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Comparative life cycle assessment of conventional and organic hazelnuts production systems in Central Italy

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Abstract

Agricultural activity is responsible of considerable negative effects on the environment. In this context, in the last years, organic cultivation is increasing being perceived as more sustainable for the environmental. Nevertheless, this higher sustainability compared to conventional agricultural systems is debated. This applied for crops but also for livestock systems.

For some of the main crops (i.e., cereals, soybean) comparative analysis were carried out but for most of the other annual and perennial crops there is a lack of information about the environmental impacr related to conventional and organic cultivation. In this study, the environmental impact of the conventional and organic farming systems of hazelnuts production in Viterbo province in Italy was evaluated using the Life Cycle Assessment (LCA) approach. Even if originally developed for industrial processes, LCA is more and more applied also to agriculture systems to quantify the environmental impact.

Primary data were collected by the main Producer Organization and elaborated considering 1 kg of hazelnuts as functional unit and a from cradle to gate approach considering the 50-years as life cycle duration of the crop. Finally, using the Recipe characterization method, 15 midpoint impact categories were evaluated.

The results show how, except than for ecotoxicity related impact categories, organic cultivation practice shows higher impact (from +5% to + 285%) respect to the conventional production. For ecotoxicity related impact categories, organic hazelnut production performs better (from -42% to -81%) than the conventional one because no synthetic pesticides are applied. The sensitivity analysis carried shows how yield is the main driver of the environmental results while the uncertainty analysis performed with the Montecarlo technique shows that the to the selection of the data source, model imprecision and data variability does not significantly affect the environmental results for the evaluated impact categories

Keywords: Life Cycle Assessment, Environmental Impact Categories, Environmental Hotspots, Cultivation practices

1. Introduction

Agricultural activity is responsible of considerable negative effects on the environment. In this context, in the last years, organic cultivation is increasing being perceived as more sustainable for the environmental (Laureati et al., 2013). Nevertheless, this higher sustainability compared to conventional agricultural systems is debated. For some of the main crops (i.e., cereals, soybean) (Brandao et al., 2011; Bacenetti et al., 2016; Tricase et al., 2018) comparative analysis were carried out but for most of the other annual and perennial crops there is a lack of information about the environmental impact related to conventional and organic cultivation. In particular for arborous crops, few attention was paid on the evaluation of the environmental performances of organic cultivation.

This applied also for hazelnuts, despite the area dedicated to this crop is increasing. More in details, the worldwide surface of hazelnut groves has almost doubled in the last 10 years, going from 607,427 ha in 2010 to over 1 million ha in 2019. This increase has been driven by a growing request especially by multinational confectionary firms (e.g., Ferrero) on the demand side, and by a growing economic profitability on the supply side (Aydogan et al., 2018).

The production is highly geographically concentrated. In 2019, the 73% of the world’s hazels surface was located in Turkey, where 734409 ha were farmed to produce hazelnuts (Aydogan and Demiryurek, 2018). Italy is the second world leading producer, in terms both of quantity produced and of cultivated surface (FAOSTAT, 2019).

In line with the world trend, the area dedicated to hazelnuts cultivation in Italy has been constantly increasing over the last years due to its high relative economic profitability (Negi, 2018). This increase was also favored by the Ferrero "Progetto Italia" initiative, a project launched in 2014 with which the multinational intended to increase the area of Italian hazelnut groves by 30% in 5 years (Delfanti et al., 2015). The province of Viterbo is one of the leading production districts in Italy, accounting averagely for the

30% of the national production (Delfanti et al., 2015); moreover, the hazels surface in the area has increased in the last years and a high share of the new plantations is farmed organically. However, organic production in the area is still limited compared to conventional one.

The intensive hazelnuts cultivation in Viterbo’s province has raised environmental concerns, especially in the Monti Cimini area where the concentration of hazelnut groves takes on the proportions of a monoculture (Piacentini et al., 2015). These environmental concerns, manifested in various forms and also at the institutional level (Zinnanti et al., 2019), regarded mostly the eutrophication of the waters of the Lake of Vico, a volcanic lake surrounded by the chain of the Cimini mountains, where in the summer there is an intense bathing activity and whose waters are used to supply drinking water to the neighboring municipalities. The phenomenon of eutrophication of lakes and inland waters used as drinking water supplies, for recreational activities and crop irrigation poses concerns also for human health, since it contributes to the diffusion and concentration in those waters of toxin producing cyanobacteria, such as the Planktothrix rubescens (Hilborn et al., 2014; Manganelli et al., 2016), which has been particularly present in the lake of Vico in the last years (Cristofori et al., 2018; Botta et al., 2011).

The European Union defines organic production as an overall system of farm management and food production that combines best environmental and climate action practices, a high level of biodiversity, the preservation of natural resources and high production standards. Organic farming has to comply with strict standards with regard to the use of chemicals (no synthetic fertilizers and pesticides is genetically modified organisms-free by definition and is committed to contributing to high level of biodiversity (Mercati, 2016; Bartzas et al., 2017).

In the European Union the total area farmed organically reached 12.6 million ha in 2017, equal to the 7 % of total EU agricultural land. There has been an impressive growth of organic production by 70% over the past ten years (European Commission, 2020). This trend is expected to be confirmed in the following years, since one of the objectives of the Farm to Fork Strategy is to achieve the share of 25% agricultural land cultivated organically by 2030 (European Commission, 2019).

Organic production is characterized by a significantly lower yield than under conventional production. For some products like wheat and maize, the yield gap is particularly important, ranging between 40% and 85%.

For other products the gap may be lower, but it still represents a strong disincentive if not compensated by higher premium prices (Fabi and Paparatti, 2011; Demiryurek and Ceyhan, 2008). The relationship between the yield gap and the premium price is a crucial factor of the economic remunerability of organic farming, and therefore of its diffusion (Yavuz et al., 2018).

Organic farming practices have been promoted as reducing the environmental impacts of agriculture (Aertens et al., 2009; Song Lee et al., 2015). Nonetheless, due to the intrinsic lower yield, the environmental sustainability of organic hazelnuts production cannot be taken for granted. Tuomisto et al. (2012) have stated that organic farming practices generally have, in comparison with conventional farming, positive impacts on the environment per unit of area, but not necessarily per product unit. Other studies which have compared the environmental impact of organic and conventional production with the Life Cycle Assessment (LCA) approach found that organic systems have a higher impact mainly due to lower yields (Bacenetti et al., 2016; Tricase et al., 2018; Van Stappen et al., 2015).

Up to now little attention was paid to assess the environmental impact of hazelnut production and, in particular, of different cultivation practice. To the best of our knowledge, no studies that compare conventional and organic hazelnuts farming have been carried out so far.

This aim of this study is twofold:

- to evaluate and compare the environmental impacts of the conventional and organic hazelnut production systems in the Monti Cimini (Central Italy), the main Italian area for hazelnuts production;
- to identify the main environmental hotspots (i.e., the sub processes, inputs and/or emissions);
- to discuss possible mitigation solutions.

In this context the LCA approach was applied. LCA is a standardized method defined by two ISO standards (14040 and 14044) (ISO, 2006; ISO, 2018) designed for assessing, with a holistic approach, the environmental impacts by considering all resources, inputs and outputs associated to a product or a service throughout the entire life cycle.

