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The carbon footprint of stone fruit production: Comparing process-based life cycle assessment and environmentally extended input-output analysis

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A R T I C L E I N F O

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A B S T R A C T

The development of sustainable products and practices must be supported by methodologies capable of evaluating their environmental performance in an objective and systematic manner. The most popular tool for carbon footprint (CF) assessment is arguably process-based life cycle assessment (pLCA). However, interest in tools such as environmentally extended input-output analysis (EEIOA) is growing rapidly due to the convenience of using economic-based inventories rather than material/energy-based ones. The objective of this investigation is to evaluate divergences between conventional pLCA and EEIOA in the analysis of CF using the production of stone fruits as a case study. The study uses a cradle to grave approach and it is based on a detailed economic, material and energy life cycle inventory of nectarines produced in Southeast Spain. The analyses yielded 1.07 kg CO_2 eq./kg for the EEIOA and 0.899 kg CO_2 eq./kg for the pLCA. This difference, which might sound acceptable, is due to the compensation of larger opposing discrepancies in the various stages and processes that make up the product life cycle. Thus, pLCA yielded significantly higher total CF emissions than EEIOA (0.23 EEIOA/pLCA ratio) in the upstream stage (agricultural and packaging processes). The opposite is observed in the core stage, where EEIOA carbon emissions were significantly higher than those calculated by pLCA (4.38 EEIOA/pLCA ratio). Differences in the downstream stage (mainly distribution and storage, and EoL phase) were less notable (1.40 EEIOA/pLCA ratio). Economic-based inputs, used in EEIOA (such as labour and service costs) and unaccounted for in pLCA, may be partly responsible for such divergences, while others should be linked to differences in the impact assessment procedures followed by each of these methodologies. These results raise some doubts about the potential of EEIOA and calls for further research on the validity, complementarity and the application domains of these methodologies. In any case, both modelling approaches agree in identifying the distribution and storage life cycle stages as main contributors to carbon emissions, calling for the implementation of measures to promote the consumption of seasonal and local fruit.

1. Introduction

The IPCC Special Report (IPCC, 2019a) on climate change reported that 23% of total anthropogenic greenhouse gas (GHG) emissions come from agriculture, forestry and other uses. Agriculture contributes to 12% of the emissions (irrigated crops 2% and 10% without irrigation). The carbon footprint (CF) is an indicator of sustainable development that describes the direct and indirect GHG emissions produced by specific products, processes and activities (Wiedmann and Minx, 2007).

Spain is the second largest exporter of fruit and vegetables in the world and was the main supplier of fruit to the EU in 2020, with an annual output of €14,595 M (MAPA, 2021). In 2021, stone fruit exports

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reached a record value of €1370 M, with an export volume of 9,476,665 t, 39% of which were nectarines, ranking first in both volume and value (MAPA, 2022). However, the sector is facing a serious crisis mainly due to the sharp rise in production and processing costs (e.g., fertilizers, phytosanitaries, plastics, electricity and fuel), the geopolitical situation and the effects of climate change (e.g., late frosts, drought, heat waves …). Due to all these causes, fruit production in Spain in 2022 is expected to be the weakest in the last decade, with nectarine output being 27.84% lower than in 2021 (Alimarket, 2022). In this context, sustainability becomes the new production paradigm to ensure not only environmental sustainability but also the economic viability of agricultural activities.

Different methodologies are available to assess the carbon footprint (and other environmental categories) throughout the value chain of products and services. Such techniques, based on the general principles and framework of ISO 14040, 2006 and ISO 14044, 2006, can be classified using two impact assessment approaches. The first one, referred to as process-based Life Cycle Assessment (pLCA), is the most widely adopted and established worldwide. It follows a bottom-up approach to determine impacts through the aggregation of the unitary process that make out the value chain of the system under investigation, which are quantified using energy and material inventories. The second one, referred to as the Environmentally Extended Input-Output Analysis (EEIOA), follows an econometric top-down approach (Leontief, 1970) and relies on a disaggregated cost inventory to assess the relationships between economic activities and environmental impacts along the value chain (Kitzes, 2013; Miller and Blair, 2009). EEIOA results can be disaggregated to determine the contribution of individual sectors and unit processes.

Due to the important commercial value and the need to improve the sustainability of stone fruit production, different studies have quantified their environmental impacts of these products, most of which utilize the pLCA approach. According to Vinyes (Vinyes et al., 2017), the CF of the cultivation of peaches in the North East region of Spain with the boundaries set from *cradle to grave* is 0.38 kg CO_2 eq per kg. Other authors report CF values in Italy as 0.22 kg CO_2 eq per kg of Sicilian peach (Ingrao et al., 2015), considering narrower boundaries of the *cradle to gate* system. In the United Kingdom (importing country), it is 2.0 kg CO_2 eq per kg of peach in a *cradle to gate* system, where the higher emissions are due to the greater distribution distances and longer storage times (Frankowska et al., 2019). Studies of agriculture systems using the EEIOA approach are scarcer. Camanzi (Camanzi et al., 2017) reported CF emissions from the EU food chain for fruits at 3.20 kg CO_2 eq per euro of product consumed. Reynold (Reynolds et al., 2015) quantified the total CF emissions of fruit products in a conventional Australian household at 0.57 kg CO_2 eq per US$.

Table 1 presents a bibliographic summary of the few studies available in the literature describing comparatively the use of pLCA and EEIOA methodologies for the CF analysis of products. Rama et al. (2021) quantified the CF generated by a Spanish city (Cádiz) with boundaries from *cradle to grave* (Cádiz, southwest of Spain), reporting 67% higher emissions when this analysis was carried out using EEIOA than with pLCA. Castellani et al. (2019) evaluated 14 categories of environmental impact related to household consumption in Europe with boundaries from *cradle to gate*. In this case, the difference between the two methods was only 14% in CF, in favour of EEIOA.

Beylot et al. (2020) analysed 14 categories related to the environmental impact produced by European trade with boundaries from *cradle to gate*. GHG emissions calculated using EEIOA were CF 3.26 higher than those calculated by the pLCA (Table 1). Alvarez et al. (2015), evaluated the CF of a wooden pallet cycle with boundaries from *cradle to gate*, reporting differences of 22% between methods. Most authors report that EEIOA benefits from the use of specific economic inventories, which are easier to collect than the energy-mass based inventories utilized by pLCA, and also from the use of databases that are free of charge.

The main objective of this investigation is to comparatively evaluate the use of conventional pLCA and econometric EEIOA methodology to quantify the carbon footprint associated with the value chain of an agricultural system. This validation of the econometric method would serve to extend its application and facilitate decision making on the sustainability of agricultural commodities by producers, companies and administrations.

2. Materials and methods

The environmental assessment has been carried out using a life cycle approach following ISO 14040-44, while identifying four stages: Goal and scope definition; Life cycle inventory (LCI); Life cycle impact assessment (LCIA); and Interpretation. The following subsections provide detailed information on the methodological decisions and assumptions applied in these stages.

Table 1

Literature review of carbon footprint studies between Process-based Life Cycle Assessment (pLCA) and Environmentally Extended Input-Output Analysis (EEIOA) methods.

References		Rama et al. (2021)	Castellani et al. (2019)	Beylot et al. (2020)	Alvarez and Rubio (2015)
System		Business, residential, and cultural activities in Cádiz	Household consumption in Europe	European Trade	Euro wood pallet
Functional unit		Inhabitant/yr	Home/yr	Euro trade/yr	1 unit of EUR-flat wood pallet
System limits		*Cradle to grave*	*Cradle to gate*	*Cradle to gate*	*Cradle to gate*
Secondary database used in inventory preparation		Ecoinvent v3.1 Agribalyse database	Ecoinvent v.3.2 Agrifootprint v.2 EU-27	Ecoinvent 2.2 combined with eurostat data	SETAC LCI
Impact assessment methodology for pLCA		ReCiPe v.1.12. midpoint	EF method pLCA-Consumer Footprint	EF method	ReCiPe process-based analysis.
Impact assessment methodology for EEIOA		Input-Output tables and emissions of the national institute of statistics Spain	Exiobase 3.3	Exiobase 3.3	Composite method of accounting accounts
Results	**EEIOA** (kg CO_2 eq)	9.08E+3	5.48E+12	5.58E+12	9.91
	pLCA (kg CO_2 eq)	5.43E+3	4.79E+12	1.71E+12	8.10
	Ratio EEIOA/ pLCA	1.67	1.14	3.26	1.22

2.1. *Goal definition*

The main aim of the study is to quantify the CF of a stone fruit produced in southeast Spain using two methodological approaches: the conventional pLCA and the econometric EEIOA method, hereby validating the latter as the more favourable method for this type of product. The following secondary objectives are proposed: i) compile and evaluate detailed life cycle material-energy and economic inventories applicable to pLCA and EEIOA methodologies; ii) analyse and compare the CF of the life cycle stages between methodologies; and iii) interpret and develop conclusions on the competence and applicability of each of these methods.

2.2. *Scope definition*

2.2.1. *Methodological structure*

The structure of unit processes was performed following IPCC guidelines (IPCC, 2019b), using the criteria for food products described in the Product Category Rules (PCR) "UN CPC 013 for fruits and nuts" (EPD, 2019) and the methodology of the Environmental Footprint of product (Zampori and Pant, 2019).

2.2.2. *System description*

The product under study is nectarine (*Prunus persica* var. nectarina) grown by a fruit company based in southeast Spain (Abarán, region of Murcia). The data describes the average of 15 seasons for a 405 ha plot, with a density of 667 plants per ha and yielding 35 t ha^{-1} yr^{-1} of fresh fruit. The product is grown, prepared, selected, and packaged to the market in Spain as a climacteric fruit.

2.2.3. *Functionality and functional unit*

The functional unit (FU) is defined as 1 kg of fruit ready to consume, including its packaging (packaging mass is not included in FU) and considering the entire life cycle (EPD, 2019).

2.2.4. *System structure and boundaries*

Fig. 1 describes the structure and limits of the system considered in the LCA analysis of the nectarine (both pLCA and EEIOA). The system was structured in three stages called upstream, core and downstream, according to (EPD, 2019). The upstream stage includes processes related to the production and transport of inputs to the agriculture plot and/or fruit processing plant and also the crop establishment. The core stage refers to the processes that occur during the crop production and in the fruit processing plant. The downstream stage refers to the processes that occur beyond the factory gates (*gate to grave*), including distribution, wholesale, consumption, and end of life of packaging and fruit elements.

2.3. *Life cycle inventory*

The background and foreground inventory data, and the methodological decisions considered to prepare the material, energy and economic life cycle inventories of the nectarine are described below.

2.3.1. *Material-energy inventory and economic inventory*

The inventory data is structured in the three stages: upstream, core and downstream. Primary data for the material-energy inventory included crop yields and input consumption (e.g., fuel for machinery and transport, fertilization, phytosanitation, irrigation and packaging). Background secondary data for specific products and processes were sourced from the ecoinvent v.3.7. database (Ecoinvent, 2020). The economic inventory is based on the cost structure of stone fruit production reported by García (2018). The following premises were assumed for the analysis of generic processes:

2.3.1.1. *Upstream material-energy inventory.* Inputs production (1): This substage includes the production of the necessary inputs throughout the

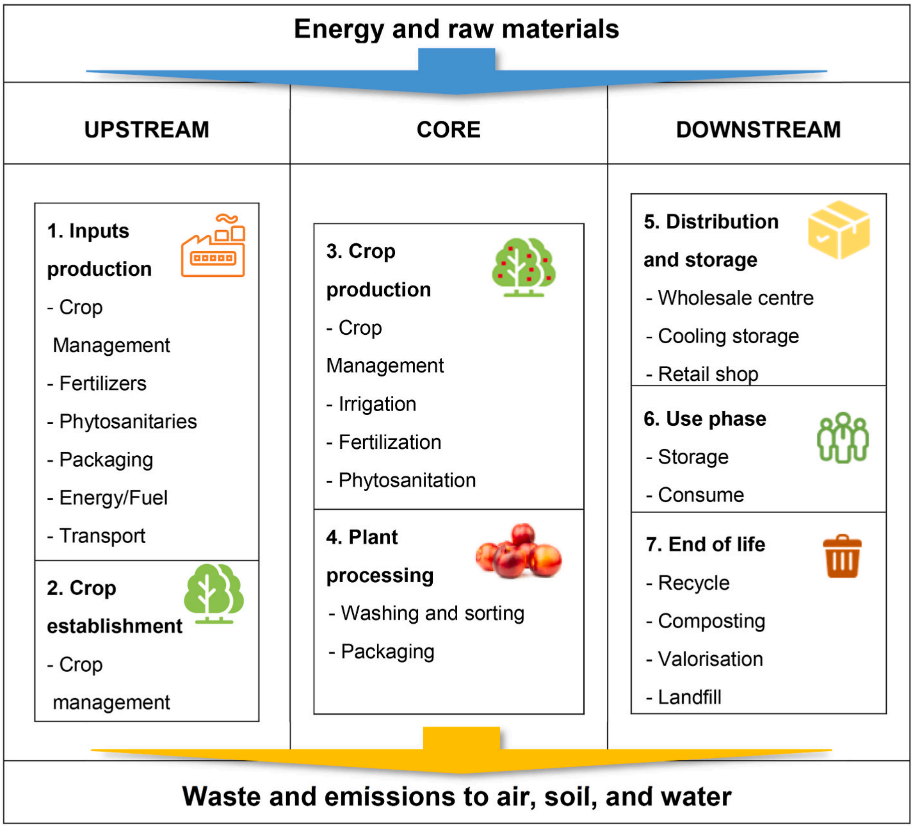


Fig. 1. Life cycle diagram describing the structure, processes, and system boundaries of nectarine production.

Table 2
Material-energy and economic inventories of nectarine production per functional unit (1 kg of fruit) in the upstream stage. The percentage represents the total contribution by stage and substage.

Life cycle stage	Material-energy inventory		Economic inventory	
	Unit	Quantity	€	%
Upstream			**1.0E-01**	**14.21**
1. Inputs production			6.1E-02	8.59
Cultivation infrastructure	p	–	1.4E-02	1.99
Irrigation system	p	2.0E-07	–	–
Phytosanitaries	kg	3.1E-04	1.5E-02	2.13
Fertilizers	kg	5.1E-02	1.4E-02	2.02
Packaging materials	kg	1.1E-01	1.4E-02	1.97
Auxiliary material	–	–	5.3E-04	0.07
Transport	tkm	3.0E-02	3.0E-03	0.41
2. Crop establishment			4.0E-02	5.63
Preparation and planting	ha	1.9E-06	8.1E-03	1.13
Irrigation	m^3	8.6E-03	3.2E-02	4.50
Crop management	ha	2.9E-05	–	–
Phytosanitation	kg	5.9E-10	–	–
Fertilization	kg	3.2E-03	–	–
Electricity	kWh	2.4E-03	–	–
Transport	tkm	2.5E-04	2.4E-05	0.00

Table 3
Material-energy and economic inventory of nectarine production per functional unit (1 kg of fruit) in the core stage. The percentage represents the total contribution by stage and substage.

Life cycle stage	Material-energy inventory		Economic inventory	
	Unit	Quantity	€	%
Core			**5.0E-01**	**69.87**
3. Crop production			3.9E-01	54.52
Irrigation	m^3	1.29E-01	–	–
Crop insurance	–	–	7.1E-02	9.98
Crop management	ha	8.58E-05	2.5E-01	35.07
Phytosanitation	kg	3.10E-04	–	–
Fertilization	kg	4.81E-02	–	–
Machinery	–	–	1.6E-02	2.30
Maintenance	p	2.86E-07	3.0E-03	0.42
Electricity	kWh	3.60E-02	3.6E-03	0.50
Staff	–	–	4.5E-02	6.23
Transport	t km	1.47E-03	1.4E-04	0.02
4. Plant processing			1.1E-01	15.35
Water use	m^3	1.30E-04	7.4E-04	0.10
Water waste	m^3	1.10E-04	1.2E-05	0.00
Workers	–	–	1.1E-01	14.82
Electricity	kWh	2.62E-02	3.0E-03	0.42

life cycle (Table 2). The following inputs are considered: fertilizers, phytosanitaries, irrigation system, seedlings and packaging materials (wood, cardboard and low-density polyethylene), and energy and fuel for transport (800 km freight lorry Euro4 25 t are considered for a long-distance scenario in the territory).

Crop establishment (2): This substage includes the process associated with crop establishment, which considers soil preparation, installation of the irrigation and conduction system, planting, and crop management (fertilization, phytosanitaries, irrigation and pruning) (Table 2). The use of diesel for machinery and transport (30 km freight lorry Euro4 25 t are considered for a short distance scenario in the territory) and electricity (Spanish medium voltage electricity mix of the year 2021) for irrigation is also contemplated. Inputs used and processes carried out in the 3-year duration of this sub stage are prorated over the 15-year duration of the crop production substage.

2.3.1.2. Upstream economic inventory. Inputs production (1): The costs of this substage include the cultivation infrastructure composed of the tool shed, irrigation system and the water reservoir (Table 2). The auxiliary material section is made up of pruning shears, baskets, hoes, and light tools. The purchases include fertilizers, phytosanitary products, and herbicides. The costs of packaging materials such as polyethylene bins, wood for pallets, cardboard boxes, Kraft paper and plastic film were obtained in the rates found on the national institute of statistics website (INE, 2020). The cost of transport inputs were obtained from the observatory of road transport costs of the Ministry of transport, mobility and urban agenda (MITMA, 2021).

Crop establishment (2): The cost of this substage include the establishment of cultivation, which comprises the preparation of the land, planting, and the cost of irrigation water (Table 2). In addition, the costs of road transport of the ministry of transport, mobility and urban agenda are included (MITMA, 2021).

2.3.1.3. Core material-energy inventory. Crop production (3): This substage includes irrigation (including water and electricity) and fertilization (including inputs and machinery), phytosanitaries (including crop inputs, machinery and fuel for their application) and crop management (including soil preparation, pruning, thinning, and harvesting and the related use of machinery and fuel) (Table 3). The consumption of fuel for machinery and transport (30 km freight lorry Euro4 35 t for a short distance scenario in the territory) and electricity (Spanish medium voltage electricity mix of the year 2021) were also considered.

Plant processing (4): This sub stage includes the use of diesel and transport (30 km freight lorry Euro4 25 t for a short distance scenario in the territory) of fruit from the agricultural plot to the processing plant where the fruit is processed in the following stages: pre-refrigeration; pre-calibration; cleaning; brushing; washing; drying; selection; calibration; packaging; cold storage and refrigeration (Table 3). The use of electricity (Spanish medium voltage electricity mix of the year 2021) for the operation of machines in the processing and cooling chambers for storage, and the use of water for washing (tap water treatment-distribution and water waste sewer-treatment) were also considered.

2.3.1.4. Core economic inventory. Crop production (3): The cost of this substage includes manual tasks such as annual pruning, thinning and harvesting, insurance on agricultural production, machinery and labour costs, maintenance of fixed assets and electricity used for irrigation and staff (6.56 €/h (BOE, 2021)) (Table 3). In addition, the costs of transporting the fruit by road from the agricultural plot to the processing plant are also included (MITMA, 2021).

Plant processing (4): The costs of this substage are associated with the electricity consumption of the fruit preparation, selection, and packaging equipment (0.1199 €/kWh) (REE, 2021) (Table 3). In addition, the cost of water use in treatment and distribution (1.12 €/m^3) and water waste sewer and treatment (0.34 €/m^3) (HIDROGEA, 2021) in the plant, and finally the cost of services provided by workers in a fruit and vegetable plant are considered (6.56 €/h) (BOE, 2021).

2.3.1.5. Downstream material-energy inventory. Distribution and storage (5): This substage includes the use of diesel and refrigerated transport (800 km freight lorry Euro4 16 t for a long-distance scenario in the territory) from the processing plant to the fruit distribution plant for wholesalers (Table 4). The packaged fruit is stacked in the cold storage chamber (2000 m^3) for a maximum period of 3 weeks pending its final distribution to retail (30 km freight lorry with refrigeration machine Euro4 7.5 t for a short distance scenario in the territory). Electricity consumption for machines in cold storage and then cooling (Spanish medium voltage electricity mix of the year 2021) is also considered.

Use phase (6): This substage considers the consumption of electricity for the refrigeration of the fruit (Spanish medium voltage electricity mix of the year 2021) and water for washing (Tap water production and water waste treatment) (Table 4).

End of life (7): This substage considers the end of life of the fruit and packaging (Table 4). The different wastes are transported to the

Table 4
Material-energy and economic inventory of nectarines per functional unit (1 kg of fruit) in the downstream stage. The percentage represents the total contribution by stage and substage.

Life cycle stage	Material-energy inventory		Economic inventory	
	Unit	Quantity	€	%
Downstream			**1.14E-01**	**15.92**
5. Distribution and storage			4.75E-02	6.65
Transport	tkm	4.20E-01	1.34E-03	0.19
Refrigeration electricity	kWh	4.30E-01	4.62E-02	6.46
6. Use			9.37E-03	1.30
Electricity	kWh	7.90E-02	8.99E-03	1.26
Water use	m^3	2.60E-04	2.13E-04	0.03
Water waste	m^3	2.60E-04	6.10E-05	0.01
7.1. End of life food waste			1.17E-02	1.64
Transport	tkm	5.10E-03	5.02E-04	0.07
Compost	kg	1.20E-01	4.05E-03	0.57
Energy recovery	kg	3.40E-02	9.58E-04	0.13
Landfill	kg	1.70E-02	6.19E-03	0.87
7.2. End of life packaging waste			4.53E-02	6.36
Transport	tkm	2.98E-03	2.93E-04	0.04
Energy recovery	kg	1.20E-03	1.06E-02	1.49
Recycle	kg	3.60E-03	–	–
Landfill	kg	7.00E-03	3.44E-02	4.82

processing centre (20 km Lorry 16 t EURO4 for a short distance for this scenario in the territory). The nectarine waste goes into compost. In reference to the packaging materials, the wood from the pallet is 15% recyclable, 12% is energy recovered and 73% goes to landfill. The cardboard is 60% recyclable, 12% is energy recovered and 28% goes to landfill. Plastic is 22.5% recyclable, 12% is energy recovered and 65.5% is destined for landfill (RETEMA, 2020).

2.3.1.6. Downstream economic inventory. Distribution & Storage (5): The transportation costs of this substage were sourced from the Spanish observatory for road transport costs (MITMA, 2021). This substage also includes the costs of electricity for storage operations (0.11 €/kWh) (REE, 2021).

Use phase (6): The costs of this substage are associated with the consumption of electricity for domestic conservation (0.11 €/kWh) (REE, 2021) (Table 4), the use of water for washing the product prior to being consumed (0.81 €/m^3) and wastewater treatment (0.23 €/m^3) (Canal Isabel II, 2021).

End of life (7): The economic costs of end of life activities were obtained using the reported management mix for fruits and packaging of a European city and the economic cost corresponding to each of these activities in Europe (Rama et al., 2021) (Table 4).

2.4. Life cycle impact assessment method

2.4.1. Process based LCA

The life cycle impact assessment (LCIA) utilized in this LCA was the Baseline model of 100 years of the IPCC 2013, included in the Environmental Footprint (EF) v.3.0 method (adapted) (Fazio et al., 2018), as suggested by the European Commission in its Product Environmental Footprint (PEF) guidelines (Zampori and Pant, 2019). Modelling and calculations for pLCA were performed using SimaPro v.9.2. software (Goedkoop et al., 2016) and PESTLCI to simulate phytosanitary emissions (Dijkman et al., 2012).

2.4.2. Environmentally extended input-output analysis

EEIOA was performed using the EXIOBASE 3.4 database (Wood et al., 2015), which includes input-output tables from 49 regions (28 European Union, 16 large economies and 5 rest of the world) and 163 economic sectors. EEIOA calculations were carried out using Matlab software (MathWorks, 2021).

As a first step, the original Input-Output database was transformed into a matrix of technical coefficients (A) which represents, in relative terms, the economic interrelation between different sectors of the international economy. Eq. (1) is then used to transform the sectoral expenditure described in the inventory (Y) into its economic derivations across the global economy (X). The expression $(I - A)^{-1}$, where (I) is the identity matrix, is known as the inverse Leontief matrix (Leontief, 1970) and describes the direct and indirect needs induced throughout the (Y) unit economy, and is also known as final demand for goods and services.

$$X = (I - A)^{-1} \cdot Y \quad \text{(Eq. 1)}$$

This model can be extended to incorporate non-economic extensions. This is the case of this research that includes the GHG emissions related to the 163 sectors and the 49 regions (UNEP, 2016). These new extensions can be calculated using Eq. (2), in which "e" represents the multipliers per unit of total production (X). In this case, the CF per unit of € traded in the specific year for each combination of regions and sectors is calculated. Thanks to the Leontief inverse, multipliers deliver the CF that correspond to total direct and indirect GHG emissions (E_t) produced through a specific final demand (Y).

$$E_t = e \cdot (I - A)^{-1} \cdot Y \quad \text{(Eq. 2)}$$

Finally, the direct and indirect GHG emissions (E_d and E_i respectively) of the final demand vector for the three life cycle stages of Nectarine, upstream, core and downstream, are obtained by Eq. (3) and Eq. (4):

$$E_d = e \cdot I \cdot Y \quad \text{(Eq. 3)}$$

$$E_i = E_t - E_d \quad \text{(Eq. 4)}$$

Direct and indirect impacts are expressed as the total environmental impact divided by the FU produced (kg CO_2 eq/FU).

2.4.2.1. Uncertainty analysis. The main sources of uncertainty in the pLCA analysis are due to the variability of inventory data and the cumulative effects of model imprecisions. Background Ecoinvent datasets used in this study include specific uncertainty values. The Monte Carlo simulation was used for uncertainty propagation and the assessment of pLCA output robustness. This simulation showed the spread of the pLCA results (95% confidence intervals, EF 3.0 Method (adapted) V 1.00) for the climate change category.

3. Results and discussion

3.1. Comparing the material-energy and economic based life cycle inventories

This section provides a comparative analysis of the material-energy and economic inventories per FU described in Section 2.2.1 (Tables 2–4), as required for the calculation of the CF of the nectarines using pLCA and EEIOA, respectively.

3.1.1. Comparison of upstream stage inventories

- Inputs production (1): The irrigation system is incorporated into the cultivation infrastructure costs (Table 2). The auxiliary materials are included in EEIOA and are also incorporated as a process in the generic Ecoinvent dataset used in pLCA.
- Crop establishment (2): The economic inventory for crop establishment (used in EEIOA) incorporate disaggregated information for preparation and planting activities, irrigation (as water use) and transport. The economic inventory does not include data for crop management, phytosanitation, fertilization and electricity, as these

activities are already incorporated in the preparation and planting stage (Table 2).

3.1.2. *Comparison of core stage inventories*

- Crop production (3): economic inventory data was available for annual pruning, thinning, harvesting, crop insurance and permanent staff. The costs of machinery for fertilization and phytosanitation, and the maintenance and electricity consumed in the irrigation process are considered at this stage excluding fertilizers, herbicides and water (Table 3). Since these are interpreted as inputs of the life cycle of the crop, its acquisition and consumption costs are included in the upstream stage. In pLCA, emissions from the application of fertilizers and phytosanitary products are applied, as well as the use of machinery and diesel consumption in crop management. The pLCA inventory does not take into consideration labour or services (insurance) which are included and have a significant contribution to the economic inventories.
- Plant processing (4): Similarly, the economic inventory includes labour costs (EEIOA), a process that is not considered in the material-energy inventories used in the pLCA (Table 3).

3.1.3. *Comparison of downstream stage inventories*

- End of life (7): The economic inventory (for EEIOA) does not consider the cost of packaging waste management activities (recycling, landfilling, etc.). The pLCA considers the recycling of the materials that are included in the packaging of the fruit.

3.1.3.1. Economic assessment. The use of monetary units makes it possible to analyse the contribution of different stages and processes in the economic inventory (used to carry out the EEIOA). The results in Table 3 show that 70% of the cost of the nectarine system stems from the core stage. Crop management is the process generating the highest economic contribution (35.9%), followed by labour costs in the processing plant (14.8%) and production insurance (9.9%). The downstream stage (Table 4) is the second largest economic contributor, representing 15.9% of total costs. The contribution of the distribution and storage stage represents 6.6% of total costs, followed by end-of-life packaging (6.4%). The contribution of the upstream stage represents 14.2% of total costs, including inputs production (1) costs (8.5%).

3.2. *Comparison of life cycle impact assessment*

This section shows the results derived from the application of the pLCA and EEIOA methodology to the material-energy based and economic inventories described in Section 2.2.1.

3.2.1. *Comparison of upstream stage*

Table 5 shows that total carbon emissions for the upstream stage calculated by pLCA amounted to 0.403 kg CO_2 eq per FU, equivalent to 44.9% of the total. GHG emissions (including both direct and indirect) calculated using EEIOA were 0.092 kg CO_2 eq per FU, corresponding to 8.6% of the total generated by the nectarine system. Both in the pLCA and EEIOA, the production of fertilizers represent by far the highest contributions with 48.5% and 60.9%, respectively.

The large differences observed in the CF calculated using pLCA and EEIOA may be attributed primarily to the characteristics of the chemical sector used to model the production of fertilizers in EEIOA. It could be argued that fertilisers are more energy intensive products (and consequently generate more GHG emissions per monetary unit) than most other products generated by the chemical sector, as included in the EXIOBASE database.

3.2.2. *Core stage comparisons*

Table 6 shows the carbon emissions for the core stage calculated using pLCA (0.095 kg CO_2 eq per FU, equivalent to 10.6% of the total) and EEIOA (0.417 kg CO_2 eq per FU, including both direct and indirect emissions, corresponding to 38.9% of the total). In this case, EEIOA emissions are significantly higher than those calculated using pLCA. The crop management in the crop production stage (3) is the process generating the highest environmental contribution in both methods (65.1% and 43.4%, respectively).

There is a considerable difference in emissions between methods in the crop production substage (Table 6), because EEIOA considers labour emissions (workers' wages), crop insurance and crop management within the production and use of the fertilizers and phytosanitaries. The difference in the irrigation process between methods is because pLCA considers the extraction and use of water with an electric drip irrigation system, whereas EEIOA considers only the use of electricity for pumping water and the water consumption in the crop management process.

3.2.3. *Downstream stage comparisons*

Table 7 shows 0.400 kg CO_2 eq per FU calculated using pLCA, equivalent to 44.5% of the total, and 0.562 kg CO_2 eq per FU calculated

Table 5
Results of the carbon footprint per functional unit calculated with pLCA and EEIOA in upstream stage.

	pLCA		EEIOA			
Upstream stage	Total emissions		Total emissions		Direct emissions	Indirect emissions
	kg CO_2 eq	%	kg CO_2 eq	%	kg CO_2 eq	kg CO_2 eq
1. Inputs production	3.99E-01	98.8	8.01E-02	87.1	5.47E-02	2.50E-02
Cultivation infrastructure	–	–	5.48E-03	5.98	1.03E-03	4.45E-03
Irrigation system	1.12E-01	28.3	–	–	–	–
Phytosanitaries	7.60E-03	1.90	1.00E-02	11.3	2.60E-03	7.80E-03
Fertilizers	1.98E-01	48.5	5.65E-02	60.9	5.01E-02	5.72E-03
Packaging materials	7.20E-02	18.1	6.69E-03	7.30	8.65E-04	5.83E-03
Auxiliary material	–	–	2.82E-04	0.31	2.99E-05	2.52E-04
Transport	8.60E-03	2.01	1.13E-03	1.23	1.04E-04	1.03E-03
2. Crop establishment	4.40E-03	1.15	1.18E-02	12.9	5.11E-03	6.74E-03
Preparation and planting	3.10E-04	0.08	3.31E-03	3.61	2.61E-03	6.97E-04
Irrigation	3.30E-03	0.83	8.53E-03	9.31	2.50E-03	6.03E-03
Crop management	1.70E-04	0.04	–	–	–	–
Fertilization	6.40E-05	0.02	–	–	–	–
Phytosanitation	3.80E-06	0.00	–	–	–	–
Electricity	4.20E-04	0.09	–	–	–	–
Transport	3.70E-04	0.09	9.31E-06	0.01	8.52E-07	8.46E-06
Total upstream	**4.03E-01**	**44.9**	**9.19E-02**	**8.60**	**5.98E-02**	**3.17E-02**

Table 6
Result of the carbon footprint per functional unit calculated with pLCA and EEIOA in core stage.

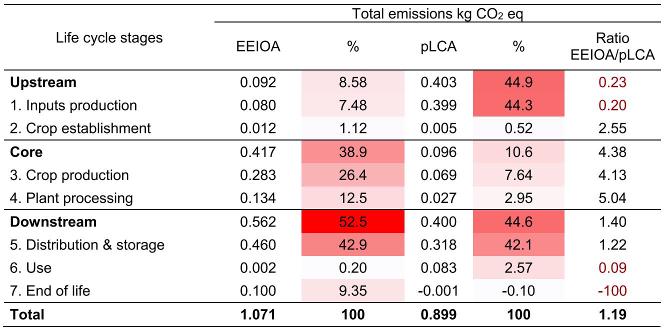
Core stage	pLCA		EEIOA			
	Total emissions		Total emissions		Direct emissions	Indirect emissions
	kg CO_2 eq	%	kg CO_2 eq	%	kg CO_2 eq	kg CO_2 eq
3. Crop production	6.86E-02	72.1	2.83E-01	67.9	1.70E-01	1.13E-01
Irrigation	2.05E-03	2.11	–	–	–	–
Crop insurance	–	–	1.03E-02	2.47	7.05E-04	9.59E-03
Crop management	6,19E-02	65.1	1.81E-01	43.4	1.58E-01	2.31E-02
Fertilization	6.97E-04	0.73	–	–	–	–
Phytosanitation	4.09E-05	0.04	–	–	–	–
Machinery	–	–	3.34E-03	0.80	2.76E-04	3.06E-03
Maintenance	–	–	1.36E-03	0.33	8.44E-04	5.18E-04
Electricity	3.20E-03	3.38	7.94E-02	19.1	9.74E-03	6.97E-02
Staff	–	–	7.75E-03	1.86	8.03E-04	6.95E-03
Transport	7.60E-04	0.80	5.54E-05	0.01	5.07E-06	5.03E-05
4. Plant processing	2.65E-02	27.9	1.34E-01	32.1	1.61E-02	1.18E-01
Water use	3.48E-05	0.04	1.97E-04	0.05	5.76E-05	1.39E-04
Water waste	3.00E-04	0.32	2.17E-05	0.01	1.42E-05	7.51E-06
Workers	–	–	1.85E-02	4.44	1.92E-03	1.66E-02
Electricity	2.62E-02	27.5	1.15E-01	27.6	1.41E-02	1.01E-01
Total Core	**9.52E-02**	**10.6**	**4.17E-01**	**38.9**	**1.86E-01**	**2.31E-01**

with EEIOA, corresponding to 52.54% of the total. In both methods, the substage with the greatest contribution is distribution and storage with 94.4% in pLCA and 81.8% in EEIOA in the stage, due to the amount of diesel and electricity that are required and the origin of the electricity mix in Spain and its high level of emissions due to fuel-based generation.

Total GHG emissions from pLCA and EEIOA by life cycle stages and substages are shown in Table 8. The total CF emitted in the production of 1 kg of nectarines was calculated to be 0.899 kg of CO_2 eq using pLCA and 1.071 kg of CO_2 eq using EEIOA. These results are within the range (0.22–2.0 kg of CO_2 eq./kg) but slightly higher than the average value (0.87 ± 0.98 kg of CO_2 eq./kg) reported in previous LCA studies carried out on peaches (Vinyes, Ingrao, Frankowska). In our study, we consider a cradle to grave approach, including medium distance transport from the processing plant to the distributor (500 km) and three weeks of fruit storage (representing an intermediate situation between the values used by Vinyes and Frankowska).

Table 8 also shows the comparison between methods in terms of ratio EEIOA/pLCA. The difference in total CF between methods is 1.19. Similar results were found by Alvarez (Alvarez and Rubio, 2015) with a

Table 8
Results and ratio between carbon footprint from EEIOA and pLCA methods according to stages and substages.



Life cycle stages	Total emissions kg CO_2 eq				
	EEIOA	%	pLCA	%	Ratio EEIOA/pLCA
Upstream	0.092	8.58	0.403	44.9	0.23
1. Inputs production	0.080	7.48	0.399	44.3	0.20
2. Crop establishment	0.012	1.12	0.005	0.52	2.55
Core	0.417	38.9	0.096	10.6	4.38
3. Crop production	0.283	26.4	0.069	7.64	4.13
4. Plant processing	0.134	12.5	0.027	2.95	5.04
Downstream	0.562	52.5	0.400	44.6	1.40
5. Distribution & storage	0.460	42.9	0.318	42.1	1.22
6. Use	0.002	0.20	0.083	2.57	0.09
7. End of life	0.100	9.35	-0.001	-0.10	-100
Total	**1.071**	**100**	**0.899**	**100**	**1.19**

Table 7
Result of the carbon footprint per functional unit calculated with pLCA and EEIOA in downstream stage.

Downstream stage	pLCA		EEIOA			
	Total emissions		Total emissions		Direct emissions	Indirect emissions
	kg CO_2 eq	%	kg CO_2 eq	%	kg CO_2 eq	kg CO_2 eq
5. