Life Cycle Assessment, C footprint and carbon balance of virgin olive oils production from traditional and intensive olive groves in southern Spain

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ABSTRACT

Olive oil production shapes the socio-economic and environmental life of many areas of the Mediterranean basin, especially southern Spain, the highest olive oil-producing region worldwide. Olive grove cultivation is tending to intensify from traditional low-density to intensive and high-density cropping systems, which might result in higher environmental impacts. The aim of this study is to estimate the environmental impacts, carbon (C) footprint and carbon balance of producing virgin origin olive oil in Spain from four traditional rainfed, four irrigated, and three intensive olive farms, including the processing phase. Environmental impacts of producing 1 kg of unpacked virgin olive oil at the farm and industrial phases were quantified with the Life Cycle Assessment (LCA) tool and a "cradle-to-gate" approach using data from surveys at these farms and 12 olive oil mills. On average, the farming phase accounted for 76.3 % of the EIs. Therefore, to reduce the impact of the virgin olive oils production, most of the efforts should be made especially in the farming phase. Despite the high variability between seasons and between independent replicates of the same farming system, intensive farming had significant higher impacts on most environmental impact categories than traditional

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rainfed farming, mainly due to the application of nitrogen fertilizer, plant protection products and herbicides. In terms of climate change, the environmental impact of the functional unit is in the ranges of 1.80-2.41, 1.59-2.78 and 2.28-3.26 kg of CO_2 eq. for traditional rainfed, irrigated and intensive, respectively. C footprint was negative and averaged -5.5, -4.3 and -2.7 kg CO_2 eq. Olive groves are efficient atmospheric CO_2 sinks mainly by fixing CO_2 into permanent and non-permanent trees structures. The lower intensification of the traditional rainfed groves contributed more in mitigating the increase of atmospheric CO_2. Finally, the C footprint and C balance are negative, especially in traditional irrigated and intensive farming. The application of organic sources of fertilizer and the implementation of temporary spontaneous cover crops, both technically and economically feasible, are sound strategies to achieve a positive carbon balance and reduce the impacts of olive cultivation.

Keywords: Life Cycle Assessment; Olive Oil Production; Environmental Impacts, Carbon Balance; Carbon Footprint.

1. Introduction

The olive tree (*Olea europaea* L), an evergreen and long-lived species, has been cultivated in the Mediterranean basin since ancient times. Olive tree cultivation has been traditionally linked with the diet, the culture and the economy of many areas of the Mediterranean basin, and the olive sector is still a key element of the European Union (EU) today (Giourga and Loumou, 2003). Indeed, olive cultivation is considered a main component of socio-economic and cultural life, preventing rural depopulation and shaping the natural rural landscapes of many of the main producer countries. Regarding future trends, the global market for olives is forecast to grow at a CAGR (Compound Annual Growth Rate) of 4.5% in the period 2019-2024. (European Commission, 2018; Mili and Bouhaddane, 2019).

The EU is the world's leading olive oil producer, and Spain devotes 2.5 million ha with more than 180 million trees to this crop. Consistently, the countries with the highest yearly average production (2015-2019) of olive oil are Spain, Italy and Greece with 1.2 10^6 tons, 0.31 10^6 tons and 0.277 10^6 tons, respectively (International Olive Oil Council, 2019). Within Spain, the Andalusian region (southern Spain) accounts for about 1.5 million hectares and about 80 % of Spanish production (Ministry of Agriculture Fisheries and Food, 2020).

Increased olive oil demand has acted as a catalyst for the intensification and expansion of olive groves. The intensification of low-input traditional olive groves implies systematic use of chemical fertilizers and pesticides with more aggressive weed control and soil management practices (Infante-Amate et al., 2016). This has been underpinned by a clear trend to further intensify farming systems by means of irrigation, increased tree density and mechanical harvesting (Russo et al., 2016b). Such intensification process has resulted in simplified landscapes with olive groves with low-nature-value, driving greater negative environmental impacts (EIs), particularly in the form of soil erosion, run-offs to water bodies, increased rates of soil fertility loss, degradation of habitats and landscapes, and over-exploitation of scarce and vulnerable water resources.

The impacts may vary significantly as a result of the practices and techniques employed as well as with the analysis techniques adopted in studying these impacts (De Luca et al., 2018; Stillitano et al., 2019). Probably the most solid approach for the assessment of the environmental sustainability of the olive oil sector is the Life Cycle Assessment (LCA) methodology. Based on mass and energy balances developed in steady state, LCA aims at computing all flows in the life cycle of a product or of a service, through its “cradle” to its “grave”, and translating them into impacts. The LCA during the farming and virgin olive oils (VOOs) processing operations might be an effective tool on which operational decisions at individual farm or cooperative and consumer levels should be based.

On the other hand, the recently agreed goal for mitigating global warming is to keep the temperature rise well below 2ºC on average by the end of this century, as compared to the pre-industrial level (Paris Agreement to United Nations Framework Convention on Climate Change, 2015). Among the efforts to meet this goal, an important one is to reduce direct and/or indirect anthropogenic GHG emissions from agricultural food production, which is recognized as a considerable net source with concomitant opportunities for mitigation (IPCC, 2014). Of the various quantitative indicators, carbon footprint has gained popularity and widespread application. The main drivers of carbon footprint calculations are legislative requirements, carbon trading, corporate social responsibility, and scientific analyses for devising effective policies to combat global warming (Carbon Trust, 2007). Moreover, carbon footprint also offers a simple mode of communication about climate responsibility of different entities among people, scientists, and policy-makers. Through carbon footprint analyses, important sources of emissions can be identified, and areas of emission reductions can be prioritized. For carbon footprint calculation, estimates of GHGs emitted/embodied at each identified step of the product's/activity's/individual's life cycle are conducted, which is technically known as GHG accounting.

Scientific analyses of carbon footprints are being conducted, mainly for consumer products and industrial processes. This tool is less frequently applied to agricultural systems, despite the fact that agriculture alone is responsible for the largest proportion of GHG emissions. There are few studies on C footprint in the different phases (olive farming and industrial processing) of olive cultivation to VOO packaging. However, methodologies used to differentiated among the studies and calculated carbon footprint usually refer to a single phase.

Over the last decade, several studies have addressed the use of LCA in the olive oil life cycle, including few reviews on the topic (Banias et al., 2017; Espadas-Aldana et al., 2019; Salomone et al., 2015). However, most of them are from olive groves and olive oil

mills (OOMs) of Italy and they generally do not include the assessment of C footprint or C balance (Espadas-Aldana et al., 2019; Rinaldi et al., 2014; Salomone and Ioppolo, 2012). Avraamides and Fatta (2008) analyzed LCA in the farming and industrial phases of the olive oil sector in Lythrodontas (Cyprus), providing quantitative results that served as an environmental inventory of reference. Pattara et al. (2016), assessed the carbon footprint of different farms and OOMs of the Abruzzo region of Italy, identifying the most relevant factors contributing to the carbon footprint. Recently, Proietti et al. (2017), analyzed the carbon footprint of olive oil production in different cases of the Umbria region, also in Italy. This study showed a significant reduction of EI due to long-term carbon sequestration in soil. Tsarouhas et al. (2015) showed a case study of olive oil production in Greece. In this case, LCA was applied taking into account fourteen sub-systems of the overall value chain providing useful managerial insights and diagnoses of the most relevant environmental "hotspots". In addition, these authors found a reduction in the environmental impacts associated with the use of by-products as fuel, fertilizers, cosmetics, and pharmaceuticals and highlighted that olive fruit harvesting and oil production sub-processes accounted for the highest environmental impacts.

Very few studies have provided information on the LCA in Spain, despite it is the highest producer worldwide. The few LCA studies undertaken in the Spanish olive sector sought to assess human impacts and EIs during packaging, OOM by-products valorization, but very few have considered the farming phase (Navarro et al., 2018; Parascanu et al., 2018b, 2018a; Romero-Gámez et al., 2017; Russo et al., 2016a). Romero-Gámez et al. (2017) found that intensive and super-intensive models of olive grove management generally showed higher EI than traditional. In addition, this study concluded that optimization of the fertilization could play an important role in reducing the EIs at the olive farming phase. More recently, the study carried out by Fernández-Lobato et al. (2021) analyzed the EIs of VOOs production in Spain for the most representative conventional

olive groves of Spain, accounting for the contribution of the inter annual variability due to the economic and yield influence.

As far as we are concerned, none of these studies assess the EIs, carbon footprint and C balance in the olive farming and VOOs extraction phases as a whole.

The objective of this study is to assess the EIs and the C footprint at the farm and industrial phases of producing VOOs in different surveyed study cases of traditional rainfed, traditional irrigated and intensive olive farming, which are the most representative of southern Spain.

2. Methodology

2.1. Study cases

2.1.1. Farming phase

Eleven olive farms, most of them in the province of Jaén, the highest VOOs producer worldwide, were selected in Andalusia. Olive cultivation accounts for 86% of the cultivated land of Jaen and contributes 25% of the total olive-growing land in Spain and 37.6% in Andalusia (Martínez et al., 2009; Rodríguez-Cohard and Parras, 2011; Sánchez-Martínez and Cabrera, 2015). Four out of the eleven olive groves are traditional rainfed, another four are traditional irrigated while three are intensive. The variety in all of the study cases was the *picual.* The main features of the selected olive groves are shown in Table 1. Traditional rainfed, traditional irrigated and intensive olive groves account for about 90% of the olive cultivation systems of Andalusia (Regional Government of Andalusia, 2015).

2.1.2. Olive extraction; the industrial phase

About 95 % (Regional Government of Andalusia, 2015) of the OOMs of Andalusia use the two-phase olive oil extraction method. Briefly, in the 2-phase process, a horizontally mounted centrifuge is used for primary separation of the olive oil fraction from the plant solid material and foliage water. The resulting olive oil is further washed to remove

residual impurities before finally being separated from this wash water in a vertical centrifuge (Cruz-Peragón et al., 2006). Two-phase extraction generates mainly three byproducts; pomace, stones and small twigs and leaves.

The main fate of the resulting pomace, which accounts for about 70-75 % of the weight of the olive fruit, is the olive mill pomace extractor where the 2-3 % of the olive oil contained in the pomace is extracted using chemical means (e.g., hexane). Usually, the olive mill pomace extractor is located elsewhere. Other uses of pomace include composting, but this is currently negligible (Vera et al., 2019).

Data on the magnitude of all inputs and outputs and the processes were obtained from data of 12 OOMs.

2.2. Goal and scope definition

The goal of the LCA in this study is to obtain characterization values of EI in different categories for the VOOs production from the most representative types of olive tree crops in southern Spain.

In previous studies for the LCA of olives or olive oils production, the functional unit (FU) was typically that related to volume, such as liter (Proietti et al., 2017; Rinaldi et al., 2014; Tsarouhas et al., 2015). The FU in this study is 1 kg of unpacked VOOs at the olive mill, which is not dependent of the temperature and it is the most relevant unit at the production level. This FU has been used previously by El Hanandeh and Gharaibeh (2016).

The scope of the study matches with an LCA “from cradle to gate” following the statements contained in the Product Environmental Footprint Category Rules (PEFCR) (Schau et al., 2016). It studies the products, processes, energy, and transport necessary to obtain VOOs as well as the waste treatment and emissions involved in the production phases (Figure 1). We first analyzed the upstream processes: inputs and outputs of the system in the farming phase. Secondly, the inputs and outputs in the transformation

processes of the industrial phase were analyzed, considering the waste treatment and by-product separation up to this point. We did not include packaging in the analysis, as it is not relevant for production. In addition, we did not include the downstream processes (e.g., distribution, consumption, waste treatment after use, and their respective inputs and outputs) as they are beyond the scope of a “cradle to gate” analysis.

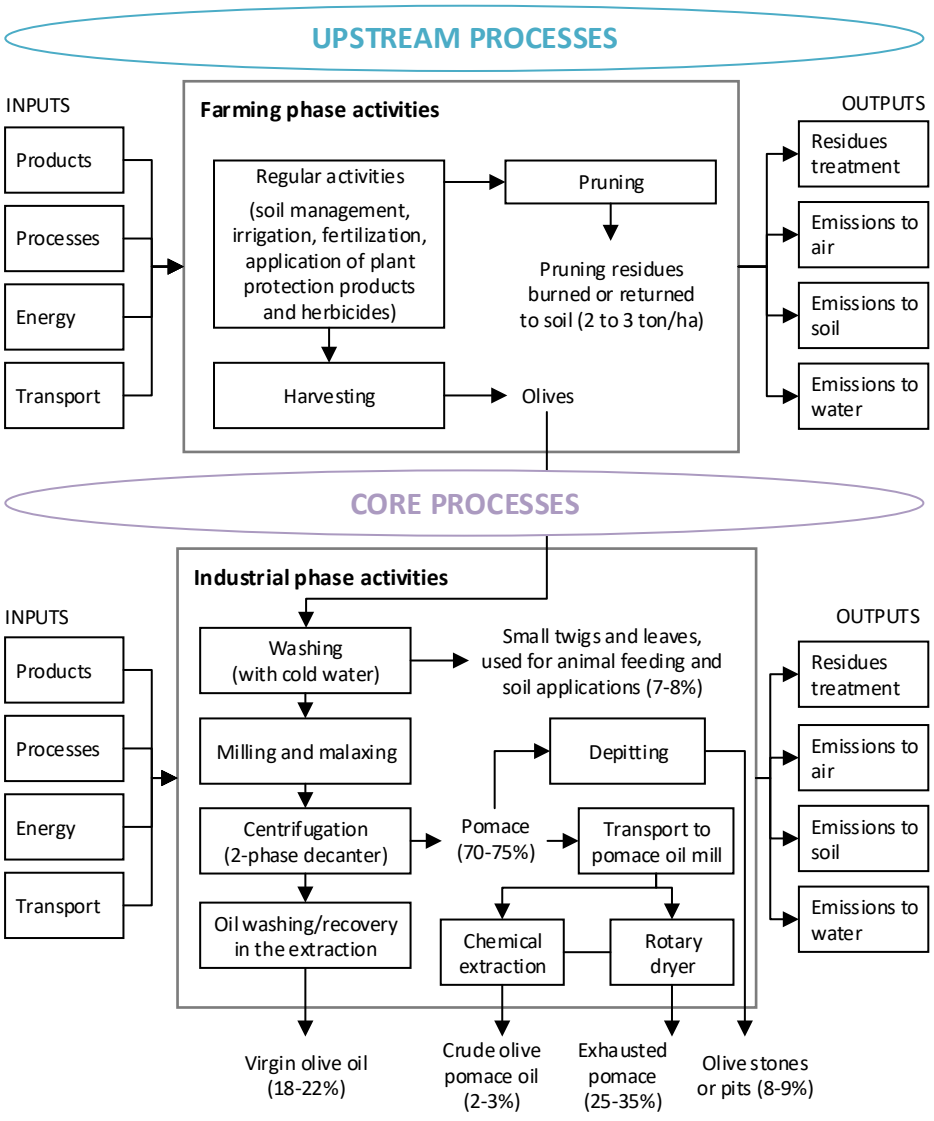

Fig. 1. Upstream and core processes of the production of VOOs considered in this study.

Primary data were collected through a complete survey with qualitative and quantitative information of the processes at the farming and industrial phases needed to obtain VOOs. Data collected was analyzed and treated according to the Data Quality Rating (DQR) of the PEFCR. All the values significantly out of range or over 1.6 in the scale of

quality proposed by the PEFCR were discarded, guaranteeing an “excellent quality” of data.

The surveyed targets where farmers with olive groves over 25 years old with different-sized agricultural holdings and persons in charge of OOMs. As required from the mentioned DQR to be considered in a high quality rating, primary data were collected for 3 recent consecutive harvests: 2017-2018, 2018-2019 and 2019-2020 seasons, accounting for low and high production campaigns.

Data from OOMs were obtained for the two-phase extraction process, with different ownership structures and sizes. The area covered by the surveys was 254.94 ha of olive groves and the total production of VOOs by the OOMs for the period studied ranged between 7,255 tons (2019-20 harvest) and 33,315 tons (2018-2019 harvest).

The questionnaires were open-ended to elicit critical observations that cannot be obtained by solely quantitative surveys. Following the example of Rajaeifar et al. (2014) and Guarino et al. (2019), the surveys were carried out face to face, by telephone and in certain cases visiting their crops and facilities to check the information given. The surveys carried out by farmers include the areas and annual production of crops in accordance with Regulation (EC) 543/2009. The questionnaires were pre-tested to guarantee the validity of their content by agricultural technicians and academics with experience in olive oil farms.

When necessary (e.g., prices of the VOO and crude pomace olive oil), data were complemented with official documents such as the PEFCR, scientific literature related to production of olives and VOOs, and the product datasheets of the consumed substances.

The product and by-products generated during 2 phase olive oil extraction receive an allocation of the EI based on their economic value and quantity (Notarnicola et al., 2015).

The waste generated requires a treatment with its impact accounted for over the generation phase. The by-products derived from the industrial phase are those with an economic value at the point of production: olive stones, crude pomace and exhausted pomace.

The products generated have followed a downward trend since the 16/17 harvest. The prices for VOOs and crude pomace olive oil ranged from 3.00 and 2.32 €/kg and 1.41 to 0.84 €/kg, respectively, for the 2017-2018 and 2018-2019 seasons. Prices for olive stones and exhausted pomace ranged from 0.073 - 0.056 €/kg and 0.014 to 0.017 €/kg, respectively (Institute for Energy Diversification and Savings, 2019; Olimerca, 2020). Table 1 shows the main features of the olive farms and OOMs surveyed.

Table 1. Main characteristics of the surveyed olive groves for the farming phase and OOM for the industrial phase in the province of Jaen.

Farming phase	**Cases 1-4**	**Cases 5-8**	**Cases 9-11**	**Source**
Type of olive farming	Traditional	Traditional	Intensive	Survey
Sub-type	Rainfed	Irrigated	Irrigated	Survey
Olive tree density (trees/ha)	80 - 150	80 - 150	180 - 325	Survey
Total surveyed area (ha)	82.4	107.5	65.1	Survey
Olive yield range (t/ha)	2.8 - 4.2	3.0 - 9.5	3.0 - 10.1	Survey
Olive yield mean (t/ha)	3.56	6.11	5.64	Survey
VOOs yield range (%)	19.1 - 20.7	20.3 - 22.2	20.0 - 21.6	Survey
VOOs yield mean (%)	20.5	21.2	20.6	Survey
Industrial phase (campaign)	**17/18**	**18/19**	**19/20**	**Source**
Average production per OOM (t)	2,858	4,550	2,509	Survey
VOOs yield (%)	20.9	20.6	20.6	Survey
VOOs price (€/kg)	2.998	2.324	2.655	Olimerca, 2020
Crude pomace price (€/kg)	1.405	0.838	1.249	Olimerca, 2020
Exhausted pomace price (€/kg)	0.014	0.015	0.017	IDAE, 2019
Olive stones price (€/kg)	0.073	0.056	0.063	IDAE, 2019
Extraction process		2-phases		Survey

In this study, 3-season average values for the farming and industrial phases were considered. There were few variations for most of the activities of the farming and industrial phases between seasons. However, the olive yield and, consequently, the harvesting activities (farming phase) fluctuated significantly from year to year

because of the changing weather conditions and the biological nature of olive groves. This is a determining factor when calculating the various EIs of the FU (Pattara et al., 2016; Rajaeifar et al., 2014; Rinaldi et al., 2014).

There is an important limitation related to the link between farming and industrial phases. It is relatively usual that farmers process their olives in different OOMs as well as OOMs generally process olives from many different farmers. By that reason, the phases have been studied separately and merged with regard to the FU described. Additionally, due to the lack of information or low representativeness of some processes, there have been considered some assumptions for different activities described in the life cycle inventory (LCI) section.

2.3. Life cycle inventory

The processes considered in the farming phase include: i) land management (e.g. tillage), ii) irrigation, iii) fertilization, iv) plant protection products (PPPs) and herbicides, v) harvesting and vi) tree pruning. Use of diesel and gasoline, active principles contained in products applied to soil, polyethylene nets, energy consumption during irrigation, among others, were considered. In general, characteristics were similar among the olive cultivation systems, but there were some differences in quantities (Annex 1).