2. Materials and Methods

This study is performed in accordance with ISO Standards for LCA (ISO, 2006), hence the next sections follow the standardized approach: Goal and Scope (section 2.1), Description of the two cultivation practices (section 2.2), Functional Unit (section 2.3), System Boundaries (section 2.4), Inventory Data Collection (section 2.5), Impact Assessment (section 2.6).

2.1 Goal and Scope

This study aims to evaluate and compare the environmental impacts of the conventional and organic hazelnut production systems in Central Italy. With a local perspective, considering the environmental load due to the intensive hazelnuts' monoculture, understanding the environmental impacts of alternative cultivation practices could be the first step for the definition of effective mitigation strategies. From an overall point of view, considering the expected steady increase in the next years of both hazel groves and organic cultivated surface, it is useful to understand the relationships between environmental impacts and production yield of both organic and conventional hazelnuts production.

This study considers the Monti Cimini (42°21'29.52''N – 12°10'39.72''E) area (Province of Viterbo - Lazio region), where the hazelnut production is concentrated. The target audience of this study are the Producer Organizations of the area, the confectionary companies that represents the demand of the hazelnuts, the numerous landowners in the region and the policymakers involved in the development of the regional rural development programs.

2.2 Description of the two cultivation practices

The crop cycle can be divided in different subsystems each one involving different operations; these operations can differ from conventional to organic cultivation but also from different hazelnut orchards depending on pedoclimatic conditions.

Five subsystems can be identified:

1) <u>Subsystem 1 - pre-planting operations</u>, this subsystem takes place in the year 1, the year before the planting and it involves the following operations:

a) soil ripping: this preliminary operation is carried using a ripper and aims prepare the soil for the subsequent tillage. During the ripping soil crusts are broken, stones and roots are moved on soil surface and the deeper soil layers are tilled and aerated,

b) crushing: averagely in the 33% of new hazelnut orchards, after the ripping, soil clod and big stones are present. In this case, crushing is necessary in order to prepare the soil for the planting;

c) heavy harrowing: this operation is performed when the soil is too tophaceous after the ripping; it is performed averagely in the 33% of cases;

d) Levelling: in the 33% of new planting, in soil with few stones, the stone crushing and heavy harrowing are substituting by a levelling;

e) installation of the irrigation system: this occurs only in the conventional orchards in those orchards located in areas where the rainfalls are less abundant in summer. Averagely, 60% of the conventional hazelnut area presents an irrigation system.

2) <u>Subsystem 2 - Planting</u>: Also, this subsystem takes place in the year 1 and involves

a) only for organic cultivation, an organic fertilization using 50 t/ha of cow manure;

b) Planting carried out using a transplanter machine equipped with GPS (Global Positioning System); the plant density is 400 plants/ha with a between-row and within-row spacing of 5 x 5 meters;

c) Harrowing: after planting an inter-row harrowing is carried our using a rotary harrow in order to control weeds.

3) <u>Subsystem 3 – Crop management</u> involves operation carried out from the 1st year to 50th year, the operations are:

a) Harrowing is performed twice per year, from year 1 to year 5;

b) Mechanical manual weed control: performed twice per year from year 1 to year 5; this operation is manual and takes place until the hazel becomes productive with the aim of removing weeds around each plant;

c) Fertilization: performed twice per year from year 1 to year 50 with a quantity of fertilizers that increase after the non-productive period (first 5 years). Fertilization is carried out using a broadcaster spreader coupled with a tractor. In the conventional cultivation, 150 kg/ha of diammonium phosphate and 50 kg/ha of nitrogen are applied from year 1 to year 5, then, from year 6 to year 50, 550 kg/ha of 20-10-10 mineral fertilizers are used. In the organic cultivation, besides the basal fertilization on the year of planting, from year 1 to year 5, 150 kg/ha of Bio Enne (an organic fertilization made of hydrolyzed leathers with 12% N) are applied. During this period, fertilization takes place only once a year. From year 6 to year 50, the fertilization involves 800 kg/ha of Bio Enne and 200 kg/ha of phosphor-nature (26% P_2O_5);

d) Breeding Pruning: this operation is performed manually once only in the third year of life of the hazel and it aims to reach the selected training system ("bushy");

e) Pruning is performed manually or using chainsaw from year 4 to year 50 during the winter season. It aims at maintaining the selected training system. On average, 1.5 m^3/ha of firewood are produced during pruning;

f) Removal of basal shoots, this operation takes place from the third year, and it can be performed either manually or using an herbicide (3.75 L/ha) applied using a sprayer equipped with bell spray nozzles for a local application on the row. In conventional cultivation the two solutions are equally applied while in organic cultivation, only the manual removal is realized;

g) Pest control: the application of plant protection products (i.e., insecticides and fungicides) is carried out using a sprayer coupled with a tractor. In conventional cultivation, the following products are applied 3 times per year: Deltamethrin (0.250 g/ha), Lambda-cyhalothrin (0.250 g/ha), Thiophanate-Methyl (0.90 L/ha), Boscalid+Pyraclostrohin (0.50 L/ha). In organic hazelnut orchards, no synthetic-chemical substances are admitted, and farmers apply 15 L per ha of a solution containing 13 g/L of a product containing copper (20%) and sulfur (14%). Besides this, 6 kg/ha of a leaf stimulant are used;

f) Shredding: starting from the 6th year when the hazel becomes the productive phase, this operation is performed 3 times per year using a lateral mulcher machine coupled with a tractor with aim of inter-row cleaning.

4) Subsystem 4 – Harvesting and post-harvest, as the previous one also this subsystem is carried out each year form year 6 to year 50, the operations foreseen are:

a) Weeding pre-harvesting: it aims to clean the soil in order to facilitate the harvesting, and it is performed once per year;

b) Harvesting: the hazelnuts fall on the soil are gathered using a self-propelled machine. More in detail, the harvester windrows hazelnuts fallen to the ground in the inter-row by using two contra-rotating brushes. By passing in the inter-row, being equipped with a lateral blower, the machine moves the hazelnuts near the plant stems in next inter-row where they will be subsequently collected. The fruits are moved by the brushes to an aspirating pipe. Once aspirated in a depression chamber they are separated from heavier materials (soil, stones, etc.). Finally, the product is collected in a conveyor where, thanks to an airflow generated by a ventilator, the leaves and other impurities are removed;

c) Transportation: using a farm trailer coupled with tractor, the hazelnuts are transported to the collection center, the average distance from the hazels and the collection centers is of 10 km. An empty return was considered;

d) Drying: the moisture content of the hazelnut is reduced from 13% to 6% using dryer fed with LPG (50% of the case) or diesel (50% of the case).

5) Subsystem 5 – Crop removal: carried out one time during the last year of the crop cycle it involves:

a) felling: the different stems produced over the years by each plant are felled and about 12 m3/ha of firewood are produced; b) soil restoring: the stumps are removed using an excavator.

2.3 Functional Unit

The functional unit is a key element of LCA, FU is a mathematical representation of the function of the system. It defines the quantitatively and qualitatively the function provided by the product and it allows a fair and quantitative comparison of alternative production systems. The choice of the functional unit in agricultural LCA is a debated methodological issue, because agricultural activities can provide multiple functions. Nemecek et al. (2010) identified three functions and the corresponding functional units:

- The land management function, reflecting the social perspective of preserving land for agricultural production; the corresponding functional unit is the hectare.
- The financial function, reflecting the perspective of the farmer, whose main goal is maximizing his profit; hence the corresponding functional unit would be the total sales, or total production times average price.

