicals. Although toxicity from direct field emissions was lower than indirect emissions, it was not negligible. Insecticides (i.e., oxydemeton-methyl) and herbicides (amitrol) in conventional and low-input systems displayed a high toxicity (Table 2). Plant protection impact for human toxicity was the highest in the organic farming systems, because of the extraction and production of sulfur-based fungicides. The scab-susceptible Golden D. cultivar, which received the highest number of pesticide applications, also had the highest impact. Both mineral and organic fertilization contributed to human toxicity in all three systems.

Aquatic and terrestrial ecotoxicity potential was mainly related to direct pesticide field emissions. In contrast, the

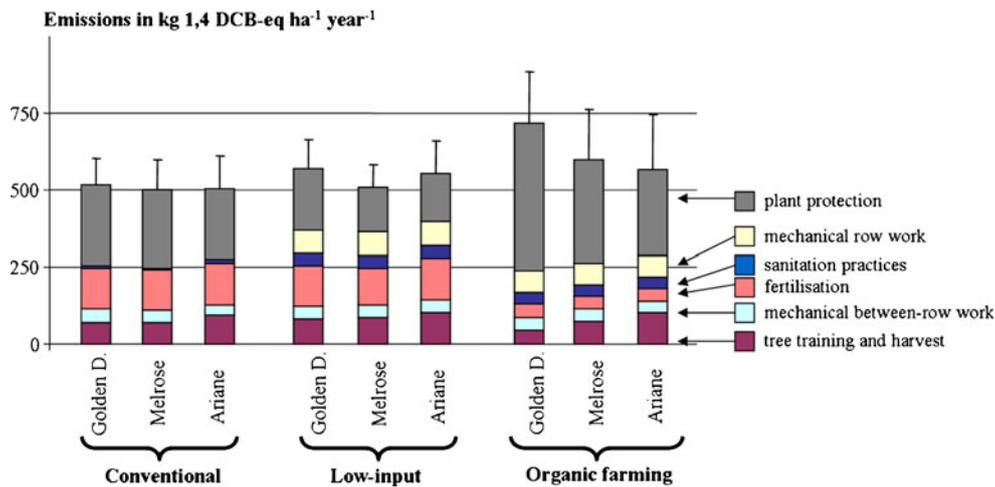


Fig. 3 Human toxicity: non-pesticide air emission origins expressed in kilograms of 1,4-dichlorobenzene-equivalent (1,4-DCB kg-eq ha⁻¹ year⁻¹) in the nine apple production systems (4-year mean). Note that the human toxicity was relatively high in all systems because

of non-pesticide air emissions associated with the production of machineries, buildings, and chemicals. Plant protection impact for human toxicity was the highest in the organic farming systems, because of the extraction and production of sulfur-based fungicides

human toxicity potential was mainly due to non-pesticide emissions related to the production of inputs. Since input production generally occurs in urban and therefore crowded areas, the potential human toxicity is thus far higher in the input production areas than in the countryside area where the inputs are applied. In the study of Mila i Canals (2006), the impact is caused by non-pesticide emissions, as well as pesticide emissions to air. However, the assessment methodology they used did not take into account the population density, where the emissions occur. Ecotoxicity and human toxicity in low-input and organic farming systems were decreased compared with the conventional Golden D. system, attesting of the importance of input reduction.

3.4 General patterns of impact and system comparison

Table 3 shows the impacts for each calculated impact category compared with the conventional Golden D. production system, which was set up to the value 1, as reference. It displays and highlights the variations in results due to the choice of the functional unit.

The low-input systems generally had the best environmental performances, when related to the surface-based functional unit. The organic farming systems also generally decreased the potential impacts for all categories except for the acidification potential. Indeed, the compost applied in the organic farming systems enhanced the acidification potential through its storage. In contrast, the eutrophication potential was lower in the organic farming compared to low-input and conventional systems, which used mineral fertilizers, since N availability is lower in organic compared to mineral fertilizers.

When considering the mass-based unit, only low-input Melrose and to some extent conventional Melrose had similar

or lower impact for global warming potential, non-renewable energy consumption, ozone formation, and acidification potential compared with conventional Golden D. The lower than expected environmental performances per mass unit of the organic farming systems except for toxicity and ecotoxicity was mainly attributed to lower yields. This result is consistent with the meta-analysis of published studies that compare environmental impacts of organic and conventional systems in Europe (Tuomisto et al. 2012). Such a yield decrease can be related to organic fertilization, since organic fertilizers lower the yield potential (Peck et al. 2006; Roussos and Gasparatos 2009). Moreover, in the present study, insufficient aphid control in the organic farming system also caused a decrease in fruit size and altered return bloom (Lyth 1985), with a decreased yield as a consequence.

Low-input Melrose was the only system presenting the best environmental performances whatever the functional unit. This system displayed either a similar or a decreased potential impact for all eight impact categories. The good performance of this system was related to a low and optimized pesticide use, and a similar yield compared with conventional Golden D.

Compared with the potential impacts per mass unit calculated by Mila i Canals et al. (2006), the present results are generally consistent with their value ranges. The authors drew the same conclusion: mechanization generates an important share of different impacts categories such as non-renewable energy consumption and global warming potential. However, a detailed comparison of the two studies shows some differences between the contributions of individual processes.