We make the following assumptions: i) Olive planting phase. Olive trees of the selected farms were over 25 years of age, and therefore the contribution of the olive planting phase on EIs was negligible (Salomone et al., 2015; Salomone and Ioppolo, 2012), ii) Irrigating. In addition to water, it requires electricity consumption, which generally comes from the Spanish electricity grid. However, some crops have a photovoltaic or diesel-powered system, but the representativeness of the total inputs was insignificant, iii) Land use change. The olive growing system is consolidated in Jaen and the use of the land has not changed for more than 100 years, so the land use is considered to be permanent crop cultivation, iv) Burning tree pruned residues. The burning of olive tree pruning is

regulated and special permission is required. Nevertheless, burning of light tree pruning continues, although in a decreasing number of cases. The carbon and the corresponding carbon dioxide and monoxide emitted by this activity are considered to belong to the short carbon cycle and are therefore not counted in the LCA (British Standards Institution, 2011). The rest of emissions and particles emitted to air, such as water vapor, CH_4, ethane, ethylene, and formaldehyde are considered negligible in this activity (Alves et al., 2019), v) Transport distances. The transport distance of the products consumed in the farms and OOMs of Jaen takes a value of 300 km. This figure is an approximate distance from this province to the main industrial cities (Seville and Madrid) and ports of Andalusia such as Algeciras, Motril and Almeria, vi) Infrastructure and related energy consumption. Infrastructure such as buildings or warehouses and their energy consumption is negligible for the study of the production of VOOs in LCA (Salomone et al., 2015), and vii) Emissions. Emissions to air, water and soil produced by agricultural processes were factored in according to the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (Amstel, 2006) and keeping the same relation to products and activities set by the PEFCR. The main processes, inputs, and outputs of the farming phase for the types of crop and harvests studied are shown in Annex 1.

The processes which were taken into account in the industrial phase were: i) Washing. When the olives are delivered to the OOM, they are usually washed with water to separate the olives from the small branches, twigs, leaves and dust. The small twigs and leaves return to their olive crop as animal feed, ii) Milling and malaxing. The olives are transformed into an olive paste before extraction, iii) Centrifugation. The two-phase decanter requires a high-energy consumption in the industrial phase, and an additional use of water and heat for transforming olives into VOOs. From this process, a pomace is obtained, iv) Extraction of olive pomace and depitting. During this process, the stone and the pomace are separated with a depitting machine. The olive stone is a by-product

that is valuable in the biomass market, and the olive mill pomace is a waste that must be treated in a consecutive process, v) Pomace drying. The pomace oil mill is responsible for the extraction of two by-products from the pomace: crude pomace, a raw material for the olive pomace oil industry, and exhausted pomace, another by-product with a lower value than in the biomass market, and vi) Oil washing. The process of obtaining VOOs ends with the oil washing.

Different assumptions were made in the LCI of the industrial phase. These include: i) Transport distances. As for the farming phase, the products used in the OOM are transported 300 km. Pomace transport has the value stated by the PEFCR, ii) Infrastructure. The relationship between the number of OOMs considered and their production, divided by their lifetime (50 years) gives the value of OOMs per FU, iii) Emissions. Emissions to air, water or land are derived from the use of fuel - the PEFCR ratio, iv) Harvested olive residues. The material resulting from the cleaning of the harvested olives is transported to the plantation to use the organic material as small ruminant (sheep and goats) feed or fertilizer, v) Olive stones. About 15% of the separated stones are burned to generate heat (Vera et al., 2019). Its emissions produce an additional EI that is accounted for in the LCA, vi) Crude pomace extraction. In Spain, pomace is considered a waste that must be treated by law. The quantity of pomace per FU comes from the survey and its LCI is provided by the PEFCR document. Annex 2 shows the values of the main activities and products during the industrial phase.

2.4. Life Cycle Assessment applied to VOO production

The LCA was carried out using the software SimaPro 9.0. The defined LCI has been the source to create an environmental model, considering different databases (Agri-footprint 4.0, ecoinvent 3.5, ELCD, Industry data 2.0). Subsequently, this model has been analyzed through the ILCD 2011 Midpoint+ method (EC - JRC, 2012, 2011) to obtain the EIs in different impact categories (Desideri et al., 2014; Proietti et al., 2017). This method

was selected to be applied because it shows the EIs of 16 differentiated impact categories, including the most relevant in the olive oil production according to the PEFCR (Climate change, water resource depletion, fresh water ecotoxicity, eutrophication, acidification, land use, resource depletion, ozone depletion and photochemical ozone formation). Results are shown by the quantity and percentage of EI in different categories for the different activities.

2.5. Carbon footprint in the farming phase

The carbon footprint of the studied olive farms was first performed by assessing the inputs and outputs of CO_2 eq. per hectare and latter normalized by kg of olive oils factoring in the olive fruit harvested and efficiency in converting olive fruit into olive oil.

Net biogenic CO_2 absorbed and emitted, which are that CO_2 which is fixed and emitted as a result of the natural carbon cycle, were considered. Fixed CO_2 eq. was that of the annual net CO_2 taking by the trees and distributed into the aboveground and belowground permanent and non-permanent tree structures, which include olive fruits and light and firewood tree pruning, whereas CO_2 eq emitted included that on farms from soil basal respiration and decomposition of the tree pruning once shredded and applied on top of the soil surface. Off-farm CO_2 eq. emissions were those of the climate change results of the LCA analysis. Products (e.g., olive fruit), residues (e.g., light and firewood tree pruning) and the stable permanent structure of the tree contain biogenic carbon derived from the CO_2 fixation by the crop.

2.5.1. On-farm fixed CO_2 eq.

Net annual tree CO_2 fixation was calculated from: i) that C fixed in the olive fruits, ii) that annual C which is stored in the stable structures of trees, and iii) that C of the tree pruning assuming that the > 25 years old of the trees maintain a stable tree volume canopy. The annual amount of C taken up from the atmospheric CO_2 and moved to the olive fruit was

estimated considering the water and carbon contents of the olive fruits. The annual amount of C storage in the stable structure of the olive trees of the *picual* variety was estimated from the relationship between the tree density and the annual rate of C accumulation in both above and belowground olive trees (Lopez-Bellido et al., 2016). The annual rate of C storage in tree pruning was based on the relationship between light and firewood tree pruning and olive yield (Civantos and Olid, 1982) considering the water content (26.6%) of the tree pruning. Finally, a small proportion of tree leaves and twigs is harvested together with the olive fruit which ends up in the OOMs. This amount, which accounted for 7% of the harvested olive fruit (Schau et al., 2016), was calculated from the olive fruit yield. The carbon content of composite samples of olive fruits and tree pruning from *picual* was determined in a CNHS autoanalyzer.

The annual amount of CO_2 fixed by the tree was the sum of that storage in the permanent structure of the olive tree, pruning, olive fruits and olive leaves and twigs. According to the survey of the olive farms, spontaneous temporary crops were controlled by a combination of herbicides and tillage and thus annual CO_2 fixation by them were not considered.

2.5.2. Off and in farm CO_2 eq. emission

CO_2 emitted during the farm operations (fertilizing, plant protection products, tree pruning, harvesting, irrigation, diesel consumption, etc.) were obtained from the results under climate change of the LCA.

Top 30 cm of soil CO_2 emission was obtained following the soil organic carbon mineralization coefficient (k2) which was calculated from Hénin and Dupuis (1945), using the following equation:

$$k2 = \frac{(1200 \times fo)}{(200 + c) \times (200 + 0.3 \times s)}$$

where c = soil clay content (g kg^{-1}), s = soil silt content (g kg^{-1}) and f_0= 0.2 x (T-0.5), with T = yearly average temperature (^oC) of the olive farms obtained from the nearest weather station. The annual mineralization coefficient was applied to the soil organic carbon content (top 30cm) of the soil of the olive farms. Soil contents of silt, clay and organic carbon, and bulk density for each olive farm were obtained from Mapa de suelos de Andalucía (IARA-CSIC, 1989).

Annual CO_2 emission from the decomposition of the olive tree pruning was accounted for as these were crushed in the field and applied onto the soil surface assuming an isohumic coefficient of 0.35 (Sofo et al., 2005). The CO_2 emissions from the decomposition of the organic carbon contained in the tree pruning were charged for a year, despite the fact that the total CO_2 is emitted during the following years.

2.6. Carbon balances in the farming phase

The carbon (C) balance was calculated for a hectare for the studied olive farms Factoring in the farm C inputs and outputs as outlined in sections 2.5.1. and 2.5.2. Inputs include C storage annually in the permanent structures of the olive trees, the non-permanent structures (olive fruit, light, and firewood pruning, and that in the olive leaves and twigs harvested with the olive fruits). Outputs included: i) the C-CO_2 fraction of the light tree pruning which decomposes in the long term, ii) C in the olive fruit, iii) C in the firewood, iv) C in the olive leaves and twigs harvested with the olive fruits, and iv) the C-CO_2 of the basal soil respiration.

3. Results and discussion

3.1. Environmental impacts of extra VOOs production

There was high variability in the harvested olive fruit between the surveyed years and among the olive farms of the same type. The mean coefficient of variation for the whole set of farms between the three years was 53.0%. In addition, the coefficients of variation

of olive yield among olive farms of the same farming system and year were 18.0%, 48.6% and 68.3%, for traditional rainfed, traditional irrigated and intensive, respectively. Variability in the olive fruit yield of every harvest for the studied cases was mainly due to weather conditions and the alternate bearing which characterize olive cropping. This variability can be observed especially for the traditional rainfed crops, which represent a relatively high proportion of Spanish olive groves, but it is not uncommon for irrigated olive groves. The coefficients of variation of olive fruit yield among the studied years were 52.3%, 22.0% and 24.9% for traditional rainfed, traditional irrigated and intensive managements, respectively.

The variability found in this study could not be compared with that of other studies by assessing LCA or C footprint at the farm level because these use models of management for each olive farm type (e.g. Guarino et al., 2019; Romero-Gámez et al., 2017) or only one olive farm (e.g. Proietti et al., 2014). This high variability in olive fruit yield within a farming system but with similar management also means high variability in the EIs, which should be considered.

Table 2 shows the results of the 16 impact categories of the traditional rainfed and irrigated and intensive olive farms at industrial phases. On average, for the whole set of olive farms and EIs, the farming phase accounted for 76.6% of the EIs. Therefore, to reduce the impact of the production of a FU unit, most efforts should be made in the farming phase rather than the industrial phase.

Per kg of VOOs, the impacts on climate change, ozone depletion, both ionizing radiation indicators, freshwater eutrophication and water resources depletion of intensive olive farming were significantly higher than traditional rainfed, and for climate change and ozone depletion also higher than traditional irrigated.