- The productive function, which reflects the goal of producing food, feed or biomass for other uses; the productive function is quantified by physical units, such as kilogram, kilogram of Dry Matter, Energy Content.

Besides this, recently, also the nutritional aspect gained relevance. According to McLaren et al (2021), nutritional LCA study should report the quantities of as many essential nutrients as possible and aim to provide information on the nutritional quality and/or health impacts in addition to nutrient quantities. However, considering that this study compares two production systems of the same product (the hazelnut) and that there is no evidence of a different nutritional composition between conventional and organic products (Magkos et al., 2017), the functional unit considered in this study was the mass of product, namely 1 kg of unshelled nuts with 6% of moisture content, which is the average moisture content required for the selling. This choice is in agreement with previously LCA studies focused on nuts crop cultivation (Bartzas et al., 2017; Roda et al., 2017; Sabzevari et al., 2015).

2.4 System Boundaries

Regarding the system boundaries, the LCA study was carried with a from cradle to drying plant gate approach, consequently they involve all the operations carried out from the soil tillage carried out before the planting to the 50th years of activity. The system boundaries also include the transportation of the harvest to the collection center and the drying of the hazelnuts. All the production phases of the hazelnut supply chain that follows the drying process (e.g., processing, packaging, distribution, etc.) are excluded. Figure 2 shows the system boundaries.

During the crop cycle, besides hazelnuts, also firewood is produced during the pruning. This multifunctionality was solved considering a system expansion. More in details, it has been considered that the produced firewood substitutes the production of the same mass of this biofuel from other sources.

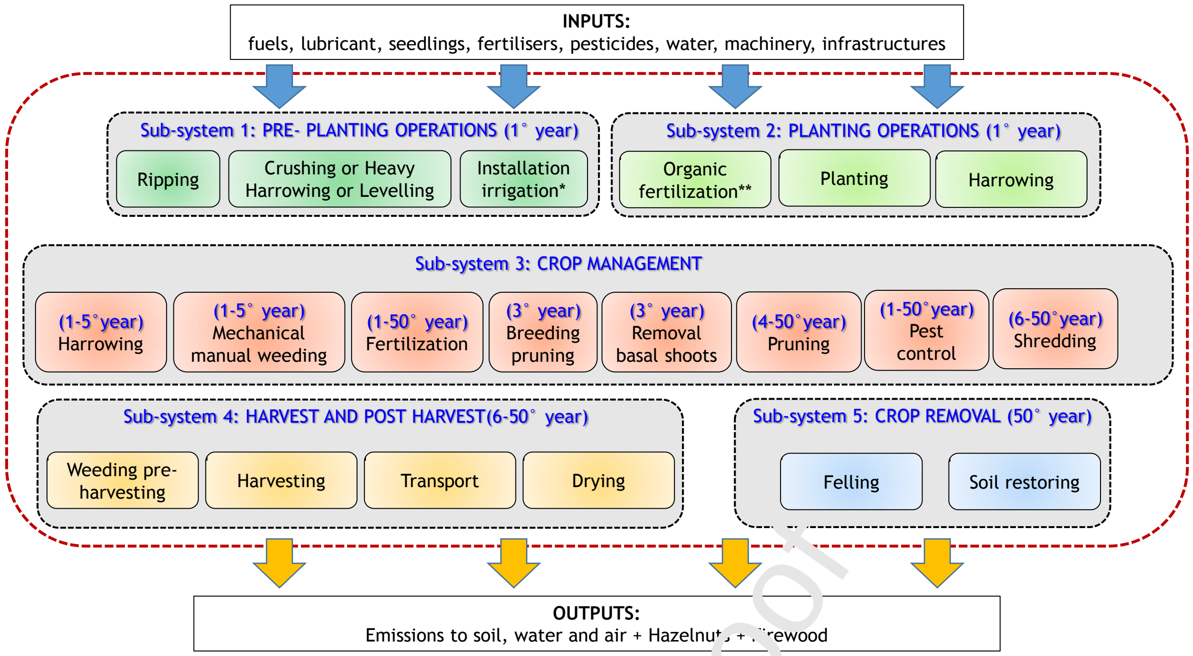

Figure 2- System Boundary (*= only for conventional, **= only for organic)

2.5 Inventory Data Collection

In this study, both primary and secondary data were used. Primary data about the cultivation practice (e.g., sequence of field operations, type and characteristics of the machinery utilized, fuel consumption, type and quantity of fertilizers and pesticides applied) were directly collected by means of surveys and interviews to the employers of the main Organization of Producers (OP) of the area and to 13 local farmers. The collected data regarding the cultivation practice refer to the latest techniques averagely utilized in the area while the ones regarding the productive performances are related to the last decade.

On the basis of these information the typical cultivation practices for conventional and organic hazelnuts cultivation were identified. Regarding the hazelnut yield in the studied area, the database of the most important Organization of Producers (OP) of the Province of Viterbo was used. In this database, the yield of the hazelnuts orchards of the different conferring members is recorded.

The mechanization of the different field operations was modelled considering the fuel consumption, the different working times as well as the main characteristics of tractors and implements. According to Lovarelli and Bacenetti (2017), the emissions related to diesel combustion in the tractor engines were calculated based on the fuel consumption while an optimal annual utilization was taken into account for the tractors.

Secondary data were used regarding emissions of nitrogen, phosphorous compounds, and active ingredient of pesticides as well as about the emissions related to the combustion of diesel in the tractor's engines. More in details, the emissions of ammonia due to volatilization, nitrate leaching and dinitrogen oxide due to denitrification were estimated through IPCC guidelines (2019). According Smil (2000) P losses were evaluated as 1% of the total applied phosphorus with fertilizers. 100% of the active ingredient of the pesticides were considered as emitted into the soil (Environdec. 2016). According to previous studies focused on crop cultivation (Gonzalez-Garcia et al., 2012; Litskas et al., 2017; Noya et al., 2018), no changes in the soil organic carbon content were considered. This aspect was excluded from the system boundary even considering that the two compared cultivation practices are similar regarding the soil tillage, the crop duration and the management of pruning residues.

Table 1 reports all the operations and the utilized machineries included in the system boundaries.

SS	Operation	Year	nn	Tractor	Operating Machine	Notes
1	Soil ripping	0	1	235 kW	Ripper	Crawler tractor
	Crushing	0	0.33	235 kW	Crusher	Crawler tractor, it is performed averagely on the 33% of the cases
	Heavy harrowing	0	0.33	235 kW	Heavy Rotary Harrow	Crawler tractor, it is performed averagely on the 33% of the cases
	Soil Levelling	0	0.33	70 kW	Leveler	It is performed averagely on the 33% of the cases
	Installation of Irrigation syst.	0	0.60	n/a	n/a	Foreseen in the 60% of the conventional area. Not installed in organic orchards
2	Organic fertilization	0	1	70 kW	Manure spreader	Only in organic area. 50 t/ha of cow manure
	Planting	0	1	70 kW	Transplanter	4200 seedling/ha considering 5% of plant mortality/substitution
	Harrowing	0	1	70 kW	Disch harrow	
3	Harrowing	0-5	1	70 kW	Disc harrow	
	Mechanical manual weed control	1-5	2	n/a	n/a	Performed manually around the plants, free of environmental charges as it does not involve the use of machinery or the consumption of fuels
	Fertilizing	1-50	2	70 kW	Spreader	One per year from 1st to 5th year in organic
	Breeding Pruning	3	1	n/a	n/a	It is performed manually
	Pruning	4-50	1	n/a	Chainsaw	It is performed mainly manually
	Basal shoots removal (suckering)	3-50	1	70 kW	Sprayer	In 50% of cases, it is performed manually without any machinery. In Organic, it is performed always manually
	Pest control	6-50	3	70 kW	Sprayer	Synthetic-chemical substances applied only in conventional cultivation
	Shredding	6-50	3	70 kW	lateral mulcher	
4	Weeding pre-harvesting	6-50	1	70 kW	Disc Ripper	
	Harvesting	6-50	1	n/a	Self-propelled harvester	
	Transport	6-50	1	70 kW	Farm trailer	Average Distance: 10 km
	Drying	6-50	1	n/a	n/a	From 13% to 6% of moisture content using LPG (50%) and diesel (50%)
5	Felling	50	1		Chainsaw	
	Soil restoring	50	1		Excavator	

Table 1 – Operations and Machinery (SS = subsystem; nn = number of repetitions per year)

Table 2 and **Table 3** reports the average data regarding the type and quantity of utilized products.