Last, labor time, which was different between systems, when manual work replaced some chemical treatments, i.e., sanitation and fruit thinning, was not considered by any of

Table 3 Percentage of variation per impact category for all apple production systems compared with the conventional Golden D. system (impact value in brackets): impacts per ha⁻¹ year⁻¹ (4-year mean) and impacts per kg⁻¹ year⁻¹ of commercial fruits in year 2009; values in

italic indicate an impact decrease compared to the reference, while values in bold indicate an impact increase; the unit 1,4-DCB kg-eq corresponds to 1,4-dichlorobenzene-equivalent

	Conventional			Low input			Organic		
	Golden D.	Melrose	Ariane	Golden D.	Melrose	Ariane	Golden D.	Melrose	Ariane
Potential impact per ha ⁻¹ year ⁻¹									
Global warming [kg CO ₂ -eq]	(1,219)	-3 %	-3 %	5 %	-10 %	0 %	5 %	-4 %	-2 %
Non-renewable energy [MJ-eq]	(17,596)	-3 %	-4 %	1 %	-15%	-6 %	-20%	-30%	-28%
Ozone formation [kg ethylene-eq]	(1)	-5 %	-4 %	9 %	-7 %	2 %	17%	2 %	5 %
Acidification [kg SO ₂ -eq]	(9)	-4 %	-3 %	5 %	-9 %	-1 %	100%	76%	75%
Eutrophication [kg N]	(17)	0 %	2 %	4 %	-22%	8 %	-53%	-54%	-54%
Terrestrial ecotoxicity [1,4-DCB kg-eq]	(114)	0 %	-2 %	-89%	-97%	-91%	-92%	-94%	-93%
Aquatic ecotoxicity [1,4-DCB kg-eq]	(358)	-27%	-10 %	-61%	-71%	-71%	-41%	-53%	-51%
Human toxicity [1,4-DCB kg-eq]	(871)	-19%	15%	-28%	-40%	-41%	-37%	-48%	-33%
Potential impact per kg ⁻¹ year ⁻¹									
Global warming [kg CO ₂ -eq]	(0.032)	8 %	20%	18%	-11%	38%	165%	59%	163%
Non-renewable energy [MJ-eq]	(0.437)	7 %	18%	19%	-8 %	31%	97%	16%	94%
Ozone formation [kg ethylene-eq]	(0.000)	6 %	18%	27%	6 %	42%	178%	63%	173%
Acidification [kg SO ₂ -eq]	(0.000)	4 %	15%	21%	-6 %	35%	515%	259%	472%
Eutrophication [kg N]	(0.001)	16%	41%	12%	-61%	61%	5 %	-36%	4 %
Terrestrial ecotoxicity [1,4-DCB kg-eq]	(0.002)	24%	26%	-97%	-99%	-100%	-95%	-98%	-73%
Aquatic ecotoxicity [1,4-DCB kg-eq]	(0.005)	-96%	88%	-78%	-82%	-100%	-98%	-99%	107%
Human toxicity [1,4-DCB kg-eq]	(0.013)	-100%	23%	18%	-2 %	-100%	-99%	-100%	177%

the two functional units used. The use of the surface- and mass-based functional unit only covered some aspects of a multifunctional agriculture, which are respectively (1) the land management, (2) the production, but did not include the (3) financial aspect corresponding to the generation of revenues as described in (Nemecek et al. 2011). This latter aspect is to be developed on pluri-annual data from 2009 onwards; using a financial functional unit will permit to consider these differences in labor time.

4 Conclusion

The present LCA aimed at assessing and comparing the environmental performances of three apple production systems, i.e., conventional, low-input, and organic, planted with the same three cultivars differing in disease susceptibility.

Low-input systems generally displayed the highest environmental performances, but the overall environmental performance of a production system was not drastically improved when changing from conventional to low-input or organic practices with no adaptation of the orchard cultivar selections to resist pests and diseases. This work therefore highlighted the importance of the choice of cultivar in the process of orchard design for attaining more environmentally friendly apple production

systems: independently from the production system, planting a scab-susceptible cultivar such as Golden D. increases negative environmental impacts in all impact categories. This study also demonstrated that no pollution transfer between impact categories could be identified when replacing chemical by mechanical practices, since the non-renewable energy consumption and the global warming potential were similar for all the practices. Pesticide processing and machinery use displayed similar impact for these two impact categories.

This study is the first apple LCA based on a multiyear system experiment, which provided the information required to compute a LCA with a reliable and high-quality dataset, as it was collected with the purpose of this evaluation in orchards under the same field context and management. Such system experiments, despite their cost and management constraints, are necessary to produce references for agricultural production systems newly assessed with the LCA methodology. This work was an opportunity to contribute to the system approach that we have been developing in apple orchards since 2005. To complete this study, the experimental production systems will be further evaluated with LCA to embrace the whole life of the orchard, from plantation to end of life stages, and estimate the relative impact of production and protection strategies within the overall impact. Within the improvement loops necessary to design innovative and less input-dependent production systems, LCA is a worthy tool to calculate the overall

environmental impact potential and to analyze strengths and weaknesses of production systems, thereby pinpointing potential areas for improvements, e.g., herbicide applications that could be replaced by mechanical weeding. LCA methodology has also provided valuable and generic tools to address complex questions related to perennial production systems and multi-criteria evaluation.

Acknowledgments We thank the staff members of Gotheron experimental unit in charge of the management of the orchards and especially C. Gros, K. Morel, K. Traverse, J. Guinaudeau, and F. Merlin for their contribution to the management of pests and diseases in the orchards, and T. Girad, L. Galet, O. Guibert, D. Riotord, and P. Ascensio. We thank A. Hélias and C. Bussi for their helpful comments on an earlier draft of the manuscript. Constructive comments from two anonymous reviewers have improved the clarity of the paper and are also acknowledged.

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