Although other studies have used different FUs, making comparison difficult, our data on the impacts on climate change are in the range of others, once converted to a

comparable scale. Thus, Romero-Gámez et al. (2017) calculated using models of traditional rainfed, traditional irrigated and intensive values in the range of 1.23 -1.94 kg CO_2 eq. kg^{-1} olive oil, 1.04-2.18 kg CO_2 eq. kg^{-1} olive oil and 1.66-2.44 kg CO_2 eq. kg^{-1} olive oil. Finally, our data on the effect of the farming system on climate change are well in the range of 0.7 to 4.8 kg CO_2 eq. kg^{-1} olive oil reported by Proietti et al. (2017) for 7 traditionally managed olive farms. Under an intensive management (2.17 kg CO_2 eq. kg^{-1} olive oil), the impact on climate change was 1.34 times higher than those of the traditional.

Fertilization (29.6%) together with plant protection products and herbicides (24.7%) contributed an average of 0.92 kg CO_2 eq. kg^{-1} olive oil (54.3%). Thus, the higher impact of climate change of intensive olive farms was mainly due to the higher amount of fertilizers, specially N-based, and pesticides and herbicides applied together with a higher level degree of mechanization compared to the traditional systems.

The higher impact of intensive olive farm on freshwater eutrophication is also directly related to the higher amounts of fertilizers applied in the intensive olive farm. Therefore, more effort should be made in the optimization of N-based fertilization and the use of plant protection products and herbicides. Previous studies have shown the relatively high contribution of N fertilizers in CO_2 emissions. A change of the type of N fertilizer and the reduction of the amounts of nitrogen are possible after an assessment of N found that olive groves synchronize in time and magnitude the availability of N with demand. It has been shown that using organic N fertilizers, such as farmyard manure combined with cover crops, could reduce the CO_2 emissions linked to N fertilizers. In addition, the presence of temporary spontaneous cover crops in olive groves controlled by physical means not only reduces the impact on freshwater eutrophication by increasing nutrient retention within the farm, but may also boost natural control of pest and diseases, reducing the needs for plant protection products, and thus the impact on climate change.

As expected, the impact of intensive olive farming on water resource depletion was the highest. Impact of rainfed olive systems was positive (study case 1 and 3) and typically between 2 to 3 orders of magnitude lower than that of traditional irrigated and intensive olive farming. Therefore, deficit irrigation in olive farms, which is a strategy that is currently on the rise, should be encouraged by the regional authorities to reduce the impact on water resources and lower the energy consumption linked to irrigation.

Interestingly, although the impact on land use was not significant among the farming systems, it tended to be higher in traditional rainfed. This trend was due to the relatively lower productivity in these traditional systems with respect to traditional irrigated and intensive. Similar results were found by Romero-Gámez et al. (2017), who showed the highest land use for rainfed and the lowest for super-intensive olive farms.

Table 2. EI of the farming phase and the industrial phase per FU. Values of the farming phase are the mean ± standard deviation of 4 or 3 olive farms. A different letter stands for significant differences (one-way ANOVA, α = 0.05 for lower case, α = 0.1 for capital letters) among olive farm models.

EI (unit)	**Farming phase**						**Industrial phase**
	Traditional rainfed		**Traditional irrigated**		**Intensive irrigated**		
	Mean	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**	**Standard deviation**	**Mean**
Climate change (kg CO_2 eq.)	1.49^{A}	0.280	1.49^{A}	0.540	2.25^{B}	0.494	0.52
Ozone depletion (kg CFC-11 eq.)	$9.5\ 10^{-8A}$	$1.18\ 10^{-8}$	$1.32\ 10^{-8A}$	$6.12\ 10^{-8}$	$1.89\ 10^{-7B}$	$1.03\ 10^{-8}$	$1.37\ 10^{-8}$
Human toxicity, non-cancer effects (CTUh)	$6.87\ 10^{-7a}$	$1.85\ 10^{-7}$	$7.43\ 10^{-7a}$	$4.40\ 10^{-7}$	$1.35\ 10^{-6a}$	$1.04\ 10^{-6}$	$6.81\ 10^{-8}$
Human toxicity, cancer effects (CTUh)	$4.87\ 10^{-8a}$	$1.33\ 10^{-8}$	$7.61\ 10^{-8ab}$	$4.18\ 10^{-8}$	$1.11\ 10^{-7b}$	$4.09\ 10^{-8}$	$1.49\ 10^{-8}$
Particulate matter (kg PM2.5 eq.)	$1.25\ 10^{-3a}$	$3.11\ 10^{-4}$	$1.32\ 10^{-3a}$	$5.49\ 10^{-4}$	$1.76\ 10^{-3a}$	$2.15\ 10^{-4}$	$7.87\ 10^{-5}$
Ionizing radiation HH (kBq U235 eq.)	$7.14\ 10^{-2a}$	$2.62\ 10^{-2}$	$2.67\ 10^{-1a}$	$1.96\ 10^{-1}$	$3.52\ 10^{-1b}$	$1.89\ 10^{-1}$	$4.90\ 10^{-2}$
Ionizing radiation E (interim) (CTUe)	$4.63\ 10^{-7a}$	$1.73\ 10^{-7}$	$9.07\ 10^{-7ab}$	$6.84\ 10^{-7}$	$1.21\ 10^{-6b}$	$3.73\ 10^{-7}$	$1.84\ 10^{-7}$
Photochemical ozone formation (kg NMVOC eq.)	$7.10\ 10^{-3a}$	$1.08\ 10^{-3}$	$6.45\ 10^{-3a}$	$4.14\ 10^{-3}$	$8.30\ 10^{-3a}$	$1.80\ 10^{-3}$	$6.13\ 10^{-3}$
Acidification (molc H+ eq.)	$8.96\ 10^{-3a}$	$2.24\ 10^{-3}$	$1.09\ 10^{-2a}$	$6.71\ 10^{-3}$	$1.52\ 10^{-2a}$	$4.88\ 10^{-3}$	$8.94\ 10^{-4}$
Terrestrial eutrophication (molc N eq.)	$4.23\ 10^{-2a}$	$7.82\ 10^{-3}$	$3.77\ 10^{-2a}$	$2.40\ 10^{-2}$	$4.84\ 10^{-2a}$	$1.53\ 10^{-2}$	$2.03\ 10^{-3}$
Freshwater eutrophication (kg P eq.)	$2.85\ 10^{-4a}$	$1.15\ 10^{-4}$	$5.66\ 10^{-4ab}$	$2.56\ 10^{-4}$	$8.42\ 10^{-4b}$	$4.47\ 10^{-4}$	$4.38\ 10^{-5}$
Marine eutrophication (kg N eq.)	$2.79\ 10^{-3a}$	$5.40\ 10^{-4}$	$2.62\ 10^{-3a}$	$1.95\ 10^{-3}$	$3.36\ 10^{-3a}$	$1.38\ 10^{-3}$	$2.05\ 10^{-4}$
Freshwater ecotoxicity (CTUe)	27.9^{a}	12.1	35.1^{a}	19.8	51.9^{a}	23.9	2.32
Land use (kg C deficit)	55.4^{a}	10.1	38.1^{a}	20.3	46.1^{a}	21.1	0.67
Water resource depletion (m3 water eq.)	$8.79\ 10^{-4a}$	$7.79\ 10^{-3}$	$1.15\ 10^{-1ab}$	$1.15\ 10^{-1}$	$1.28\ 10^{-1b}$	$8.98\ 10^{-2}$	$-8.03\ 10^{-4}$
Mineral, fossil & ren resource depletion (kg Sb eq.)	$1.51\ 10^{-4a}$	$8.30\ 10^{-5}$	$1.41\ 10^{-4a}$	$1.41\ 10^{-4}$	$2.29\ 10^{-4a}$	$2.30\ 10^{-4}$	$4.69\ 10^{-5}$

Fig. 2 shows the weighted 3-year mean contribution of the different activities and inputs of the industrial phase on EIs. The highest contribution of the industrial phase (46.0 %) compared to the farming phase was for the photochemical ozone formation or “summer smog” or ground level ozone, which is formed by the reaction of volatile organic compounds and nitrogen oxides in the presence of heat and sunlight. This impact mainly depends on the amounts of carbon monoxide, sulfur dioxide, nitrogen oxide (NO) produced during the treatment of the pomace.

Electricity consumption is one of the inputs with more impact in most of the categories, accounting for between 20 to 60 % of the impacts. The pomace treatment contributed to the 85.0% (0.44 kg CO_2 eq. kg^{-1} olive oil) of the impact of the whole industrial phase on the climate change, whereas electricity only accounted for the 9.7% (0.05 kg CO_2 eq. kg^{-1} olive oil). In addition, the pomace treatment accounted for most of the impact on photochemical ozone formation. These relatively high impact on both categories is mainly due to the combustion of the exhausted pomace which is used to dry the crude pomace with a typical water content of between 60 and 70%.

