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Assessing variability in carbon footprint throughout the food supply chain: a case study of Valencian oranges

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ABSTRACT

PURPOSE: This study aims to analyse the variability in the carbon footprint (CF) of organically and conventionally produced Valencian oranges (Spain), including both farming and post-harvest (PH) stages. At the same time, two issues regarding sample representativeness are addressed: how to determine confidence intervals from small samples and how to calculate the aggregated mean CF (and its variability) when the inventory is derived from different sources.

METHODS: The functional unit was 1 kg of oranges at a European distribution centre. Farming data come from a survey of two samples of organic and conventional farms; PH data come from one PH centre; and data on exportation to the main European markets were obtained from official secondary sources. To assess the variability of the farming subsystem, a bootstrap of the mean CF was performed. The variability of the PH subsystem was assessed through a Monte Carlo simulation and a subsequent subsampling bootstrap. A weighted discrete distribution of the CF of transport and end-of-life (EoL) was built, which was also bootstrapped. The empirical distribution of the overall CF was obtained by summing all iterations of the three bootstrap procedures of the subsystems.

RESULTS AND DISCUSSION: The CF of the baseline scenarios for conventional and organic production were 0.82 and 0.67 kg CO_2 equivalent·kg orange^{-1}, respectively; the difference between their values was due mainly to differences in the farming subsystem. Distribution and EoL was the subsystem contributing the most to the CF (59.3% and 75.7% of the total CF for conventional and organic oranges, respectively), followed by the farming subsystem (34.1% and 19.8% for conventional and organic oranges, respectively). The confidence intervals for the CF of oranges were 0.72-0.92 and 0.61-0.82 kg CO_2 equivalent·kg orange^{-1} for conventional and organic oranges, respectively, and a significant difference was found between them. If organic production were to reach 50% of the total exported production, the CF would be reduced by 5.4-8.4%.

CONCLUSIONS: The case study and the methods used show that bootstrap techniques can help to test for the existence of significant differences and estimate confidence intervals of the mean CF. Furthermore, these techniques allow several CF sources to be combined so as to estimate the uncertainty in the mean CF estimate. Assessing the variability in the mean CF (or in other environmental impacts) gives a more reliable measure of the mean impact.

Keywords: bootstrap, carbon footprint, confidence interval, variability, oranges, organic

1 Introduction

In the past few years, stakeholders have placed the carbon footprint (CF) of food products under increasing scrutiny, and many studies have been performed to calculate the CF of food (e.g. Iriarte et al. 2014; Heidari et al. 2017; Canellada et al. 2018). Studies, such as those by Weidema et al. (2008), Finkbeiner (2009) and Laurent et al. (2009), have analysed advantages and limitations of CF calculations and what is needed if they are to be improved. These authors agree that the main limitation of CF is that it focuses on one environmental impact only. As Jones et al. (2015) state, it "provides an emissions' benchmark against which mitigation targets can be set and progress measured". It can thus be considered as a transition indicator toward systematic use of more holistic approaches, such as life cycle assessment (LCA).

Inventory data are key in life cycle approaches (and, therefore, in CF). A relevant aspect concerning inventory data is the representativeness of the foreground system. Agricultural systems show a high degree of variability due not only to their dependence on farm features, such as soil type, the availability of water and nutrients and climate, but also to the numerous management decisions and variety of agricultural practices (Boone et al. 2016; Notarnicola et al. 2017). Therefore, primary data representativeness is a crucial aspect to be taken into account so as to capture this variability related to management practices and its influence on the farm yield. The results of LCAs exhibiting a high degree of variability demonstrate true differences among alternative production processes. This information can further guide system optimization, product development, and policy (Steinmann et al. 2014).

However, as Notarnicola et al. (2017) point out, agricultural LCA studies vary greatly depending on whether they consider sources of variability or not and, if so, how it is quantified. Many agricultural inventories are based on sampling, as it is usually not possible to measure all the subjects of a population (farms, in this case) (e.g. Backet et al. 2009; Boulard et al. 2011; Ribal et al. 2017). Sampling allows a population subgroup to be used to infer characteristics of the real population. In other studies in which a representative data sample of the foreground system is not available, the foreground system is modelled to create representative scenarios. These scenarios can be based on statistics, literature, expert opinion or systems models (Boone et al. 2016; Sanjuan et al. 2005; da Silva et al. 2010; Williams et al. 2010). Monte Carlo simulation is one of the methods applied most often to analyse not only uncertainty in parameters and emission factors but also variability in farming and systems (Chen and Corson 2014; Renouf et al. 2010; Röös et al. 2010). Heijungs and Huijbregts (2004) include Monte Carlo simulation among sampling methods which use computing power to repeat calculations many times. In this way, a sample of results can be obtained, and its statistical properties can be analysed. In fact, Monte Carlo simulation yields a distribution of possible values for each inventory parameter, which can be used to generate a distribution of possible values for each impact category indicator and confidence intervals. This variability estimation can also be used to test hypotheses in a relative manner, as proposed by Henriksson (2015).

Variability can also affect factors within other life cycle stages, such as processing conditions, type of packaging, transport distance and duration of refrigerated storage (Keyes et al. 2015; Meneses et al. 2012; Meneses et al. 2016; Röös et al. 2011). As regards processing, agricultural production is more segmented in many countries than the food processing sector. It is a "many-to-few" relationship with many farmers and few processing companies. This can be explained by the need for high capital expenditures and the search for economies of scale. This "many-to-few" relationship means that variability in the first link of the food supply chain is higher than that in the second link. Therefore, variability in processing is expected to be lower than that of raw material production and thus influence measurement of the overall variability in the mean CF.

Previous studies of the CF and LCA of citrus in the main producer countries (i.e. Brazil, Italy and Spain) have focused on the agricultural stage (Bessou et al. 2016; Coltro et al. 2009; Pergola et al. 2013) and also on juice (Beccali et al. 2009; Knudsen et al. 2011). Analysis of the literature emphasises that researchers have paid little attention to PH stages of citrus for fresh consumption; to our knowledge, only lo Giudice et al. (2013) and Nicolo et al. (2017) assessed the PH treatment of oranges, although they did not address the variability issue.

As Spain, specifically its Comunitat Valenciana region, is a large producer and exporter of oranges, there is a need to assess the entire CF of oranges. Citrus production in the Comunitat Valenciana consists mainly of oranges and mandarins for fresh consumption. In 2015, the area devoted to citrus cultivation in the region was 162,888 ha, with a production of 3.12 million t (CAMACCRD 2017a). Most of this production is exported to other countries (93.5% of total production in 2015, i.e., 2.92 million t), mainly in the European Union (EU) (CAMACCRD 2017a). The production of organic citrus, although still low, has increased 186% in the past 15 years, with a production of 26,894 t in 2016 (CAMACCDR 2017b), which was also mostly exported to EU countries.

The citrus sector in the Comunitat Valenciana expanded during the 20th century, and it has been the cornerstone of the economy in the region for many years. However, it is currently facing many problems, one of which is related to the concentration of the distribution and retail stages. It must be noted that, in the framework of the food system, the ownership of supply chains of agricultural and food products is becoming more concentrated (Henson and Reardon, 2005), and supermarkets dominate the retail distribution of food in several European countries (Josling, 2002). Poore and Nemeck (2018) state that processors and retailers make up concentrated markets. Consequently, retail distribution takes many of the decisions related to the food supply chain and leads its overall strategy. In the Valencian citrus sector, this has affected orange exporter companies, which are in charge of the harvest, PH treatment and export of the oranges to wholesale markets, with subsequent consequences for farmers (mainly price-related). The number of exporters boomed in the 1960s but has decreased since the 1970s, when food distribution in Europe began to be concentrated among a few companies. In this regard, Van der Krogt et al. (2007) state that one of the major structural developments in the agri-food industry in recent years is the wave of consolidations through mergers, acquisitions and alliances.