Table 2 - Fertilizing and Treatments Products – Conventional Farming

Commercial Product or Active Substance	**Operation**	**Amount**
Phosphate Diammonicum 18 46	Fertilizing (year 1 to 5)	150 kg/ha
Fertilizer (30 N)	Fertilizing (year 1 to 5)	50 kg/ha
Fertilizer (20-10-10)	Fertilizing (from year 6)	550 kg/ha
Herbicide	Removal of Basal Shoots	3.75 L/ha
Insecticide (Deltamethrin)	Pest control	0.250 g/ha
Insecticide (Lambda- cyhalothrin)	Pest control	0,250 g/ha
Fungicide (Thiophanate-Methyl)	Pest control	0.90 L/ha
Fungicide (Boscalid+Pyraclostrobin)	Pest control	0.50 L/ha

Table 3 – Fertilizing and Treatments Products – Organic farming

Product	**Operation**	**Amount**
Cattle Manure	Basal Fertilization	50000 kg/ha
"Bio Enne" (12 N)	Fertilizing (year 1 to 5)	150 kg/ha
"Bio Enne" (12 N)	Fertilizing (from year 6)	800 kg/ha
"Fosfonature" (26 P)	Fertilizing (from year 6)	200 kg/ha
"Cuthiol" (20% copper + 14% sulfur)	Pest control	15 L of solution/ha 13 g/L of solution
Leaf stimulant "Blackjak"	Pest control	6 kg/ha

Table 4 reports the main information about the productivity: yield of unshelled hazelnuts (at 6% of moisture), losses and the processing efficiency. This latter expresses the ration between the shelled and the unshelled hazelnuts and it takes into account also the losses.

Table 4 – Hazelnut yield, processing efficiency parameters

.	**Conventional**	**Organic**
Dry Unshelled Hazelnuts (DUH)	2,469 kg	812 kg
Damaged by insects (% of DUH)	15.8%	15.5%
Rotten (% of DUH)	1.8 %	1.9 %
Processing efficiency (% of DUH)	42.25 %	43.25%

Regarding the yield, both for conventional and organic farming, data refer to the last 10 years and were retrieved from the database of the Organization of Producers. For conventional cultivation, the productive data were collected for a global area of 100.34 ha while for the organic one the data refer to an area of 76.14 ha. On average, organic hazelnut cultivation shows a strong reduction (about 60%) of yield while, between the two farming systems, the processing efficiency as well as share of nuts rotten and damaged by insects are similar.

Besides hazelnuts, during the crop cycle during the crop cycle also pruning residues are produced. Although the interest about pruning residues valorization for energy purpose is growing (De Franchi and Boubaker, 2014; Moneti et al., 2015; Bacenetti, 2019), there is no systemic and economic utilization of these by-products in the Monti Cimini area. On the contrary, the firewood produced by the pruning of big branches and /or the substitution of stems is locally valorized. In this case, as explained before, a "system expansion" approach was applied considering the Lower Heating Value (17.2 MJ/kg) (Acampora et al., 2021) of the produced firewood. The list of the processes retrieved from databases is reported in the Supplementary Material by highlighting the modifications done during the modelling.

2.6 Impact Assessment

The inventory dataset was characterized by means of the ReCiPe 2016 Midpoint (H) method, version 1.04/World (Huijbregts et al., 2017). In total, 15 midpoint impact categories were evaluated (**Table 5**). ReCiPe 2016 Midpoint (H) was chosen because, first, it was widely used in previous carried out LCA studies focused on agricultural products and, secondarily, because by including different toxicity related impact categories it is particularly suited for the comparison between cultivation practices that differ mainly for the use of pesticides.

Table 5 – List of selected impact categories

Impact category	Acronym	Unit of measure
Global Warming	GW	kg CO_2 eq
Stratospheric Ozone depletion	ODP	mg CFC11 eq
Ozone formation, Human health	HOFP	g NOx eq
Fine particulate matter formation	PMFP	g PM2.5 eq
Ozone formation, Terrestrial ecosystems	EOFP	g NOx eq
Terrestrial acidification	TAP	g SO2 eq
Freshwater eutrophication	FEP	g P eq
Marine eutrophication	MEP	g N eq
Terrestrial ecotoxicity	TETP	kg 1,4-DCB
Freshwater ecotoxicity	FETP	kg 1,4-DCB
Marine ecotoxicity	METP	kg 1,4-DCB

Human carcinogenic toxicity	HTPc	g 1,4-DCB
Human non carcinogenic toxicity	HTPnc	kg 1,4-DCB
Mineral resource scarcity	SOP	g Cu eq
Fossil resource scarcity	FFP	kg oil eq

3 Results and Discussion

Table 6 reports the absolute results for the two cultivation practices and shows the impact variation between conventional and organic hazelnuts production. For 12 of the 15 evaluated impact categories, the conventional production performs better than the organic one. This latter shows an impact increase ranging from 5% of Human non-carcinogenic toxicity to 285% of Terrestrial Acidification while presents a lower impact for the three ecotoxicity related impact categories (TEFP, FEFP and MEFP). The impact increase is due to le lower yield but also to the different fertilization involving higher emissions of N and P compounds in the atmosphere. For TEFP, FEFP and MEFP, the impact is lower than in organic because, for these impact categories, the lower yield is completely offset by the non-use of synthetic pesticides.

Table 6 – Comparison between the environmental impact of the two cultivation practices: Conventional (C) and Organic (O) for the selected impact categories. The results are expressed in relation to the functional unit, i.e., 1 kg of unshelled nuts at 6% moisture, at the drying plant gate. The variation (Δ) is assessed as [(impact of O/impact of C)-1]*100.