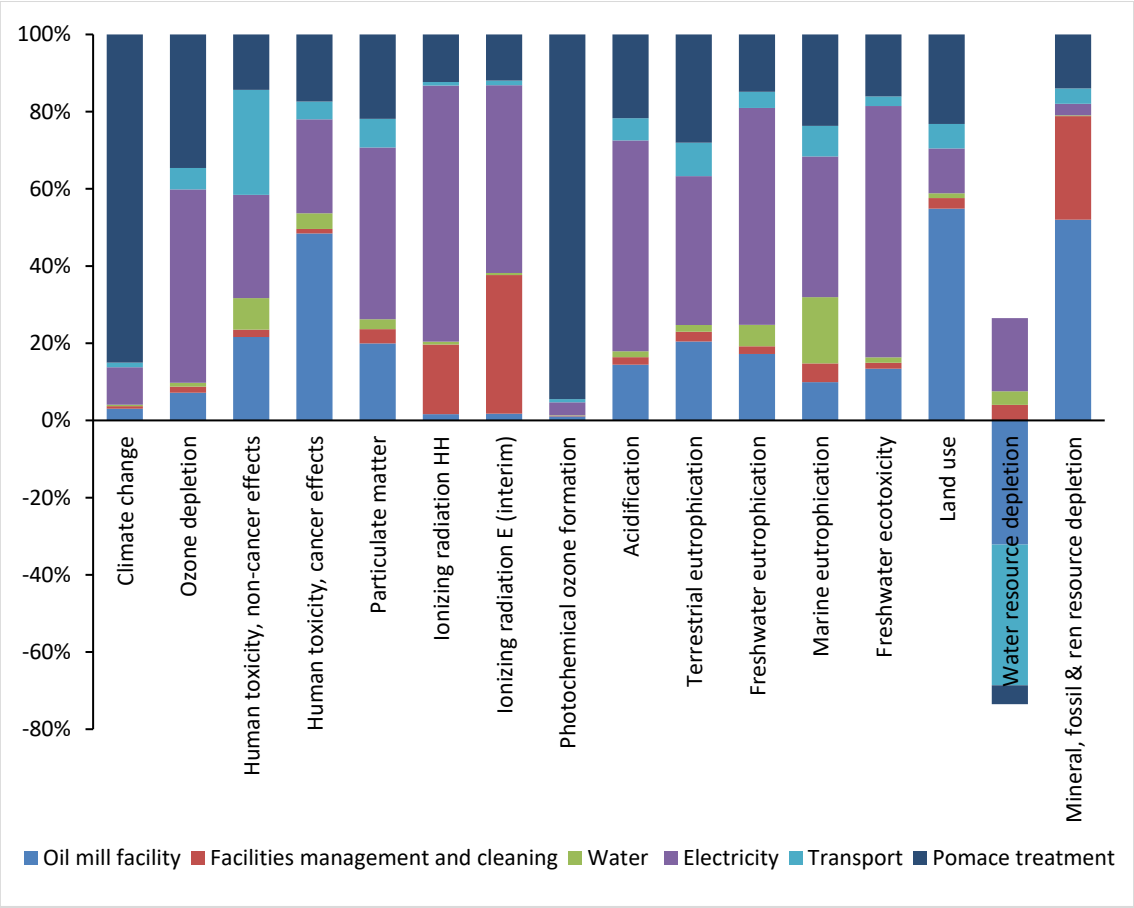

Fig. 2. Distribution of EI of the industrial phase in different categories for the weighted average.

Despite the relatively high impact of olive pomace treatment, it is a recommended practice because other alternatives to dry the crude olive pomace (e.g., electricity) could even impact much more, and it is a way to valorize the exhausted olive pomace. Interestingly, the use of a significant amount of aluminum in the fabrication of the OOM facilities had a positive impact on water resource depletion by significantly reducing the use of water. The reason is that the ILCD method considers that the generation of aluminum from the database Ecoinvent 3 (Althaus et al., 2004) impacts positively in water resources with 102 m^3 eq. per kg of aluminum produced, despite salt water input and water output of the process is approximately the same quantity (0.12 m^3).

Figure 3 shows the impact on climate change of both farming and industrial phases. For the production of 1 kg of unpacked VOOs, between 2.00 kg CO_2 eq. (traditional rainfed

olive farming) to 2.69 kg CO_2 eq. (intensive olive farming) is emitted, with significantly higher values for the latter compared to traditional farming.

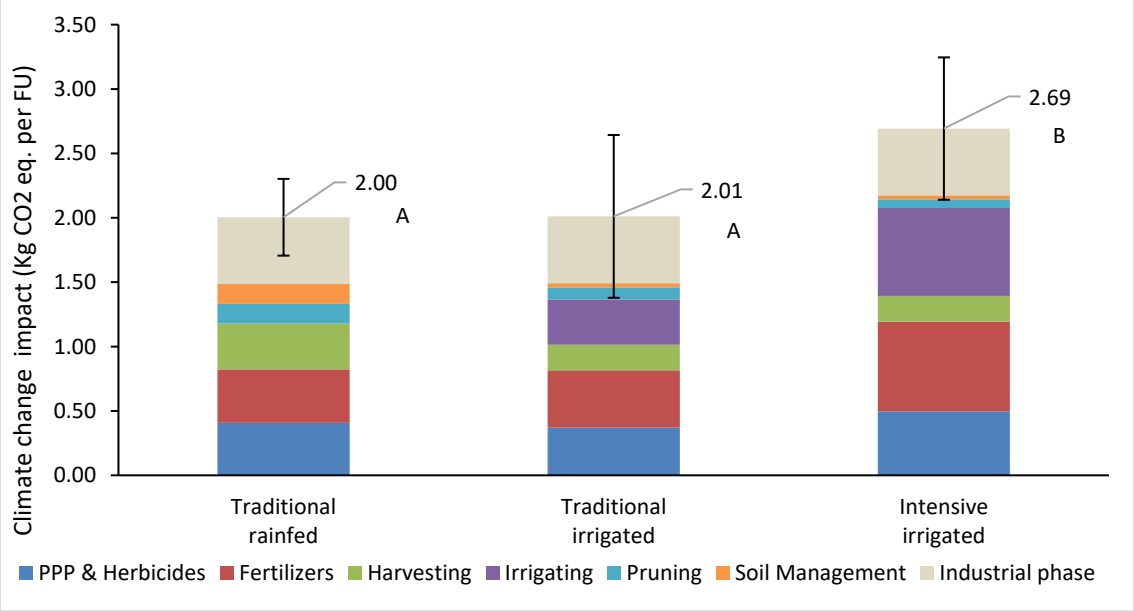

Fig. 3. Distribution of EI in climate change category. Data are the mean of 3 or 4 olive farms. Different letters stand for significant differences among olive grove systems (one-way ANOVA, $\alpha = 0.10$).

These results are consistent with those obtained by other authors in several case studies. In Table 3 there is a compilation of the results of other authors and two EPDs (Environmental Product Declarations).

Table 3. Impact on climate change of producing different olive oil FU at the farm and industrial phases published by other authors (EPD Sellas, 2013, EPD Borges, 2015, Pattara et al., 2016, Proietti et al., 2017 and Romero-Gámez et al., 2017).

	Romero-Gámez et al.			**Pattara et al.**		**Proietti et al.**		**EPD Borges**	**EPD Sellas**
Location	Andalusia (Spain)			Abruzzo (Italy)		Umbria (Italy)		Spain	Greece
Years studied	period between 1980-2016			1 (2014-15)		1 (2014-15)		3 (2012-15)	1 (2012-13)
System boundaries	Farming phase			Cradle-to-gate		Cradle-to-gate		Cradle-to-grave	Cradle-to-gate
FU	1 ton of olives			5 L EVOO		1 L EVOO		1 L EVOO	1 kg VOO
Case studied	Traditional		Intensive	Case 2 (lowest impact)	Case 5 (highest impact)	Case A (lowest impact)	Case G (highest impact)	-	-
	Rainfed	Irrigated							
Density (trees/ha)	100	100	250	± 200	± 200	390	478	-	-
Olive oil yield (L/ha)	-	-	-	1,345	1,025	1,172	467	-	-
Global impact	95-277	178-260	224-309	4.48	10.1	0.67	4.48	4.18	2.36
Farming phase	95-277	178-260	224-309	3.34	7.74	0.3	3.33	2.8	1.6

Industrial phase	-	-	-	1.14	3.2	0.37	1.14	0.11	0.29
Olive oil extraction	-	-	-	0.44	0.61	0.18	0.14	-	-

Romero-Gámez et al. (2017) studies different subtype models of every tree crop in the farming phase (e.g. per ton of olive fruits). The EI in the climate change category for 1 ton of olives fruits in our study averaged 303, 316 and 464 kg CO_2 eq. for traditional rainfed, traditional irrigated and intensive, respectively, which are higher than that reported by Romero-Gámez et al. (2017). This could be due to the fact that the referred study used long term data (from 1980 to 2016), with olive grove having a lower level of intensification. It is noteworthy that in our study the variability and application rate of fertilizer and PPP were higher than those of Romero-Gámez et al. (2017).

The study of Pattara et al. (2016) showed that the impact is between 4.48 kg CO_2 eq./5L oil and 10.10 kg CO_2 eq./5L oil. However, their data are not fully comparable as the traditional rainfed olive grove under study had a tree density around 200 trees/ha, far exceeding the density range of the traditional olive groves of our study (80-150 trees/ha). The impact of the farming phase in the study by Pattara et al. (2016) ranged 3.34 kg CO_2 eq./5L oil to 7.74 kg CO_2 eq./5L oil, whereas in our study, the range was 4.93 to 12.63 kg CO_2 eq./5L.

Proietti et al. (2017) found values between 0.67 kg CO_2 eq./L oil to 4.48 kg CO_2 eq./L oil for a traditional olive grove. Our data (between 1.46 kg CO_2 eq./L oil to 3.00 kg CO_2 eq./L oil, considering the farm and the industrial phases) are included in that range. It is remarkable that the VOOs yield of the cases studied by Proietti et al. (2017) ranged 430 to 1,172 L oil/ha , whereas our study get values from 600 L oil/ha in traditional rainfed cases to more than 2,000 L oil/ha in some irrigated cases (traditional and intensive) .

Borges' EPD found an EI of 2.91 kg CO_2 eq./L in the climate change category, of which 2.80 kg CO_2 eq./L are emitted during the farming phase and the other 0.11 kg CO_2 eq./L during the industrial phase. The range of 0.99-2.53 kg CO_2 eq./L oil of our study is lower than that of Borges' EPD, whereas the EI of the industrial phase of this study (0.48 kg CO_2 eq./L oil) was 4.4 times higher.

Sellas' EPD obtained an impact value of 1.89 kg CO_2 eq./kg, which is lower than Borges' but within the range of our study. 1.60 kg CO_2 eq./kg was produced during the farming and the other 0.29 kg CO_2 eq./kg in the industrial phase. The impact of the irrigation in the Sellas' EPD study was 0.12 kg CO_2 eq./kg, which is much lower than most of the irrigated cases analyzed in this study (0.10-0.64 kg CO_2 eq./kg oil for traditional cases and 0.41-0.88 kg CO_2 eq./kg oil for intensive).

3.2. C footprint

Table 4 shows the fluxes of C and CO_2 eq. of the main processes in the farming phase used to calculate the C-footprint and C balances. C footprint per hectare and kg olive oil is shown in Figure 4. C footprint was negative (e.g. net CO_2 fixation) and averaged -4182.6, -6290.4 and -4070.7 kg CO_2 ha^{-1} y^{-1} for traditional rainfed, irrigated and intensive, respectively. Mean values for traditional rainfed and intensive olive farming were not significantly different, but they were significantly lower than those of traditional irrigated. This was mainly due to the fact that in the four studied cases with traditional irrigation, CO_2 was fixed in the harvested olive fruits, and olive leaves and twigs and light and firewood pruning tended to be higher than the other management techniques. Although off-farm CO_2 eq. emissions were significantly higher under intensive olive farming, the higher CO_2 fixation by olive fruit yield and tree pruning in these systems counterbalanced the higher off farm emissions.