In a previous LCA study, Ribal et al. (2017) estimated variability in environmental impacts of organic and conventional citrus farming in the province of Valencia (Spain) to highlight the influence of management practices (i.e., within-group variability, (Huijbregts, 1998)) on environmental impacts of agriculture. Considering the importance of transport in the supply chains of vegetable products, and to contribute to assessment of the CF of foods, we went a step further in this study and analysed variability in PH stages and their influence on the CF of Valencian oranges. At the same time, this case study addresses two questions regarding sample representativeness. The first question refers to the existence of a significant difference between the mean CF based on two small samples, that is, how to calculate confidence intervals when only small samples are available. The second question to be answered is how to obtain the aggregated mean value (and its variability) of the CF when the inventory is derived from different sources.

2 Methods

The case study aims to determine the CF of Navel oranges (*Citrus sinensis* (L.) Osbeck) at the entrance gate of a European distribution centre, comparing oranges from conventional and organic production and assessing the variability in the CF of both farming systems.

Specifically, cultivars corresponding to early- and mid-season oranges were considered, such as Navelina, Newhall, Navel, Navel Late, Navel Lane Late, Navel Powell. The rationale underlying the selection of this group of cultivars is that it is the most widespread of the sweet oranges, covering 82% of the registered area of sweet oranges in the Comunitat Valenciana in 2015 and 81% of its production (CAMACCDR 2017a).

2.1. Functional unit and system boundaries

In accordance with the scope of the study (i.e. orange production), the functional unit chosen was 1 kg of Navel oranges at a European distribution centre entrance gate. Within the system boundaries, the foreground system comprises three subsystems: (1) farming, which includes agricultural practices and agricultural input production; (2) PH treatment, which includes the transport of oranges to the PH centre, PH treatment and packaging production; and (3) distribution and end-of-life (EoL), which includes export of the oranges to European countries and treatment of packaging waste after selling the oranges (Fig. 1). The manufacturing and maintenance of machinery, buildings and equipment were excluded, according to PAS 2050-1 (BSI 2012). Consumption of oranges was excluded due to lack of reliable data and to the relatively low impact of this stage, as previously shown for other fruits (Vinyes et al. 2017).

As for temporal boundaries, the farming data correspond to the 2012-2013 season. However, to include the variability of parameters such as the price of commercial oranges and their co-products, the exported quantities or the kind of packaging material, data corresponding to a longer range of years were included, depending on their availability.

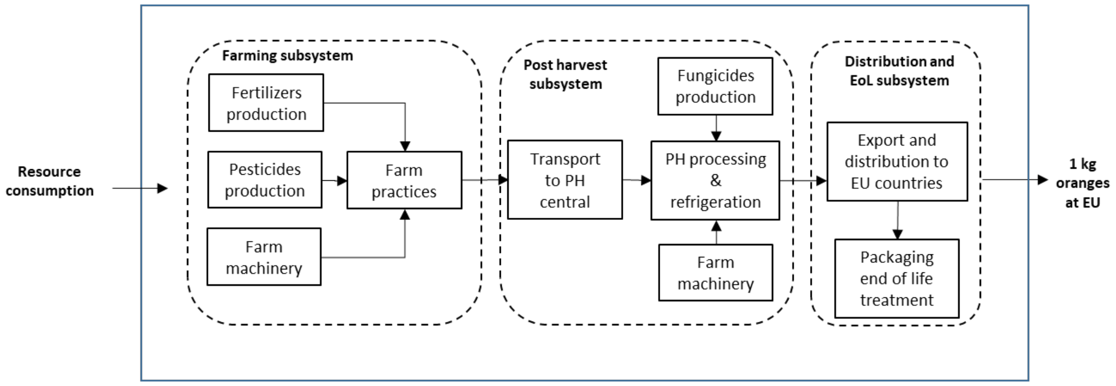

Figure 1. System boundaries and subsystems considered in the study

2.2 System description

2.2.1 Farming subsystem

In this subsystem, field-work processes at a typical orange farm in the region were assumed for both organic and conventional production, as described by Ribal et al. (2017). In their study, 267 Valencian citrus farmers were surveyed. From their responses, farms producing only navel cultivars were selected: 21 organic and 23 conventional farms, with a mean area of 0.83 and 1.46 ha, respectively.

To detect possible outliers, boxplots of the CF of oranges from both types of farms were produced, which indicated that farms P1, P2 and P3 were potential outliers (Fig. 2a). In addition, each farm's CF of oranges was plotted against its total production (Fig. 2b), area (Fig. 2c) and yield (Fig. 2d), providing additional information about potential outliers. Finally, the absolute deviation around the median (median absolute deviation (MAD)) was calculated for the CF of oranges to identify univariate outliers (Leys et al. 2013).

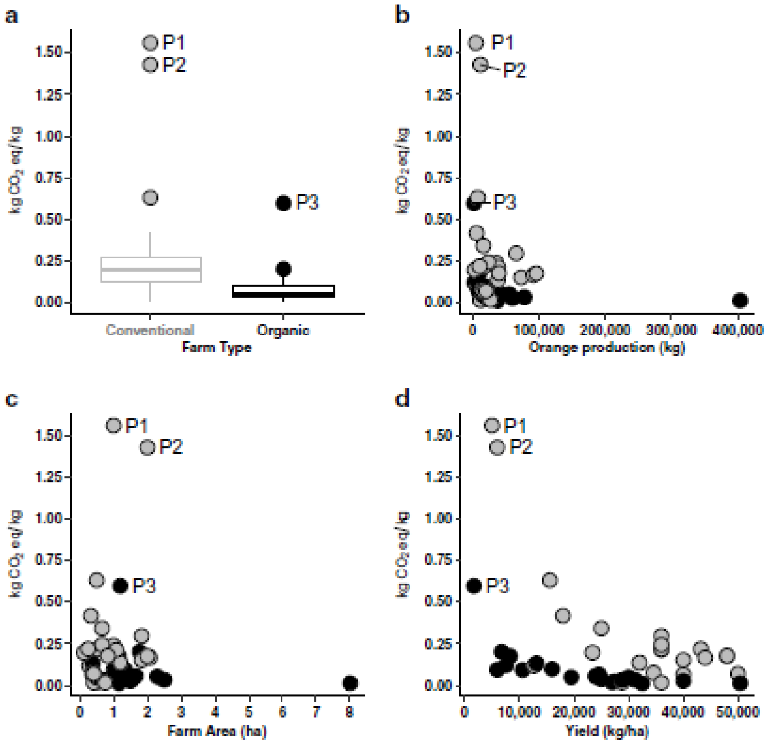

Figure 2. Contribution of the farming subsystem to the carbon footprint (CF) of conventional (grey) and organic (black) orange farms. Original sample farms. A: Conventional and organic CF boxplots. B: CF vs. orange production (kg). C: CF vs. farm area (ha). D: CF vs. farm yield (kg ha^{-1}).

MAD was calculated assuming a log-normal distribution. Based on a threshold of ±3 times MAD, only two conventional farms (P1 and P2) were considered outliers. Consequently, they were removed from the original sample, leaving 21 organic and 21 conventional farms. The mean, standard deviation, and minimum and maximum value of each characteristic of the studied farms are presented in Table 1.