Impact category	Acronym	Unit	C	O	Δ
Global warming	GW	kg CO_2 eq	1.287	1.793	39%
Stratospheric ozone depletion	ODP	mg CFC11 eq	23.847	30.741	29%
Ozone formation, Human health	HOFP	g NOx eq	4.571	7.695	68%
Fine particulate matter formation	PMFP	g PM2.5 eq	3.199	9.868	208%
Ozone formation, Terrestrial ecosystems	EOFP	g NOx eq	4.943	7.830	58%
Terrestrial acidification	TAP	g SO2 eq	16.500	63.510	285%
Freshwater eutrophication	FEP	g P eq	0.244	0.442	81%
Marine eutrophication	MEP	g N eq	4.498	10.860	141%
Terrestrial ecotoxicity	TEFP	kg 1,4-DCB	4.743	2.758	-42%
Freshwater ecotoxicity	FEFP	kg 1,4-DCB	0.178	0.034	-81%
Marine ecotoxicity	MEFP	kg 1,4-DCB	0.138	0.047	-66%
Human carcinogenic toxicity	HTPc	g 1,4-DCB	22.880	28.472	24%
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DCB	1.172	1.233	5%
Mineral resource scarcity	SOP	g Cu eq	9.452	11.301	20%
Fossil resource scarcity	FFP	kg oil eq	0.174	0.259	49%

Figure 2 shows the results of the contribution analysis. The different sub-processes, inputs and emission sources were grouped in: (i) mechanization, including all the field operations and consequently, the machinery employed, diesel fuel and the related emissions; (ii) drying; (iii) fertilizers, (iv) other production factors (seedlings, and pesticides), (v) emissions due to fertilizing, (vi) emission due to pesticide application, (vii) avoided impact due to firewood production. The results of the contribution analysis expressed in relative values (%) is reported in the Supplementary Material for both the evaluation cultivation practices.

The main outcomes of the contribution analysis are:

- the mechanization of the field operations is the main responsible of HOFP (Ozone formation, Human health, mainly due to the emissions of nitrous oxide) and EOFP (Ozone formation, Terrestrial ecosystems, due to the emissions of nitrous oxide to and non-methane volatile organic compounds in the exhaust gas from tractor engine) for both the cultivation practices and for the different toxicity related impact categories (TETP, FETP, METP, HTPc and HTPnc) and FFP (Fossil resource scarcity) in the organic cultivation. The share of the impact related to the mechanization of the different field operations ranges from 0.3%-0.4% for MEP (Marine eutrophication) for conventional and organic production, respectively, to 55.7%-88.9% for HOFP for conventional and organic production, respectively. For HOFP and EOFP, in the case of organic production, the share of the impact due to mechanization is higher respect to the conventional practice even because is lower the role of fertilizers. However, in absolute term, the impact of the mechanization is more than twice in the organic respect to the conventional cultivation. This is due to the lower yield and, as mentioned before, to the non-use of synthetic fertilizers.
- Drying of the hazelnuts has a minor role in the definition of the environmental load of the produced hazelnuts; except than FFP in the conventional system and for HTc in the organic one its contribution is always lower < 5%;
- Fertilizers production plays a different role in the two cultivation practices. Compared to the organic production, in the conventional one, the impact due to the consumption of fertilizers is higher (from 3.8 to 80.2% for the conventional and from 0.9 to 55% for organic) because synthetic products are applied and, in particular, for the nitrogen ones, those production is an energy intensive process.

- The consumption of the other production factors (e.g., seedlings, pesticides) is responsible of less of the 2% of the impact in all the evaluated impact categories mainly due to the lower amount applied (i.e., pesticide) or non-continuous use (e.g., seedlings);
- The emissions of N and P compounds due to the application of fertilizers are the main hotspot of PMFP (mainly due to the ammonia volatilization, being ammonia a precursor of secondary particulate matter), TAP (again due to the emission of NH_3) and MEP (due to nitrate leaching) for both the cultivation practices and for FEP (mainly due to the loss of phosphate) in organic hazelnuts. The emission of dinitrogen oxide has not negligible role also in GW being responsible, for 1 kg of hazelnuts, of 0.3 kg of CO_2 eq. (23% of the total) and 0.8 kg of CO_2 eq. (42% of the total) in conventional and organic cultivation, respectively. For the ODP the emission of dinitrogen oxide is the main responsible of the total impact for both the cultivation practices. The impact of the emissions of N and P compounds is higher (both in absolute than in relative term) in the organic cultivation, this is due to the higher losses of nutrient associated with the organic fertilizers (e.g., volatilization and denitrification) and to the higher nutrient application;
- The emission of the pesticide active ingredients is important for conventional cultivation for the ecotoxicity related impact categories and, in particular, for FEPT and MEPT where is responsible of more than 50% of the impact. In organic cultivation, the share of the impact is always lower of 3.5%;
- the environmental benefits related to the production of firewood and, consequently, to the avoided production of it from other sources, has a positive effect for all the evaluated impact categories. This benefit is proportionally higher in the case of organic production where this avoided impact is splitted on a lower total production of hazelnuts. More in details, in organic production the exploitation of the firewood produced during pruning and final removal of the orchard involves a non-negligible benefit (>5%) for GW, HOFP, FEP, TEFP, HTPc, and FFP while, in conventional cultivation, this benefit is lower than 5% of the total impact for all the evaluated impact categories.

Even if the same hotspots can be identified for both the cultivation practices and for all the evaluated impact categories, some differences between conventional and organic hazelnut cultivation can be identified. These differences are not only related to the different yield but also to the different features of the two cultivation practices:

- conventional production benefits of the lower emissions related to the fertilization achieved thanks to the use of synthetic fertilizers but, on the other hand, has an higher share if the impact due to the consumption of energy-intensive products such as nitrogen synthetic fertilizers;
- organic cultivation performs better than conventional one for most of the toxicity related impact categories thanks to the avoided use of synthetic pesticides but is negatively affected for all the other impact categories by the lower yield (achieved also due to the higher presence of pests and disease).

The contribution analysis provides useful information for the identification of alternative cultivation practices as well as possible mitigation strategies. In particular, for organic cultivation, a fertilization more calibrate on the real needing of the crop could reduce the emissions of N and P compounds resulting in a lower impact for MEP (thanks to lower nitrogen leaching) and TAP (affected by ammonia volatilization). Regarding the valorization of the pruning residues and firewood produced, their exploitation for the production of renewable energy could increase the benefits that in the actual modellization are limited to the substitution of firewood.

To provide a more comprehensive assessment of the two cultivation practice an additional indicator related to the energetic aspect was evaluated. The Cumulative Energy Demand (CED) represents the energy demand, valued as primary energy during the complete life cycle of a product (Verein Deutscher Ingenieure, 1997; Frischknecht et al., 1998). Also for this indicator, the comparison shows that conventional cultivation performs better than the organic one. More in detail, the results are: i) 8.25 MJ/kg and 11.87 MJ/kg for “Non renewable, fossil - CED” for conventional and organic cultivation, respectively; ii) 0.59 MJ/kg and 0.74 MJ/kg for “Non renewable, nuclear - CED” for conventional and organic cultivation, respectively.

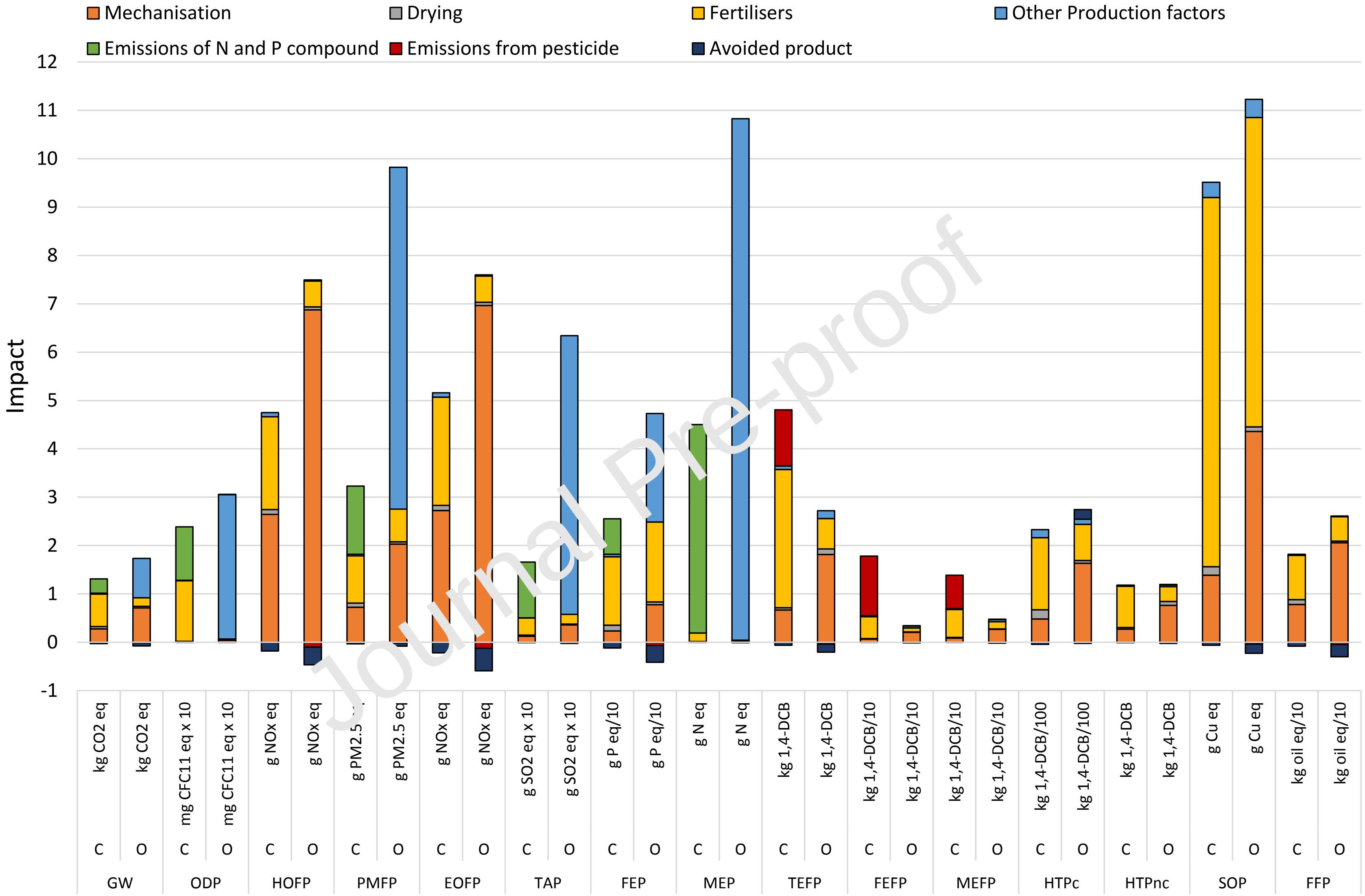

Figure 2 – Contribution analysis for the two cultivation practices (Note: GW: Global warming; ODP: Stratospheric ozone depletion; HOFP: Ozone formation, Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formation, Terrestrial ecosystems; TAP: Terrestrial acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TEFP: Terrestrial ecotoxicity; FEFP: Freshwater ecotoxicity; MEFP: Marine ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non-carcinogenic toxicity; SOP: Mineral resource scarcity: FFP: Fossil resource scarcity).

3.1 The role of mechanization

The mechanization of the field operations plays a relevant role in the definition of the environmental load of both the cultivation practices under study being the main hotspot for two impact categories for conventional production and for 8 in the case of organic production.

Figure 3 shows the role of the different field operation grouped for subsystem and report the share of the total impact related to mechanization. This share could be slightly higher if a sub-optimal annual tractor utilization would be considered (Bacenetti, 2022). Despite this, it should be considered that most of the field operations are usually carried out by contractors because the required machineries are not usually present in the farm machinery fleet and that contractors usually fully exploit their tractors and equipment.

As expected, the main share of the impact related of mechanization is due to the field operation carried out more frequently during the crop cycle. For this reason, crop management (subsystem 3) and the harvesting and post harvesting operations (subsystem 4) are by far the two subsystems most contributing to the impact with a share of the total score of mechanization ranging from 90% to 94%.

3.2 Sensitivity and Uncertainty analysis

The sensitivity analysis was carried out to investigate the effect of yield variability as well as of the use of a different characterization method. About yield, the environmental impact of hazelnuts was evaluated considering, instead of the average one, also the minimum and maximum yield recorded in the considered period. The results, reported in the Supplementary Material, highlight how the yield is one of the main drivers of the environmental impact. When the lower yield is considered, the impact increases up to 27.9% and 12.8% in conventional and organic cultivation, respectively, while when the higher yield is taken into account the environmental load is reduced by 38.2% in conventional system and by 22.6% in the organic one. The role of yield is evident also by comparing the impact of the two cultivation practices but considering different yield variations. Conventional hazelnut presents lower environmental impact than organic one if the same yield levels are considered (average vs average, minimum vs minimum and maximum vs maximum) but when the minimum yield is considered for conventional and the maximum one is considered for organic cultivation, this latter achieves a lower environmental impact for 8 of the 15 evaluated impact categories (in particular for GW the reduction is equal to 15.6%).