We did find a significant relationship between olive fruit yield and the magnitude of the C footprint (Figure 5.). Thus, from an annual olive fruit yield of between 2826 to 7588 kg

olive fruit ha^{-1}, the higher the olive fruit yield, the more negative (e.g. more net annual CO_2 fixed by trees) the C footprint was. However, for a production of about 8000 kg olive fruits, the C footprint remained relatively constant, mainly due to the increase in the off-farm CO_2 eq. emissions, but also because of higher soil basal CO_2 emissions. Although there are no statistics, typically, high-yield intensive and super-intensive olive groves are cropped on soils with medium to high levels of soil organic matter which emitted more CO_2 during soil organic matter decomposition. Interestingly, according to the function which related olive yield and C footprint, for a harvest lower than 1835 kg olive fruit ha^{-1} y^{-1}, the C footprint is zero. This is mainly due to the fact that the CO_2 fixed by trees does not exceed the emitted off-farm CO_2 and that which is emitted by basal soil respiration. However, this should be interpreted with caution, because typically the lower the olive fruit production the lower the farm operations and inputs, and thus the off-farm CO_2 emissions.

Table 4. On and off-farm C and CO_2 eq. in and out fluxes considered in calculating the C footprint and C balances in traditional rainfed, traditional irrigated and intensive olive groves. Values are the mean ± standard deviation of 4 or 3 olive farms. A different letter stands for significant (one-way ANOVA, $\alpha = 0.05$) differences among olive farm models.

		Unit	Traditional rainfed	Traditional irrigated	Intensive
Non-permanent structures	Olive fruit + twigs and leaves	Kg C ha^{-1} y^{-1}	1187.4^{a}±213.3	2037.2^{a}±990.6	1879.5 ^{a}±1283.5
		Kg CO_2 ha^{-1} y^{-1}	4354.8^{a}±782.0	7469.4^{a}±3631.9	6891.1^{a}±4705.9
	Light pruning	Kg C ha^{-1} y^{-1}	542.8^{a}±97.3	540.9^{a}±93.3	522.8^{a}±73.9
		Kg CO_2 ha^{-1} y^{-1}	1990.6^{a}±356.9	1983.5^{a}±342.0	1917.2^{a}±270.9
	Firewood	Kg C ha^{-1} y^{-1}	464.6^{a}±83.6	462.9^{a}±80.1	447.4^{a}±63.5
		Kg CO_2 ha^{-1} y^{-1}	1703.6^{a}±306.7	1697.5^{a}±293.9	1640.5^{a}±232.8
Permanent structures	Tree permanent structures	Kg C ha^{-1} y^{-1}	295.1^{a}±9.8	292.8^{a}±10.6	357.0^{b}±24.6
		Kg CO_2 ha^{-1} y^{-1}	1080.2^{a}±35.9	1071.8^{a}±38.9	1306.9^{b}±90.1
Soil CO_2 emissions	Decomposition of light pruning	Kg C ha^{-1} y^{-1}	352.8^{a}±63.3	351.6^{a}±60.6	339.8^{a}±48.0
		Kg CO_2 ha^{-1} y^{-1}	1293.9^{a}±232.0	1289.3^{a}±222.3	1246.2^{a}±176.1
	Soil basal respiration	Kg C ha^{-1} y^{-1}	725.0^{a}±82.1	830.8^{a}±49.0	1153.9^{b}±181.9
		Kg CO_2 ha^{-1} y^{-1}	2653.7^{a}±300.7	3040.9^{a}±179.4	4223.2^{b}±666.0
Farm operations and inputs CO_2 eq. emissions		Kg CO_2 eq. $ha^{-1}y^{-1}$	1001.1^{a}±156.0	1603.7^{ab}±713.5	2218.2^{b}±1054.0

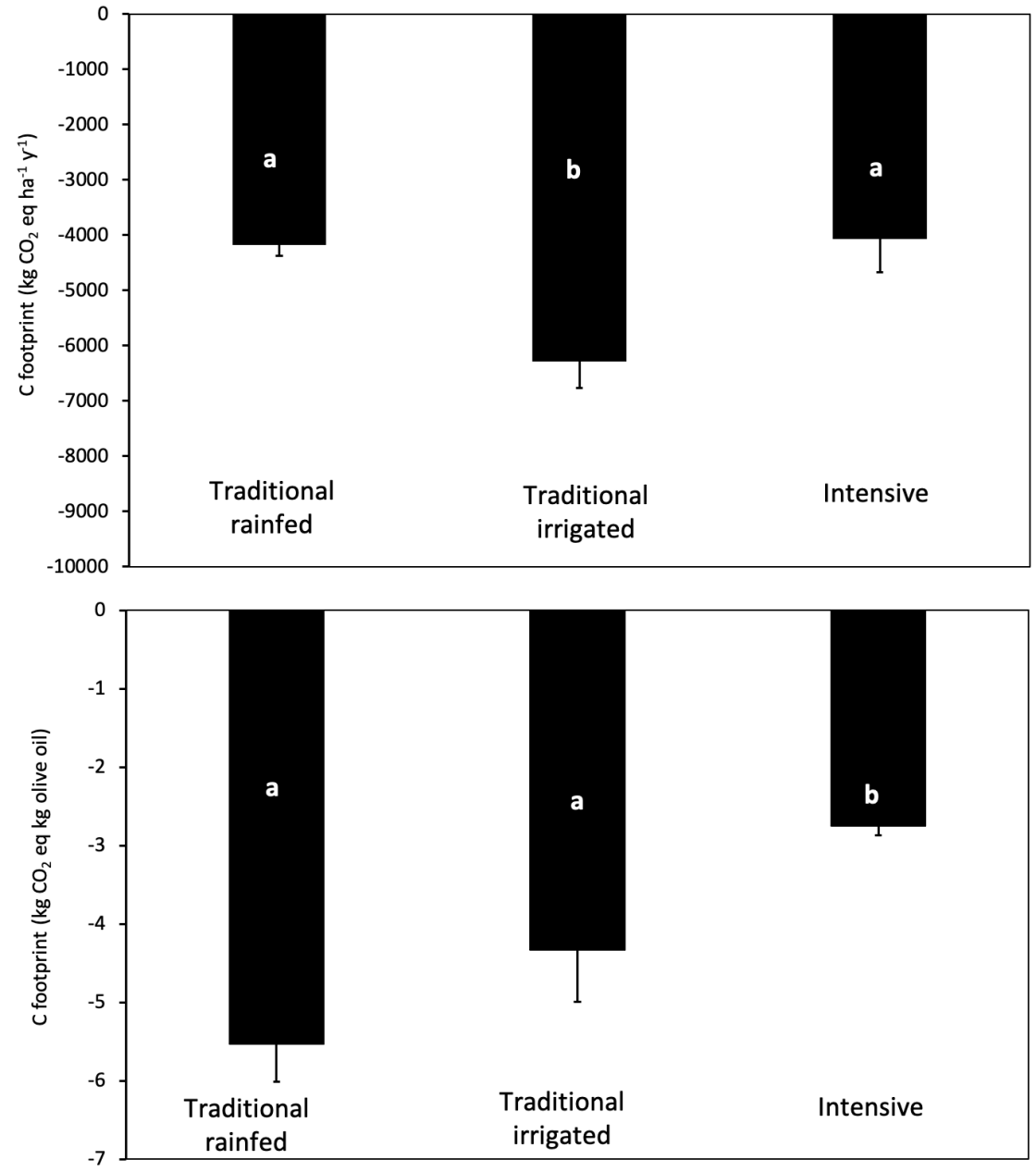

Fig. 4. C footprint (kg CO_2 ha^{-1}) per hectare and year in the farming phase (a) and in the farm and industrial phases (kg CO_2 kg^{-1} olive oil) (b) in traditional rainfed, traditional irrigated and intensive olive groves. Data are the mean of 3 or 4 olive farms. Different letters stand for significant differences among olive groves systems (one-way ANOVA, $\alpha = 0.05$).

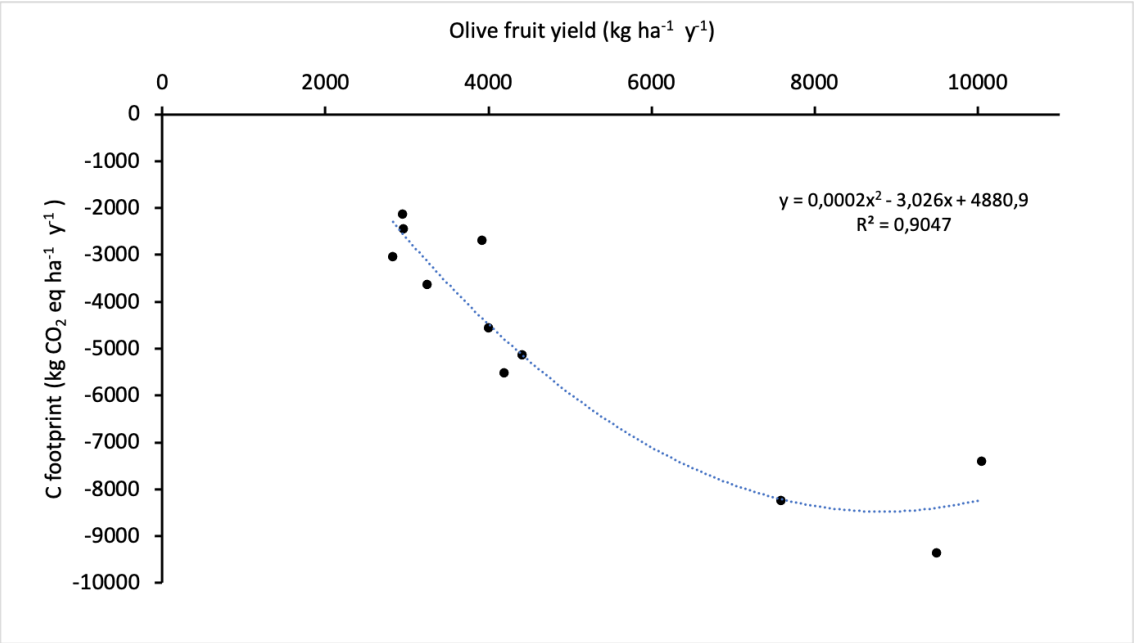

Fig. 5. Relationship between fresh olive fruit yield and C footprint (kg CO_2 ha^{-1}) in the 11 study cases.