All data came from farms with trees in full production, which best represent the practices, material inputs and environmental impacts. In an LCA of Moroccan oranges, Bessou et al. (2016) observed an alternating yield phenomenon and recommended including part of the inter-annual variability using representative means. Nevertheless, this alternating yield depends on the orange cultivar and management practices; in practice, Valencian farmers avoid this phenomenon by performing chemical or manual thinning (Agustí et al. 2002).

The specific harvest moment depends not only on the orange cultivar, but also on other factors, such as the weather conditions, cultivation site and, therefore, the degree of ripeness of the fruit. As the Navel group comprises a great variety of cultivars, one can find early oranges, such as Newhall (harvest from mid-October to mid-January), and late ones, such as Navel Late (harvest from late January to late March) or Navel Lane Late (harvest from late January to mid-April) (Pardo et al. 2016).

Table 1. Main characteristics per year of the sample conventional and organic orange farms studied (n = 21 of each)

		Conventional				Organic			
Characteristic	Unit	Mean	Std. dev	Min.	Max.	Mean	Std. dev	Min.	Max.
Area	ha	0.8	0.6	0.1	2.1	1.5	1.6	0.3	8.0
Yield	kg/ha	34,251	10,489	12,700	50,000	21,647	12,363	1,700	50,400
Pesticides	L active ingredient/ha	20.9	16.6	0.0	61.8	28.1	32.5	0.0	93.6
Chemical fertilisers	kg N/ha	155.2	82.9	13.0	336.0	0.0	0.0	0.0	0.0
	kg P_2O_5/ha	36.3	29.8	0.0	90.0	0.1	0.3	0.0	1.2
	kg K_2O/ha	85.9	49.4	0.0	161.0	6.4	27.2	0.0	124.8
Manure	kg/ha	643.4	48.0	0.0	125.0	14,348	10,416	583	30,405
	kg N/ha	0.5	1.0	0.0	3.9	96.3	55.4	0.7	193.1
Diesel	MJ/ha	1,574.0	1,042.7	0.0	3,974.0	4,626.0	2,931.0	0.0	13,604.0
Petrol	MJ/ha	29.0	132.7	0.0	608.0	661.0	762.1	0.0	2,517.8

2.2.2 PH treatment subsystem

The harvested oranges are packed in high density polyethylene (HDPE) crates containing ca. 20 kg of fruit and transported by truck to the PH centre. Although exporting companies buy oranges throughout the region, we assumed that they focus on a mean radius of 80 km, with a maximum distance of 200 km and a minimum of 10 km (if oranges are bought in the same town as the centre). This distance variability was included in the subsequent variability assessment. The HDPE crates are reused in the same PH centre (closed loop). On average, each box is refilled 90 times per year and has a lifetime of 12 years.

Upon arrival at the PH centre, fruits are weighed and discharged in loading bays to identify the delivery. The oranges then pass through PH treatment (Fig. 3). First, the crates pass to the drencher, where the fruits are treated with a solution of water and fungicides (Thiabendazole, Imazalil and Fosetyl-Al). In this way, the oranges can be stored in refrigerated chambers at 4.5ºC when they cannot enter the following process steps directly. On average, 17.5% of the oranges are refrigerated before completing the PH treatment. This value was calculated by assuming that Navel oranges harvested at the beginning (September and October) and end (April) of the season are more likely to be stored. Therefore, the total production of Navel oranges (CAMACCRD 2017a) was multiplied by the mean percentage of oranges exported during these months each year (2012-2016; FEPEX 2017). The mean refrigeration duration is 3 days.

The fruits are then dumped onto a conveyor belt and carried to a washing pool with soap, whereas, before being reused, the HDPE crates are cleaned in a washing machine. The oranges are subsequently pre-dried, and then those with unstable defects are sorted by hand. These fruits (4.75% of the oranges entering the process, on average) are normally used to produce fodder. Wax with fungicides (Thiabendazole, Imazalil) is applied to the remaining fruits, and they are then dried in a tunnel and once more sorted by hand. This second sorting process focuses on oranges with stable defects (mostly defects in appearance). These fruits (11% of the oranges entering the process, on average) are sold for orange juice production. The oranges that pass the second sorting are calibrated and packed according to size. The packaging is weighed and palletized. Until they are transported to the distribution centre, 6.8% of the oranges are stored in a refrigerated chamber at 4.5ºC for ca. 4 days, although the duration can vary from 1-60 days depending on the season and market conditions. As the oranges harvested at the end of the season are more likely to be stored to extend the sales season, the percentage of oranges refrigerated was estimated as the mean percentage of oranges exported in April for the years 2012-2016 (FEPEX 2017). The contribution of refrigerant leakage to the CF was not included as most refrigerated chambers in the region use ammonia, which is not a greenhouse gas (GHG).

This is the basic PH process; nevertheless, at the beginning of harvesting, oranges can appear green but have the right degree of ripeness (measured by sugar:acid ratio) and thus be subjected to a degreening treatment. This treatment is performed in a chamber with a continuous flow-through system with ethylene (2-5 ppm) at 20-22ºC, which accelerates the change in colour of the fruit from green to orange (Martínez-Jávega et al., 2007). The mean duration of degreening is 2.5 days, although it can vary from 1-4 days. On average, 12% of oranges are subjected to degreening. As only the early cultivars harvested in October are treated, the percentage of degreened oranges was calculated as the mean percentage of oranges exported in October for the years 2012-2016 (FEPEX 2017).

The PH system differs for organic oranges in that the degreening treatment is not permitted by EU regulations and that only authorised fungicides can be used in the drencher and wax application (European Union, 2008).

Once treated, the oranges are packed in either wooden or cardboard boxes, which are used once, or in re-useable plastic (polypropylene) crates integrated in a plastic pool system, which are increasingly used. The size and material of the packaging depends on the destination country and the customer. In this study, 15-kg orange boxes, the most common, were assumed. As to the packaging material, data from Anecoop (pers. comm.), an association of most of the agricultural cooperatives in the region, for the 2015-2016 season were used: 52% of the oranges were exported in cardboard boxes, 32% in plastic crates, and 16% in wooden boxes. For the variability assessment, the maximum and minimum values of these percentages corresponding to the period 2004-2005 to 2015-2016 were used. For the plastic crates, a lifetime of 10 years and five fillings per year were assumed, following Albrecht et al. (2013). The maximum and minimum values of this parameter were taken from the same source.

2.2.3 Distribution and EoL subsystem

Trucks refrigerated at 6-7ºC transport the packaged oranges to European countries, the main destination of Spanish oranges. Based on official data on the quantity of oranges exported to European countries from CAMACCDR (2017a) and the main distribution markets in each country, the transport distance for the baseline scenario was calculated as a weighted mean of the distance to multiple European destinations (1,826 km). Table 2 shows the main countries importing Valencian oranges, the main distribution markets in those countries, the relative weight (percentage) of exports to each country (by mass), and the distance from the city of Valencia to each main distribution market. The return trip was excluded, as backhaul rates are commonly high. The minimum and maximum weighted distances corresponded to Rome, Italy, and Warsaw, Poland. Due to a lack of official data on organic orange exportation, the same weighted mean distance was used for these oranges. Refrigerant (R134) leakage during transport was considered, as it is included in the process from ecoinvent 3.4 used.