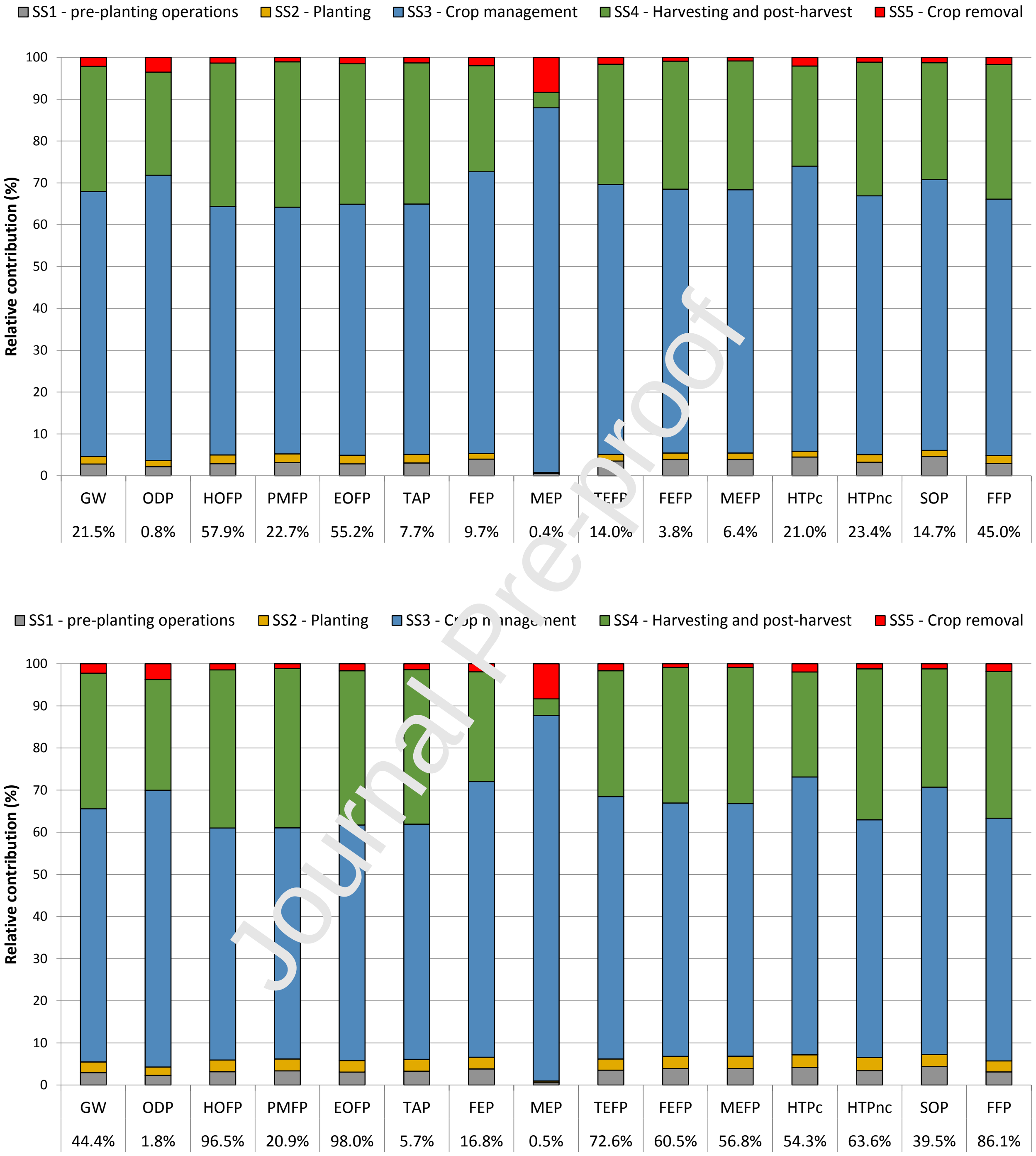

Figure 3 – Contribution analysis for mechanization considering the field operations foreseen in the different subsystems for conventional (<u>on the top</u>) and organic (<u>on the bottom</u>) cultivation. The percentage reported in the abscissa axis indicates the share of the total impact due to mechanization. (<u>Note</u>: GW: Global warming; ODP: Stratospheric ozone depletion; HOFP: Ozone formation, Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formation, Terrestrial ecosystems; TAP: Terrestrial acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TEFP: Terrestrial ecotoxicity; FEFP: Freshwater ecotoxicity; MEFP: Marine ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non-carcinogenic toxicity; SOP: Mineral resource scarcity: FFP: Fossil resource scarcity)

Regarding the characterization method, the analysis was carried out also using the ILCD 2011 Midpoint method released by the European Commission, Joint Research Centre (EC-JRC, 2011). Despite the use of different unit of measure, the differences in the evaluated impact categories, the results (reported in the Supplementary Materials), reported in the supplementary material, are similar. in fact, despite some difference due to the different characterization factors (e.g., for N2O and CH4) and to the modelling of biogenic carbon, organic hazelnuts cultivation show higher impact than the conventional ones except than for the freshwater ecotoxicity and for the impact category of mineral, fossil and renewable resource depletion.

Uncertainty analysis was carried out using the Monte Carlo technique (5,000 iterations and a confidence interval of 95%) to test the robustness of the results. **Figure 4** reports the main results of the uncertainty analysis, from which emerges that for all the evaluated impact categories the uncertainty is low. The modelling of the two hazelnut cultivation systems evaluated is robust, thus the results are trustworthy. Except for HTPc and SOP, for all the other impact categories the uncertainty level is zero or < 0.3%. Therefore, the uncertainty that is related to the selection of the data source, model imprecision and data variability does not significantly affect the environmental results for the evaluated impact categories.

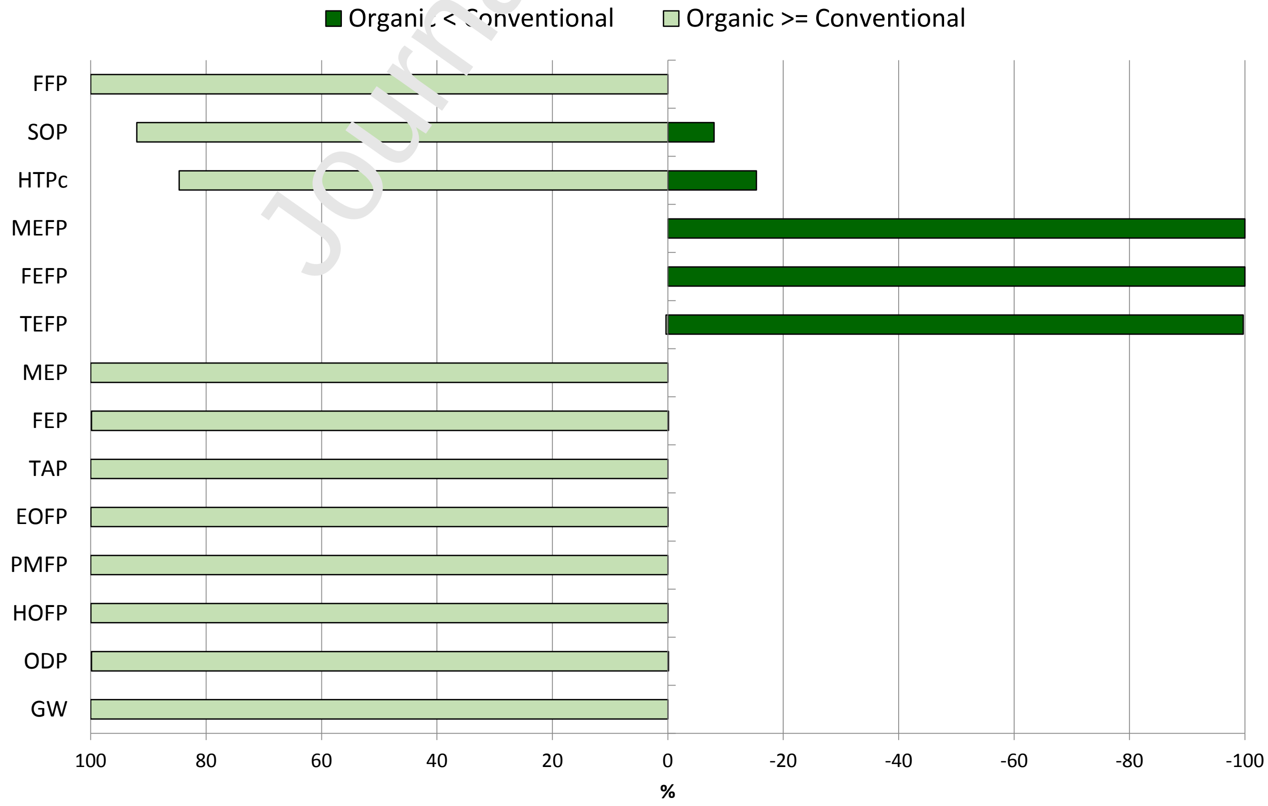

Figure 4 – Results of the uncertainty analysis

3.3 Comparison with previous LCA study of hazelnut

Despite Turkey is by far the main hazelnuts producers, there are no LCA studies focusing on hazelnut production in this country. The previous LCA study on hazelnuts were carried out in Iran. More in details:

- Nayeri et al. (2014) evaluated the GHG emissions for hazelnuts using data collected in 36 farms. The selected functional unit was 1 ha, in rain fed farming system, total greenhouse gases emissions for hazelnut production were 66,955 kg CO_2 eq/ha.

- Kouchaki-Penchah et al. (2015) assessed environmental impact of hazelnuts production in Iran. The functional unit adopted was 1 ton of hazelnuts. The system boundaries are substantially the same of our study because a “from cradle to gate” approach was considered. Mechanization was identified as the main contributor for all the impact categories except than for Eutrophication, for which the hotspot is the pesticide applications. GW for 1 kg of hazelnuts ranges from 0.665 kg CO_2 eq for medium size orchards to 0.775 kg CO_2 eq for small size orchards and, consequently, in both the cases, it is lower than the one assessed in this study.

- Mostashari-Rad et al (2020) focused on Iran hazelnuts production. A mass based functional unit was selected and all the processes until the harvesting were included in the system boundary. The GW was 1.6 kg CO_2 eq/kg of hazelnuts a value higher than the one found in this study for conventional cultivation but similar to the one achieved for organic cultivation. The same inventory data was used to assess the damages and the cumulate energy demand (Mostashari-Rad et al., 2021).

3.4 Discussion

The outcomes of this study can be useful to help farmers and other stakeholders to improve agricultural production moving towards cleaner and better designed cultivation practices. Considering that the comparison between the conventional and organic practice highlights trade-offs among the different evaluate environmental effects the achieved results can be useful to set up policies (e.g., Rural Development Programmes) for a hazelnuts cultivation more related to the site-specific features. For example, considering the higher impact of conventional cultivation for most of the toxicity related impact categories, organic cultivation should be favored in sites close to wet areas (e.g., lakes) and/or with high natural value. On the contrary, in the other areas where the need to protect the environment and biodiversity is less pressing, the conventional cultivation with its higher yield would be the most rationale choice. In this latter case, particular attention should be paid on the selection of updated and well calibrated machines for pesticide application as well as on the selection of the synthetic fertilizers aiming at their substitution with organic one locally available.

This study relies mainly in primary data and, in particular, several farmers were interviewed and the yield (turned out as the main driver of the environmental results) was inventoried thanks to the information of the main association of producers in the area. Although this, the use of secondary data about the emissions of N and P compounds as well as the fate of the active ingredient of the pesticide is a limit of the study. Considering the effects of these emissions on the different evaluated impact categories additional efforts should focus on the measurements on these flows. Besides this, a limitation of the study requiring a specific focus in future activity is related to water consumption for irrigation. Being the irrigation not performed with fixed schedule but applied only when weather and soil conditions involve drought for the plants, the farmers did not take note of water consumption in period-considered (last 10-years) even if this process can affect Water Scarcity (impact category not considered in this study for this reason).

FInally, regarding the farms involved in the data collection about the two cultivation practices, it should be underlined that usually more up-to-date and innovative farmers are the more predisposed to be involved in this kind of study. Therefore, the results achieved could not fully representative for all the type of farms/farmers. In this regard, an improvement could rely in a stratification of the sample of farms paying particular attention to the size of the farms, to the age of the farmers and to their openness to innovation and to updated cultivation practices.

4. Conclusion

In this study, the environmental impact of conventional and organic farming system of hazelnuts was evaluated taking into account the area of the Monti Cimini (Province of Viterbo – Central Italy), the most important Italian area for hazelnuts production.

The LCA results highlighted how organic system shows higher impact (from +5% to + 285%) for most of the evaluated environmental effects even if performs better than the conventional one for the ecotoxicity related impact categories (from -42% to -81%). The yield is the main driver of the environmental results and, considering the considerably lower yield of the organic systems, this aspect explains most of the differences highlighted between the two cultivation practices. Beside yield, the fertilization and the related emissions are the main responsible for all the environmental effects related to emissions of nitrogen and phosphorous content in the environment (i.e., eutrophication, acidification and particulate matter formation). The co-production of firewood involves a limited environmental benefit even if this biofuel can be exploited locally.

Being the comparison between the two systems characterized by trade-offs among impact categories, the achieved results cannot be used to define general guidelines. Despite this, some useful indications can be draft for the development of policies as well as of subsidy framework. Considering that organic hazelnut cultivation shows lower impact for the toxicity related impact categories this cultivation practice should be preferred in areas with high biodiversity and ecological value. Instead, about conventional practice, particular attention should be paid to pesticides application and a subsidy framework aiming at substitute older and not updated spreader machines (i.e., atomizers) could results in an improvement of environmental sustainability.

Future research activities could consider the selection of different functional unit more directly related to the economic (higher for conventional ones) of the nutritional value of hazelnuts and of the modelling of shorter or longer crop cycle involving different yields.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

On behalf of all the Authors

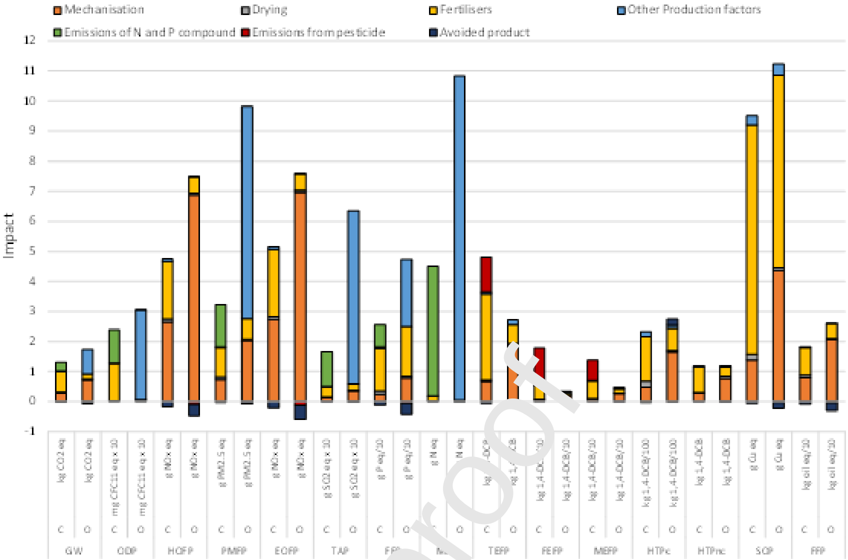
Author Contributions: Conceptualization, G.C., L.R.G. and J.B.; methodology, A.F., M.C. and J.B.; data collection, G.C.; data processing, G.C., M.C., J.B.; writing— original draft preparation, G.C., and J.B.; writing—review and editing, A.F., J.B., and L.R.G.; and supervision, J.B and D.P.

All authors have read and agreed to the published version of the manuscript.

Graphical abstract

AIM

To evaluate and compare the environmental impact of the conventional (C) and organic (O) hazelnut production systems in Central Italy



GW: Global warming; ODP: Stratospheric ozone depletion; HOFP: Ozone formation Human health; PMFP: Fine particulate matter formation; EOFP: Ozone formatio Terrestrial ecosystems; TAP: Terrestrial acidification; FEP: Freshwater eutrophication; MEP: Marine eutrophication; TEFP: Terrestrial ecotoxicity; FEFP: Freshwater ecotoxicity MEFP: Marine ecotoxicity; HTPc: Human carcinogenic toxicity; HTPnc: Human non carcinogenic toxicity; SOP: Mineral resourc scarcity: FFP: Fossil resource scarcity

Highlights

- Conventional and organic hazelnut production systems were analysed
- Life Cycle assessment approach was applied to quantify the environmental impact
- Conventional cultivation shows lower impact for 12 of the 15 evaluated impact categories
- Organic cultivation has lower impact for the toxicity related impact categories
- Yield is the main driver of the environmental results