As far as we are aware, there are no studies that assess the C footprint on a per hectare basis in olive groves following the methodology described in this study. Aguilera et al. (2015) provided a C footprint of +1106 kg CO_2 eq. (net CO_2 emission to the atmosphere) ha^{-1} y^{-1} for conventionally managed olive groves with a mean olive fruit yield of 3.79 tons h^{-1} y^{-1} (fresh weight). However, in that study the CO_2 fixed in the stable structures of the trees and that of the olive fruit were not taken into account. In addition, changes in the stock of soil organic carbon were estimated as zero, as it was assumed that soil carbon was in equilibrium for a conventional olive farm with no organic inputs. On the other hand, Lopez-Bellido et al. (2016) found that C footprint for 22 olive farms of different tree densities, varieties and management averaged -7795 kg CO_2 ha^{-1}, a figure similar to that of our study. However, the data are not comparable because CO_2 fixed by olive fruits was not considered and that study estimated an annual increase in soil C stock which was calculated as SOC stock at sampling divided by the age of the plantation. Finally, Proietti et al. (2014) calculated an average C footprint from year 3 to 11 of an intensive *Lecino* cultivar olive plantation of -5050 kg CO_2 ha^{-1} which is similar to our data. However,

basal soil CO_2 emissions and that emitted during the decomposition of light pruning after chipping were not considered.

C footprint per kg of olive oil averaged -5.5, -4.3 and -2.7 kg CO_2 eq. kg olive oil in traditional rainfed, traditional irrigated and intensive olive groves, respectively, which significantly (P<0.01) higher values for intensive olive groves (Figure 4c). Therefore, in terms of CO_2 eq. emissions, the lower intensification of the olive tree cultivation the higher the contribution of producing 1 kg VOOs in mitigating the increase of atmospheric CO_2.

Our study highlights that olive groves are efficient atmospheric CO_2 sinks on an annual basis mainly by fixing CO_2 into permanent and non-permanent tree structures. For instance, averaging the C footprint in the three olive groves systems, which represent most of the olive grove cultivation in Andalusia, about 7.3 millions of tons of CO_2 are fixed annually, after deducting that CO_2 which is emitted off farm and that emitted by soil basal respiration and tree pruning decomposition in the farming phase. This figure accounts for about 0.86 tons of CO_2 per capita in Andalusia, which equates to more than 100% of the commitment of the Andalusia region to decrease in 2030 the diffusive CO_2 eq. per capita of 2005 by 18%.

However, caution should be taken, because most of the CO_2 fixed within the olive fruit will end up as CO_2 in the short-term in other phases (e.g., consumers). In addition, the CO_2 fixed in the stable structure of trees (roots, trunk and main branches) throughout the trees' lives, will end up as firewood, and then the accumulated CO_2 in the biomass will be returned to the atmosphere when olive groves are renewed or when there is a change in the type of crop. Furthermore, the CO_2 fixed in the permanent structure of the tree and that of the olive fruit does not provides services to the ecosystem other than the productive.

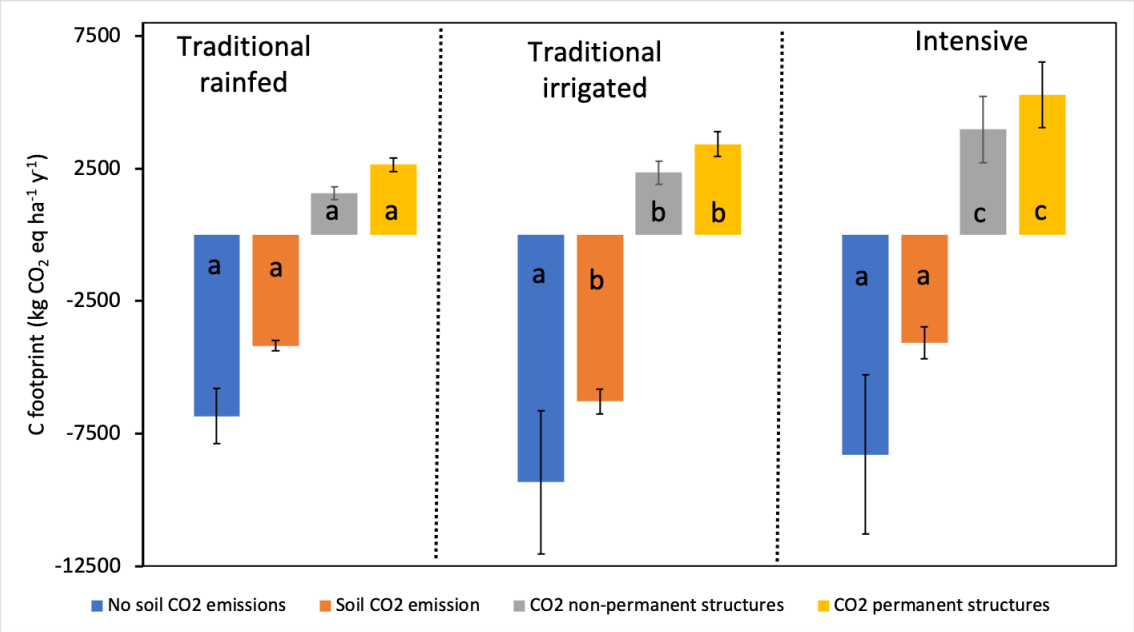

Fig.6. C footprint (kg CO_2 eq. ha^{-1} y^{-1}) per hectare and year in the farming phase, assuming no soil CO_2 emission, soil CO_2 emission, CO_2 emission from the non-permanent tree structures or CO_2 emission of the tree permanent structures in traditional rainfed, traditional irrigated and intensive olive groves. Data are the mean of 3 or 4 olive farms. Different letters stand for significant differences among olive groves systems (one-way ANOVA, $\alpha = 0.05$).

According to the on-farm carbon flows taken into consideration, the magnitude and sign of the C footprint differ significantly (Figure 6). If the net balances between the on and off-olive farm CO_2 eq. emissions and the CO_2 fixation by the permanent and non-permanent tree structures, but not the CO_2 emissions due to soil basal, are considered, then averaged C footprint ranged from -6836 to -9331 kg CO_2 eq. ha^{-1} y^{-1} or -8.0 to -9.4 kg CO_2 eq. kg^{-1} olive oil, without significant differences among managements. However, if soil basal CO_2 emissions and the CO_2 fixed in the non-permanent structure (olive fruit and firewood pruning) are considered as emitted CO_2, as this CO_2 will be returned to the atmosphere in the short-term (< 2 years), the C footprint averaged +1567.6 (traditional rainfed), +2348.1 (traditional irrigated) and +3973.4 (intensive) kg CO_2 ha^{-1}, with significant differences among olive grove systems. In terms of olive oil, it would be +2.52 (traditional rainfed), +2.31 (traditional irrigated) and +4.17 (intensive) kg CO_2 eq. kg^{-1} with

significantly higher values for the latter. Finally, if CO_2 fixed annually in the permanent structures of the trees is also considered to be emitted CO_2, as this CO_2 will be returned to the atmosphere from the landscape at the end of the cultivation cycle, then, mean C footprint would result in +2649, +3421 and +5282 kg CO_2 ha^{-1} or +3.44, +3.00 and +5.27 kg CO_2 kg^{-1} olive oil for traditional rainfed, traditional irrigated and intensive, respectively, with significantly higher values for the last of these.

The fact that, by considering different processes in the C footprint calculations, the C footprint can change from being negative (net CO_2 fixation) to positive (net CO_2 emission) is noteworthy. The need for carbon footprint calculations of the olive oil sector to comply with legislative requirements, carbon trading or corporate social responsibility has promoted the creation of companies and software to calculate the C footprint. Relevant calculations and processes are usually secured under intellectual property rights and not available to researchers, which considerably reduces confidence in the values provided by these companies.

3.3. C balance

On-farm C balances for the three olive farming systems are shown in Figure 7. C balances in all the farming systems were negative (e.g., net loss of C). Values ranged from -239.9 to -613.8 kg C ha^{-1}, mainly due to CO_2 emissions by soil basal respiration, which ranged from 656 to 1386 kg C ha^{-1} y^{-1} in the studied cases. Soil basal respiration in our study was significantly lower than the 7840 kg C ha^{-1} y^{-1} estimated by Bertolla et al. (2014) in a sandy-clay super-intensive olive farm in Tuscany (Italy). A lower negative balance was obtained for traditional rainfed whereas the largest was achieved in intensive farming, and differences among managements were significant. Therefore, despite C footprint, including net balance of greenhouse emissions emitted and fixed during a year, is negative (e.g., net atmosphere CO_2) in each of the study cases, the analysis of C balance indicates that representative traditional rainfed, traditional irrigated

and intensive olive groves of Andalusia lose carbon annually. The magnitude of these losses could be even higher if losses of C due to soil erosion were considered.

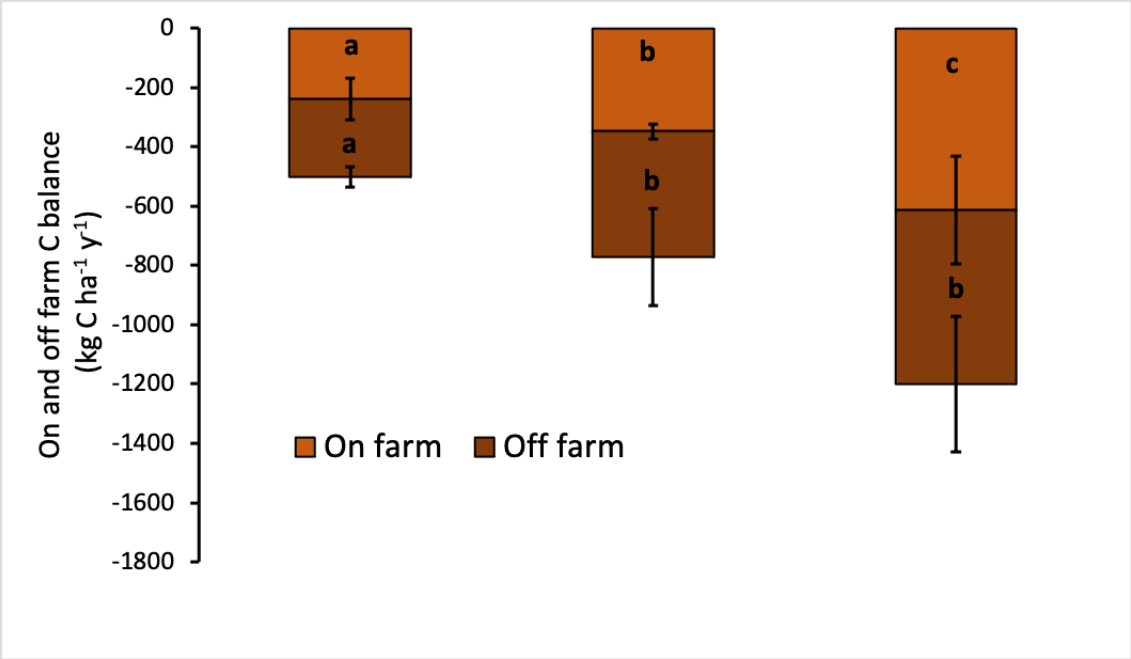

Fig. 7. C balances on farms factoring in the CO_2 eq. emitted during farming operations (kg C ha-1 y^{-1}) in traditional rainfed, traditional irrigated and intensive olive groves. Data are the mean of 3 or 4 olive farms. Different letters stand for significant differences among olive grove systems (one-way ANOVA, $\alpha = 0.05$).

These negative C balances can be offset by implementing technical and economic management practices aimed to increase the annual input of organic carbon. Indeed, remarkable soil carbon accumulation in olive groves applying recommended management practices had been previously recorded in olive farms (e.g., García Ruiz et al., 2012; Palese et al., 2013). These management techniques include temporary spontaneous cover crops and the application of manure or composted pomace to the soil. The possibility of maintaining cover crops among and beneath olive trees could be a clear advantage for switching C balance from negative to positive in olive groves. Temporary spontaneous cover crop can increase total biomass production in the olive groves while reducing external resource use of mechanical or chemical weeding operations, as well as of N fertilizers. Besides the effects on C balance, the agronomic

benefits of cover cropping also extend to aspects related to adaptation and other ecological services, such as reduced soil erosion, increased water infiltration, and enhanced N retention. Therefore, efforts to enhance olive fruit yields should also account for the multifunctional character of these woody cropping systems, which can provide not only the crop product quantified as yields but also other ecological services.

4. Conclusion

We found a relatively high variability in olive yield and in the impacts between years and for the same farming system of the 4, 4 and 3 cases of traditional rainfed, traditional irrigated and intensive studied farms. Per kg of unpackaged VOOs, the farming phase accounted on average for 76.6% of the EIs. Therefore, to reduce the impact of VOOs production, the efforts in reducing the impact should be focused on the farming phase rather than on the industrial phase.

In the farming phase, intensive olive farming showed higher yields but also significantly higher EI in climate change, ozone depletion, both ionizing radiation indicators, freshwater eutrophication, and water resources depletion, than the other managements. For the climate change category, the EI produced ranged from 1.80-2.41 kg CO_2 eq., 1.59-2.78 kg CO_2 eq. and 2.28-3.26 kg CO_2 eq. for traditional rainfed, traditional irrigated and intensive farming systems, respectively. Fertilizers (29.6%), plant protection products plus herbicides (24.7%) and irrigation (20.3%) accounted for most of the EI of the farming phase on climate change. For this reason, the higher impact of intensive olive farms on climate change was mainly due to higher consumption of fertilizers, especially N based, pesticides, fungicides, herbicides and energy applied together with a higher degree of mechanization compared to traditional systems.

Electricity consumption in the industrial phase contributed generally between 20 and 60% of the impacts. Therefore, renewable energy sources in the OOM operations should be encouraged to reduce the impacts. Pomace treatment contributed to the 85.0% of the

impact of the whole industrial phase to climate change, and also accounted for most of the impact on photochemical ozone formation. These relatively high impacts on both categories were mainly due to the combustion of the exhausted pomace which is used to dry the wet pomace.

C footprint was negative, highlighting that olive groves are efficient atmospheric CO_2 sinks on an annual basis mainly by fixing CO_2 into permanent and non-permanent tree structures. However, different C footprint values can be achieved by factoring in different C fluxes. C footprint (per kg olive oil) was significantly more negative for traditional rainfed, highlighting the greater contribution of this system for the mitigation of greenhouse gas emissions.

Although the C footprint was negative, C balance was negative (e.g. net loss of C), especially in traditional irrigated and intensive farming. The application of organic sources of fertilizer and the implementation of temporary spontaneous cover crops, both technically and economically feasible, are sound strategies to achieve a positive carbon balance and reduce the impacts of olive cultivation.

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Annex 1. Life cycle inventory of olives production.

Inventory data per ha	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9	Case 10	Case 11	Source
Harvesting												
Olives production (ton)	2.83	3.24	4.19	4.00	2.95	4.41	7.58	9.50	2.95	3.92	10.05	Survey
Density (trees)	96	93	100	138	83	100	92	135	195	286	184	Survey
Petrol, two-stroke blend (kg)	8.271	14.600	24.589	16.257	9.165	21.610	13.204	12.764	13.792	-	32.945	Survey
Transport, tractor and trailer (tkm)	11.861	16.354	22.566	7.656	15.843	21.543	39.564	49.687	15.324	79.000	51.642	Survey
Polyethylene (kg)	3.684	1.956	1.333	5.000	0.933	1.127	4.156	2.984	1.548	2.200	2.981	Survey
Cutting												
Petrol, two-stroke blend (kg)	0.649	2.664	2.587	1.787	0.767	2.687	1.650	2.487	1.853	-	4.394	Survey
Lubricating oil (kg)	-	0.444	0.543	-	0.452	0.678	0.795	0.413	0.826	-	0.790	Survey
Irrigation												
Electricity, low voltage (kwh)	-	-	-	-	852.286	49.102	280.234	2083.569	1256.360	-	560.273	Survey
Water (m3)	-	-	-	-	80.000	602.541	350.000	3500.000	798.341	67.900	680.000	Survey
Petrol, two-stroke blend (kg)	-	-	-	-	-	-	-	-	-	46.000	-	Survey
PPP & Herbicides*												
Use of field sprayer (ha)	-	3.000	3.000	-	-	-	2.000	4.000	3.000	6.000	3.000	Survey
Water (m3)	0.577	0.923	0.608	0.520	1.025	1.350	4.432	1.357	0.224	3.310	1.033	Survey
Organophosphorus-compound (kg)	0.078	0.240	0.267	-	0.922	-	0.542	-	0.195	0.608	1.010	Survey
Transport, tractor and trailer (tkm)	0.001	0.005	0.002	0.001	0.003	0.002	0.010	0.006	0.001	0.002	0.003	Survey
Glyphosate (kg)	0.357	1.123	0.620	1.399	1.100	3.045	10.671	1.354	0.395	0.307	0.245	Survey
Copper oxide (kg)	0.945	1.328	0.423	-	1.556	1.018	2.493	3.300	-	9.876	1.598	Survey
Polypropylene (kg)	0.886	1.345	0.988	0.723	1.513	1.845	3.416	1.201	0.333	3.184	1.482	Survey
Polyethylene, high density (kg)	0.070	0.049	0.049	0.068	0.126	0.144	0.078	0.023	0.042	0.045	0.041	Survey
Transport, lorry 7.5-16 t (tkm)	26.698	18.953	12.345	26.513	20.761	24.518	92.945	27.276	13.415	13.374	13.451	Survey
Soil Management												
Harrowing (ha)	1.000	0.333	0.500	1.000	1.000	2.500	1.330	1.400	2.000	1.000	3.000	Survey
Ploughing (ha)	-	0.660	0.660	-	1.500	1.500	1.500	-	-	-	2.000	Survey
Tillage (ha)	-	0.660	0.500	-	1.500	1.500	2.000	0.700	1.000	1.000	2.000	Survey
Mowing (ha)	0.500	0.500	-	0.500	-	-	-	0.600	0.500	0.500	-	Survey
Transport, lorry 7.5-16 t (tkm)	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	0.081	PEFCR
Occupation, permanent crop (ha)	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	PEFCR
Pruning												
Transport, tractor and trailer (tkm)	0.131	0.105	0.125	0.131	0.158	0.162	0.153	0.164	0.341	-	0.349	Survey
Agricultural machinery (kg)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	PEFCR
Fertilizing*												
Nitrogen fertilizer (kg N)	-	29.613	-	37.605	36.000	-	-	60.948	7.426	64.300	0.950	Survey
Potassium fertilizer (kg)	-	19.562	0.102	37.650	44.000	0.401	-	80.623	4.195	64.300	2.826	Survey
Phosphate fertilizer (kg)	0.014	12.423	0.019	37.700	34.667	-	-	41.435	2.365	64.300	0.875	Survey
Ammonium sulfate (kg)	95.627	-	-	-	-	70.924	-	-	-	-	-	Survey
Potassium nitrate (kg)	8.208	10.542	-	-	-	9.145	-	-	-	28.000	54.267	Survey

Urea (kg)	3.437	25.681	-	0.105	-	0.172	462.651	0.796	14.208	-	364.238	Survey
Ammonium phosphate (kg)	3.860	-	-	-	-	-	-	-	-	12.800	23.564	Survey
Transport, lorry 7.5-16 t (tkm)	49.351	42.156	0.069	48.154	48.742	32.102	105.649	78.104	12.024	59.400	188.642	Survey

*Products considered are the main active substances present in different products, sometimes in a low proportion considering the application rate.

Annex 2. Life cycle inventory of VOOs production.

Inventory data per 1.000 kg of VOOs	Unit	Quantity	Data source
Olive oil extraction			
Olives	kg	4,819.74	Survey
Electricity	kWh	156.13	Survey
Water	m^3	2.02	Survey
Cellulose fiber	kg	1.11	PEFCR
Olive stones	kg	61.18	Survey
Transport with tractor and trailer	tkm	19.57	Survey
Petrol	kg	0.01	Survey
Lubricating oil	kg	0.07	Survey
Cleaning products	kg	0.36	Survey
Dedicated portion of facilities (average)	u	$6.47\ 10^{-6}$	Survey
Pomace treatment			
Exhausted pomace	kg	596.10	Survey / PEFCR
Electricity	kWh	69.61	Survey / PEFCR
Water	m^3	177.72	Survey / PEFCR
Transport with lorry 16-32 ton	tkm	71.09	Survey / PEFCR
Hexane	kg	5.55	Survey / PEFCR
Dedicated portion of facilities (average)	u	$2.06\ 10^{-7}$	Survey / PEFCR
By-products generation (outputs)			
Olive stones	kg	346.71	Survey
Crude pomace	kg	156.04	Survey / PEFCR
Exhausted pomace	kg	1,222.46	Survey / PEFCR