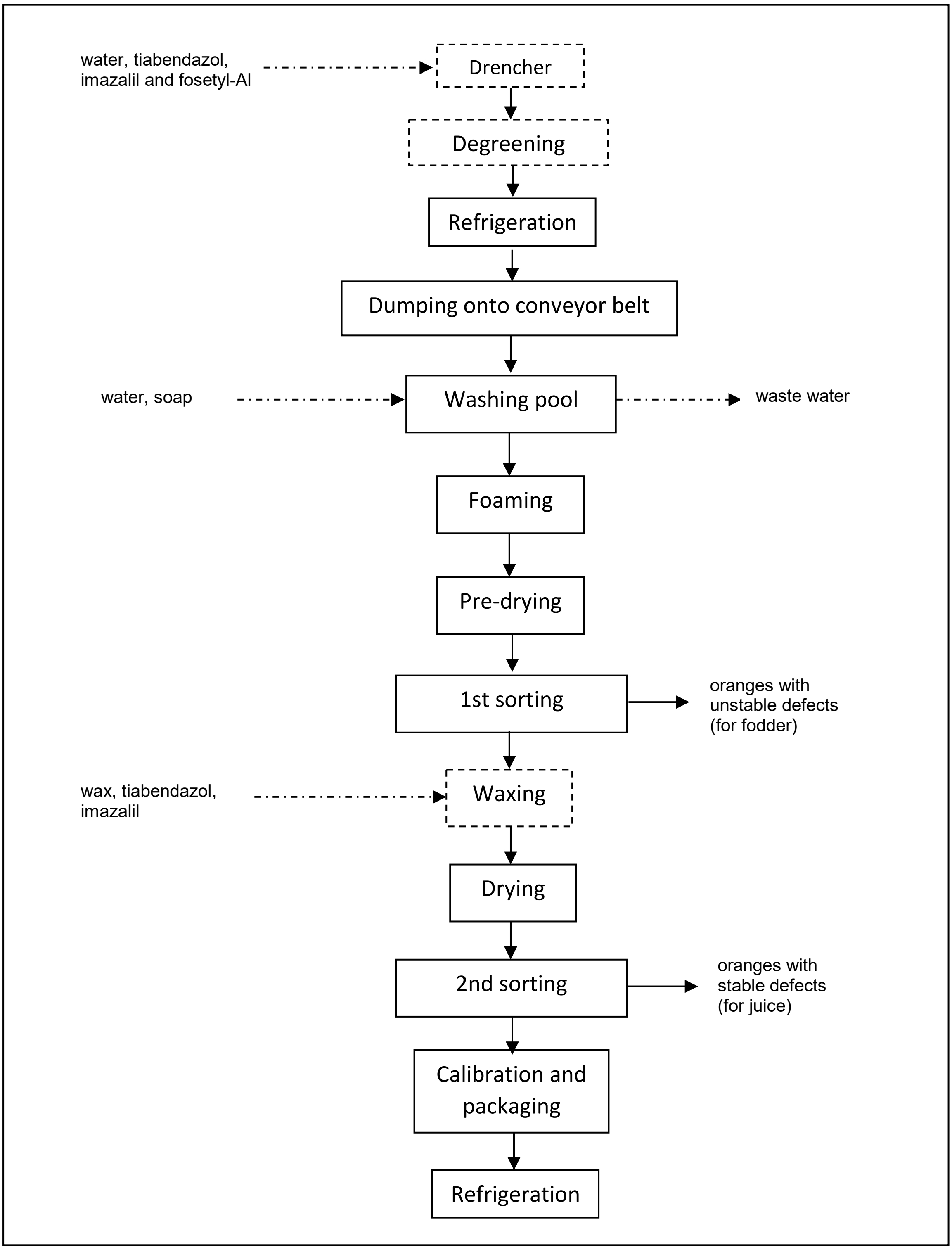

Figure 3. Flowchart of post-harvest treatment of the oranges. Process steps outlined in dashed lines are those that are avoided (degreening) for organic oranges or require authorised additives (drencher and waxing)

Different EoL options for packaging waste were considered. Cardboard boxes and plastic crates can be either recycled or incinerated with energy recovery, whereas wooden boxes can be recycled into particleboard or incinerated with energy recovery. Recycling rates for each type of packaging were set based on those for packaging waste in the EU28 for 2015 (Eurostat, 2018a): 39.9% for plastic, 83% for cardboard, and 40.1% for wood. Incineration rates were 31.4% for plastic, 7.7% for cardboard, and 25.7% for wood. These values were set by subtracting recycling rates from recovery rates in the EU28 for 2015 (Eurostat 2018b), as recycling is a kind of recovery. For the variability assessment of recycling the highest rates in 2015 of the importing countries considered were used to set the maximum rates: Slovenia for plastic (63.4% recycling), Denmark for cardboard (95.3% recycling) and Portugal for wood (86.5% recycling). The minimum rates correspond to the minimum recycling targets for packaging waste reported in EU Directive 94/62/EC: 22.5% by weight for plastics, 60% by weight for paper and cardboard, and 15% by weight for wood. As to the variability in incineration, the maximum and minimum rates of the importing countries considered in 2015 were also calculated as the difference between the recovery and the recycling rates. The resulting maximum incineration rates for each kind of packaging were those of Denmark (67.4%) for plastic, Luxembourg (21.6%) for cardboard, and Norway (85.6%) for wood. In contrast, the minimum incineration rate was 0% for all of the packaging materials, corresponding to Bulgaria, Croatia, and Lithuania for plastic; the same countries plus Sweden for cardboard; and Bulgaria, Croatia, and the United Kingdom for wood.

Table 2. Main countries importing Valencian oranges, main distribution market in each country, relative weight (percentage) of the export market (by mass) and road distance from the city of Valencia to the main distribution market of each country.

Country	Main distribution market	% export weight (by mass)	Distance from Valencia to main distribution market (km)
Germany	Frankfurt	26.72	1671
France	Paris	24.98	1412
Netherlands	Amsterdam	9.00	1875
Italy	Rome	7.40	1696
United Kingdom	London	6.50	1833
Poland	Warsaw	5.25	2693
Belgium	Brussels	3.98	1687
Sweden	Stockholm	3.16	3127
Czech Republic	Prague	2.45	2060
Switzerland	Zurich	1.82	1402
Norway	Oslo	1.38	2970
Austria	Vienna	1.19	2140
Denmark	Copenhagen	1.05	2482
Slovakia	Bratislava	0.74	2226
Croatia	Zagreb	0.63	1933
Hungary	Budapest	0.63	2262
Romania	Bucharest	0.58	3085
Lithuania	Vilnius	0.55	3144
Finland	Helsinki	0.53	3740
Portugal	Lisbon	0.42	881
Slovenia	Ljubljana	0.34	1800
Ireland	Dublin	0.33	2422
Latvia	Riga	0.19	3341
Estonia	Tallinn	0.08	3653
Luxembourg	Luxembourg	0.07	1494
Bulgaria	Sofia	0.04	2715
Greece	Athens	0.01	2985

2.3 Allocation

As described, the main output of the PH process is the oranges for fresh consumption to be exported, but there are also the two by-products: the oranges with unstable defects and the ones with stable defects. As these by-products have different functions, according to PAS 2050-1 (BSI, 2012), economic allocation was performed based on the price of each by-product at the exit gate of the PH centre.

The mean price of conventional and organic oranges for fresh consumption was 0.53 and 0.69 € kg^{-1}, respectively. These prices were obtained from official statistics of the Comunitat Valenciana (CAMACCRD 2017a) and Andalucía (CAPDR 2017) for conventional and organic oranges, respectively. Minimum and maximum prices for 2012-2015 were used in the variability analysis. The income from conventional and organic oranges sold for juice production was 0.09 and 0.11 € kg^{-1}, respectively (A. Puchol, Frío Mediterráneo S.A. Museros (Spain), pers. comm.), whereas oranges for fodder production had no economic value. In the resulting allocation, 97.8% and 98.3% of inputs were allocated to the functional unit of conventional and organic oranges, respectively.

2.4 Data sources

As mentioned (section 2.2.1), data for the farming stage were elicited from surveys of orange producers. Calculation of additional inventory data (e.g. direct and indirect N_2O emissions from fertilisers, emissions from fertiliser and pesticide production) and other related assumptions are explained by Ribal et al. (2016).

Data for the PH process (energy consumption of equipment) were elicited from one representative PH centre in the region, which exports both organic and conventional citrus. As mentioned, we assumed typical citrus production in the region, with many farms and few exporting companies. Other primary data, such as prices, production of oranges in the region and the quantity of oranges exported were obtained from the official sources previously cited. All relevant background data such as energy, transport, chemicals (fungicides and detergents) and packaging materials (boxes and wooden pallets) were taken from ecoinvent 3.2, whereas treatment processes for packaging waste were taken from the GaBi professional database. Table 3 summarises the main inventory data of PH treatment, packaging EoL, and exportation subsystems, as well as their sources. The baseline value of each was a central position statistic (mean, mode, or median), which was used along with maximum and minimum values in the subsequent variability analysis.

2.5 Analysis of variability in mean CF

Variability in the mean estimate of the CF is the standard error of the mean; this standard error should not be mistaken for the variability in the CF. It provides information about the expected size of the error related to the mean estimate. As mentioned, two issues regarding sample representativeness were addressed in this case study: the small sample size and the integration of data from multiple sources. Both issues were addressed using bootstrap methods.

Bootstrapping is one of a larger group of methods that resample from an original data set and, thus, are called resampling procedures (Chernick 2008). Bootstrapping makes no parametric assumptions; hence, it is a non-parametric method. Non-parametric statistics do not assume any functional shape in the variable distribution. Heijungs and Huijbregts (2004) classify non-parametric statistics as a non-traditional method to address uncertainty, which is not included in the classic statistical curriculum. Bootstrapping provides information about the distribution of the sample and allows confidence intervals to be built (Chernick and LaBudde 2011).

To assess variability in the mean CF of conventional and organic oranges, the variability of each of the three subsystems (farming, PH, and distribution/EoL) was evaluated separately. For the farming subsystem, a bootstrap of the mean CF was performed with 10,000 iterations, yielding an empirical distribution of the average CFP of that subsystem and the confidence interval. As we had a sample of farms for each kind of orange, we applied a regular bootstrap to the two small samples. One 10,000 × 1 matrix was obtained for each type, which is the empirical distribution of the mean CF of the farming subsystem.

To study variability in the PH subsystem, Monte Carlo simulation was performed considering the main process parameters and their distribution for conventional and organic oranges (Table 3). For a given parameter, the baseline probability distribution showed the best current knowledge about the variability in the input (Lacirignola et al. 2017). The truncated Gaussian distribution from GaBi software was used to avoid negative values or values tending to infinity.

Once the distribution of the CF for the PH process is simulated, calculating the standard error of mean CF is not trivial. Chernick et al. (2011) explain that sampling independently with replacement in a dependent situation (i.e. the PH stage) creates estimates with less variability than that in the original data. It is known that the standard error of the mean is a function of the sample size. For the PH stage, the size is the number of simulations of the Monte Carlo simulation, which can be as large as desired. To address this issue the sample size of the PH stage was related to the size of the farm sample using iterative resampling with a size equal to the number of real observations in the farm stage. This is actually subsampling, which assumed that 1 kg of oranges of each farm of the group of 21 was received at the PH centre, and that each of them had a random CF according to the Monte Carlo distribution of the PH stage. The mean of these 21 random CFs was a possible mean CF. This procedure was repeated 10,000 times, yielding 10,000 possible mean CFs at the end of the iteration process in order to calculate a reliable standard error.

For example, conventional production had a subsample size of 21, the same as the number of farms. Thus, 21 random CF observations were obtained from the Monte Carlo simulation of the PH CF; then, the mean CF of these 21 observations was calculated and recorded. The size of the primary source (i.e. the farm survey) is the limiting one. If this procedure is repeated 10,000 times, one 10,000 × 1 matrix is obtained for each type of production, which is the empirical distribution of the mean CF of the PH subsystem.

For the export to European countries, a discrete distribution of transport distance was built from the quantities exported and the distances to the European destinations, which was subsequently transformed into a discrete distribution of the CF of exportation per functional unit. Thereafter, a subsampling procedure similar to the one applied to the PH subsystem was performed, obtaining one 10,000 × 1 matrix for each type of orange, which is the empirical distribution of the mean CF of the exportation; according to the central limit theorem, this distribution tends to be normal.

The empirical distribution of the overall CF was obtained by adding up piece-wise each iteration of the three bootstrap procedures of the subsystems for both conventional and organic production. The iterations for each subsystem were independent of those for the other subsystems and independent between the two production types. However, the sample size of the farming subsystem influenced the subsampling of the other two subsystems. Fig. 4 summarizes the entire procedure.

There are several ways to determine the confidence interval of the mean CF. Chernick and Labbude (2011) state that in small and moderate samples, the percentile method is not suitable for asymmetric distributions and that some modifications are needed. The bootstrap-t percentile method was applied, as it is easier to use than other methods, which are more complicated and computer-intensive (Chernick 2008).

Table 3. Baseline values, minimum and maximum of the key parameters for the Monte Carlo analysis

Parameter	**Min.**	**Max.**	**Baseline**	**Source**
Distance from farm to post-harvest (PH) centre (km)	10	200	80	Assumption
% Degreened oranges (only conventional oranges)	2.70	3.33	2.97	FEPEX (2017)
Degreening time (days) (only conventional oranges)	1	4	2.5	Martínez-Jávega et al. (2007)
% oranges refrigerated before PH	5	30	17.5	FEPEX (2017) CAMACCDR (2017^{a})
Refrigeration before PH (days)	1	30	3	A. Puchol (Frío Mediterráneo S.A. Museros (Spain), pers. comm.)
Line processing capacity (kg h^{-1})	43500	64000	53750	A. Puchol (pers. comm.)
% oranges refrigerated after PH	0	15	6.8	FEPEX (2017) CAMACCDR (2017^{a})
Refrigeration after PH (days)	1	60	4	A. Puchol (pers. comm.)
Distance to market (km)	1319	2693	1770	Google Maps (2018)
Price of conventional oranges at the gate of PH centre (CIF* price, €)	0.45	0.58	0.53	CAMACCDR (2017^{a})
Price of organic oranges at the gate of PH centre (CIF price, €)	0.62	0.69	0.72	CAPDR (2017)
Price of juice from conventional oranges (€)	0.06	0.12	0.09	A. Puchol (pers. comm.)
Price of juice from organic oranges (€)	0.07	0.15	0.11	
% oranges with unstable defects	0.5	9.0	4.75	
% oranges with stable defects	2	20	11	
% cardboard boxes	52	63	60	Anecoop (pers. comm.)
% wooden boxes	15	24	18	
% plastic crates	13	33	22	
Lifetime of plastic crates (years)	6	10	10	Albrecht et al. (2013)
% cardboard boxes incinerated	0	13.6	7.7	Eurostat (2018a; 2018b)
% cardboard boxes recycled	60	90.7	83	
% wooden boxes incinerated	0	77.8	25.7	
% wood recycled to particle board	15	74.9	40.1	
% plastic crates recycled	22.5	61.7	39.9	
% plastic crates incinerated	8.5	55.7	31.4	

*CIF: Cost, insurance, and freight

3 Results and discussion

3.1 Mean CF of conventional and organic oranges

For conventional oranges, the distribution and EoL subsystem contributed the most to the CF (59.4% of the total baseline CF (Table 4). This is due to the use of refrigerated trucks for exportation to Europe, whereas the EoL treatment of the packaging after selling the product had a negative value due to avoided loads (electricity production from waste incineration). The farming subsystem also contributed a relatively large percentage to the CF of the oranges (34.1%). The PH subsystem contributed little to the CF (6.5%); for instance, transport of the oranges to the PH centre represented 2.5% of the total CF and the packaging production 3.7%; the PH treatment, however, was the stage with the lowest contribution (0.3%).

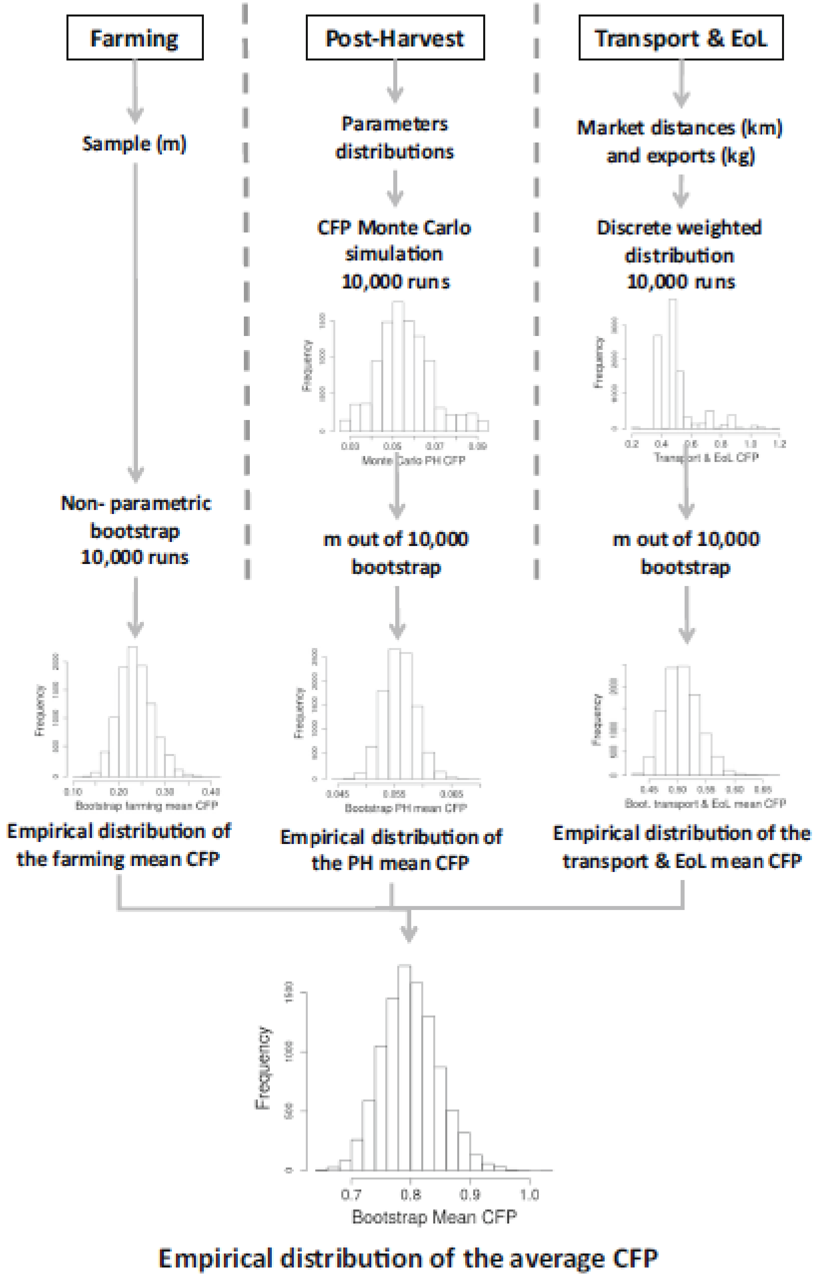

Figure 4. Procedure to integrate the variability in each subsystem into the variability in the mean total CF. EoL = end of life

The total baseline CF for organic oranges was 18% lower, (0.82 vs 0.67 kg CO_2 equiv·kg orange^{-1} for conventional and organic oranges, respectively). This was due mainly to differences in farming practices, and to a lesser degree, to differences in the PH treatment. Specifically, the distribution and EoL subsystem contributed 72.5% to the CF of organic oranges. It was followed by the farming subsystem, which contributed 19.7% to the CF of organic oranges and had a CF value (0.13 kg CO_2 equiv·kg orange^{-1}) 52.5% lower than that for conventional oranges. The PH subsystem contributed 7.8% to the CF of organic oranges and had a CF value (0.05 kg CO_2 equiv·kg orange^{-1}) 27% lower than that for conventional oranges.

As explained by Ribal et al. (2017), the difference in farming impact between conventional and organic oranges is attributed mainly to the use of manure as the only fertiliser on organic farms, thus avoiding chemical fertiliser production, which contributes a large percentage of the CF. As described, the lower contribution of the PH treatment for organic oranges is because no fungicides are used and no degreening is performed, although the latter represents only 0.3% of the CF of conventional oranges.

Table 4. Contribution of subsystem stages to the carbon footprint of conventionally and organically produced Navel oranges in baseline scenarios

Subsystem	Stage	**Conventional** (kg CO_2 equiv·kg orange^{-1})	**Organic** (kg CO_2 equiv·kg orange^{-1})
Farming	Farming	0.278	0.132
Post-harvest (PH)	Transport to PH centre	0.021	0.021
	PH treatment	0.003	0.002
	Packaging	0.030	0.030
Distribution and end-of-life	Exportation to Europe	0.506	0.506
	Packaging end-of-life	-0.020	-0.020
Total carbon footprint		0.815	0.668

3.2 Results of the variability analysis of the mean CF

The main results of the empirical distribution of the mean CF for each subsystem are summarised in Fig. 5, along with the total CF for both conventional and organic oranges. Mean CF of the conventional farming subsystem was greater than that of the organic one. To test the for the existence of statistical difference between them, the distribution of the difference in both empirical distributions was built, showing that this difference was positive in 99.31% of the cases, i.e. conventional farming contributed significantly more to the total CF than organic farming.

As explained, the mean CF of the PH subsystem is similar for the two types of oranges and is one order of magnitude lower than those of the other two subsystems. As expected, no statistical difference was found for this subsystem. The distribution and EoL subsystem contributed most to the CF and is significantly larger than the other two. This subsystem is assumed to be the same for both types of oranges; thus, there is no difference between them. Table 5 shows mean and standard error of the CF by production type and subsystem, along with mean endpoints of 95% confidence intervals. These means do not equal those calculated from the centre values of the distributions of the inventory parameters (Table 4).

Table 5. Endpoints of 95% confidence intervals of the mean carbon footprint for each subsystem and type of orange

Subsystem	Type	Mean	Std. error	2.5%	97.5%
Farming	Conventional	0.2363	0.0360	0.1772	0.3321
	Organic	0.1116	0.0318	0.0700	0.2518
Post-harvest	Conventional	0.0559	0.0028	0.0505	0.0626
	Organic	0.0565	0.0028	0.0510	0.0631
Distribution and end-of-life	Conventional	0.5077	0.0305	0.4587	0.6218
	Organic	0.5077	0.0305	0.4587	0.6218
Total	Conventional	0.8000	0.0473	0.7178	0.9199
	Organic	0.6758	0.0438	0.6050	0.8239

Testing for significant differences between both empirical distributions was straightforward. The null hypothesis was that the mean CF of the two production types did not differ significantly. Randomly subtracting the organic distribution from the conventional one yielded a new bootstrap distribution (Fig. 6). The zero-threshold showed 0.71% of cases (bootstrap iterations) in which the mean CF of the organic production was greater than the mean CF of the conventional production. Thus, the null hypothesis can be rejected at $\alpha = 0.01$, and there is a significant difference between the two production types. When the analysis was repeated without removing outliers, a significant difference was found at $\alpha = 0.01$ as well. The farming subsystem determines the existence of significant differences in total CF. The difference between the two types of production in the other subsystems is negligible. Despite this, the entire life cycle was checked to assess whether extreme cases could lead to an inability to reject the null hypothesis.

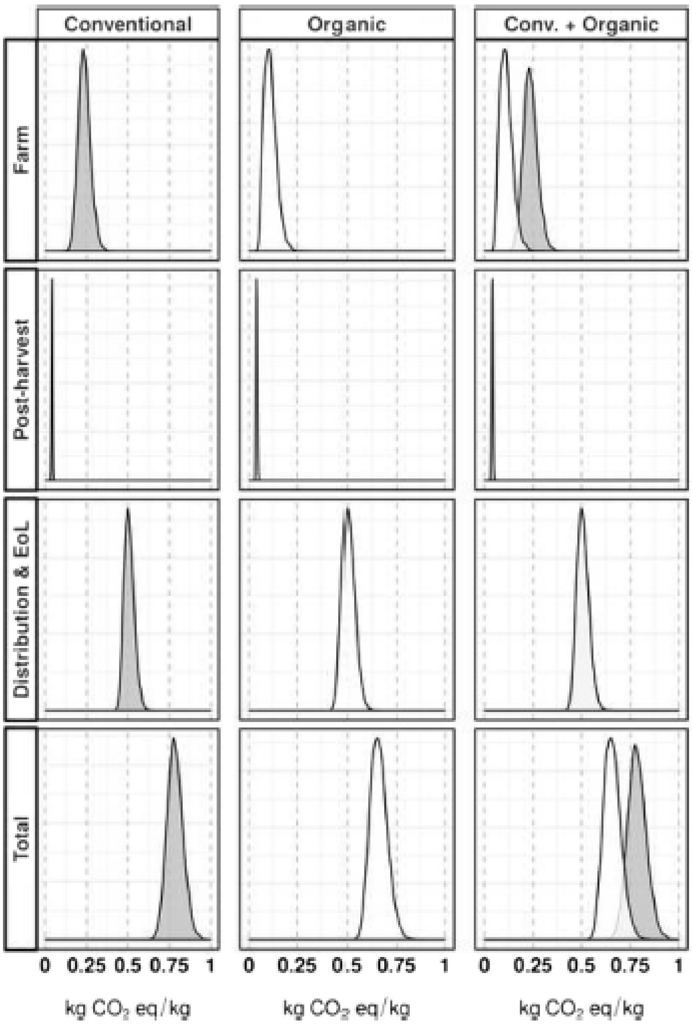

Figure 5. Mean empirical distribution of the carbon footprint (CF) of conventional and organic oranges as a function of stage and farming system

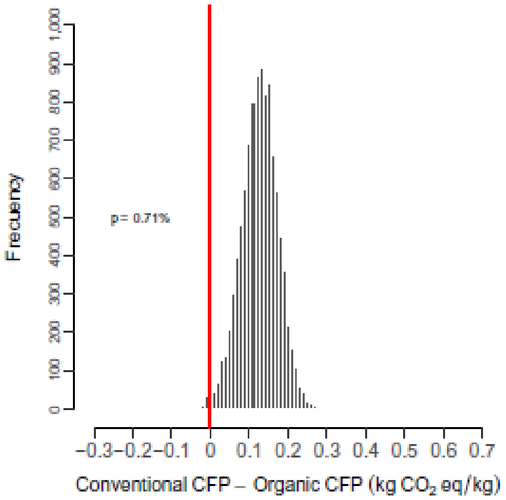

Figure 6. Empirical distribution of the difference in mean carbon footprint (CF) of conventional and organic oranges

3.3 Discussion

3.3.1 Overall CF of Valencian oranges exported to European countries.

LCA studies usually report mean impacts per functional unit for the system under study. Rightly so, as at a macro level, mean impact (for a given category) is the fundamental unit from which to estimate the total environmental impact (for a given category) of a company, region or country (e.g. Roibás et al. 2017). To estimate the CF in a reliable way, not only does the mean CF need to be calculated, but also its confidence interval. The confidence interval also allows statistical comparisons to be made, for instance, of different production years, geographical origins or products.

For example, in the present study, we can estimate the overall CF of the oranges exported from the Comunitat Valenciana (Spain) to other European countries and the most likely confidence interval for the CF if conventional farms change to organic production. Given the total exported production in 2016 (1.56 million t) and the confidence interval (Table 5), the total CF would lie in the range of 1.04-1.34 million t CO_2 equiv. If the percentage of organic production is changed, the expected confidence interval of the change in CF can be estimated. For instance, if organic production reaches 50% of total exported production, the CF would thus decrease by 5.4-8.4% (Table 6). It must be noted that this study focused on CF only; thus, consequences of a potential increase in organic production on land use or other impact categories should also be evaluated.

Table 6. Expected decrease in the 95% confidence interval of the carbon footprint of exported oranges as a function of the percentage of organic oranges exported (by mass)

	Decrease in confidence interval of the % CF reduction	
% Organic orange production	**2.5%**	**97.5%**
10%	1.0%	1.5%
50%	5.4%	8.4%
90%	10.3%	16.3%

This small confidence interval may seem disappointing, but more than half of the CF of oranges is due to transport, which cannot be decreased by changing the farming method. The relative importance of transport varies by type of food; it is much higher for fresh fruits and vegetables, as processing these products uses relatively less energy (Weber and Mathews, 2008).

Therefore, to reduce the difference in CF between organic and conventional oranges, measures to decrease GHG emissions in the farming stage should be implemented. However, to reduce the overall CF of both types of oranges, exportation is the key hotspot to address.

3.3.2. Comparison of the CF of oranges to those in other contexts

Results of the present study are consistent with those of other studies of oranges produced in other countries (Table 7). The influence of the system boundaries set should be kept in mind when comparing CF data, as by-products or fruit losses are not considered in studies whose boundaries are set at the farm gate, thus yielding a lower CF. Furthermore, Knudsen at al. (2011) and Beccali et al. (2009) assessed oranges for juice production, which usually imply lower intensification of agricultural practices, which also implies lower GHG emissions. In contrast, retailers and consumers demand fruit without defects for fresh consumption, which implies more intensive management practices and their subsequent environmental consequences.

Yield is another factor that influences the CF of oranges and of agricultural products in general. For a given production system, great differences in yield were observed among the reviewed studies. As expected, organic oranges have lower yield, except for the yield of Knudsen et al. (2011) for conventional oranges. For organic oranges, the highest yield corresponds to de Luca et al. (2014), at 32 $t \cdot ha^{-1} \cdot year^{-1}$, and Pergola et al. (2013), at a mean of 24.7 $t \cdot ha^{-1} \cdot year^{-1}$ and a maximum of 32.2 $t \cdot ha^{-1} \cdot year^{-1}$. For conventional oranges, Bessou et al. (2016) and de Luca et al. (2014) reported the highest yield, at 42 and 41 $t \cdot ha^{-1} \cdot year^{-1}$, respectively. In particular, Bessou et al. (2016) aimed to show the effect of annual variations in yield on subsequent variations in environmental impacts. The yield varied from 20.5-66.2 $t \cdot ha^{-1}$ over three years, which explains the variability in their CF values (Table 7) and also that they are higher than those estimated in the other studies. As mentioned, this alternating yield depends on the orange cultivar and management practices, as chemical or manual thinning precludes it. CFs of orange estimated by Pergola et al. (2013) and de Luca et al. (2014) (Table 7) were calculated by taking into account the total impact per unit area for the full crop cycle and the yield in the productive years. This can explain the lower CFs of these authors as, due to a lack of data, we assumed the same yield for the entire cycle.

Besides the present study, only Nicolo et al. (2017) assessed the contribution of PH treatment to the CF. Their value was 16% lower, perhaps because they excluded degreening and refrigeration, which contributed 10% of the PH subsystem impact in our study.

3.3.3. Decreasing the CF of Valencian oranges

Several studies have compared impacts of local vs. imported fruit and vegetable production, and some of them highlight that importing fruits and vegetables from southern to northern regions is preferable in months when northern regions require heating systems (e.g. Hospido et al. 2009; Webb et al. 2013). Oranges are not grown in greenhouses, but importers can select those with lower impacts of their agricultural practices, packaging or transport system. Therefore, implementing measures to decrease the CF of fruit and vegetable supply chains can improve product image and sustainability in a competitive market.

Using cluster analysis, Ribal et al. (2017) showed that conventional orange farms can attain the same level of impacts as organic ones while maintaining the yield, which reveals both the great influence of a farmer's decisions on the variability in farming impact and the importance of farmer training. An essential aspect to be encouraged is that of improving monitoring of soil nutrients to adjust the dose of fertilisers applied. This would help to decrease fertiliser emissions on both organic and conventional farms and increase the yields of organic farms.

On the other hand, variability in the export stage is related to market distances and market share. Exporters cannot modify these two variables, but transport infrastructure can be improved to decrease its impact. Among the cost-effective solutions for a more climate-friendly transport system in the short term, Luè et al. (2017) encourage (1) more efficient, lighter vehicles with advanced internal combustion engines, (2) reducing road transport demand and (3) fostering GHG emission legislation. At the same time, Spanish exporter companies are already adopting intermodal transport systems within Europe, namely combining road and train (Linerail 2014) or road and short shipping transport (Zaragozà 2016).

It is also noteworthy that the percentage of non-marketable oranges can reach up to 20% (Table 2). Changing the concept of marketable oranges (ugly fruits) would directly influence the CF. Halving the number of ugly fruits, possibly by changing consumer perceptions, would decrease the CF as much as producing 50% of exported oranges on organic farms (Table 4).

3.3.4 Methodological issues

The use of a wide range of information sources is common when performing life cycle studies (e.g. Pérez Neira et al. 2018; Escobar et al. 2014). The method developed integrates data sources of differing natures and shows how variability in the mean CF of life cycle stages leads to variability in mean impact. This study used primary information (LCAs of individual farms), Monte Carlo simulation from information on the variability in key parameters from one PH treatment centre, and secondary information for statistical data on exportation and distance to markets. Specific data sources on packaging material and market destinations for organic oranges were not used, as no official data are available. Use of data on the former should not change the mean CF significantly. The latter might affect the mean CF more, however, as market destinations are more or less the same, but each country's share of the market can change.

Representing relevant variability in LCA results without collecting an extremely wide range of data is a challenge for LCA practitioners (Notarnicola et al. 2017). Along these lines, non-parametric statistics, and specifically bootstrap techniques, are reported to work well with a sample size as small as 20 (Chernick and LaBudde, 2011) or 30 Chernick (2008). However, the best solution to the small sample-size problem is to increase the sample size, because small samples may not represent the population; unfortunately, this is not possible in every circumstance.

To avoid "data dredging" (Altman and Krzywinski 2017), that is, introducing bias into sample selection, the entire analysis was repeated without removing the two conventional farm outliers, and a significant difference at $\alpha = 0.01$ was still found between the mean CF of both types of oranges.

4 Conclusions

With this citrus case study, we addressed two relevant research questions. As regards the first question, – the existence of significant differences between mean CF from two small samples – bootstrap techniques can both help to test the existence of significant differences and to estimate confidence intervals of the mean CF. As to the second question, the procedure developed provides a clear illustration of how to combine several CF sources to estimate variability in the mean CF. Although the procedure is designed for a specific case study, it shows a fairly common case. The mean was selected as the most representative statistic, as it allows the aggregated CF to be calculated. However, this kind of analysis could be performed for other statistics, such as the median or variance.

Therefore, strong points of the non-parametric approach are that it measures overall variability and integrates the variability of the several subsystems. Assessing the variability in CF (or in other environmental impacts) gives a more reliable measure of mean impact. Furthermore, it can also help identify practices with the lowest CF to design strategies to reduce GHG emissions.

Table 7. Carbon footprint (CF) of 1 kg of oranges produced with different production systems and system boundaries in different countries

Product	Geographical origin	Type	System boundaries	yield* ($t\cdot ha^{-1}$)	Farming	Post-harvest	Transport	Source
					($kg\ CO_2$-equiv $\cdot kg^{-1}$)			
Navel oranges for fresh consumption	C. Valenciana (Spain)	conventional	from farm to a distribution centre in the European Union (EU)	12.7-50.0	0.28	0.053	0.51	this study
		organic	from farm to a distribution centre in the EU	1.7-50.4	0.13	0.053	0.51	
Navel oranges for fresh consumption	Calabria (Italy)	conventional (40 years)	from farm to post-harvest centre exit gate	28	8.75	0.0441	-	Nicolo et al. (2017)
Oranges for juice production	Sao Paulo (Brazil)	organic small scale	farm gate	18 (12-21)	0.084	-	-	Knudsen et al. (2011)
		organic large scale		23 (17-29)	0.114	-	-	
		conventional small scale		20 (14-26)	0.112	-	-	
Oranges for juice production	Sicily (Italy)	conventional	farm gate	-	0.14 - 0.17	-	-	Beccali et al. (2010)
Oranges for fresh consumption	Sicily (Italy)	conventional (50 years)	farm gate	28.6 (22.5-34.5)	0.13	-	-	Pergola et al. (2013)
		organic (50 years)		24.7 (17.8-32.2)	0.04	-	-	
Oranges	South Calabria (Italy)	conventional (40 years)	farm gate	41	0.159	-	-	De Luca et al. (2014)
		organic (40 years)		32	0.071	-	-	
Sidi Aissa Clementine	Beni Mellal (Morocco)	conventional; full cycle (25 years)	farm gate	42	0.329	-	-	Bessou et al. (2016)
		full production, 3-year mean		29	0.401	-	-	
		full production, 3-year range		20.5-66.2	0.201-0.663			

*yield referred to high productive trees. Values in brackets correspond to yield range given in the article, although in all cases the authors used the mean.

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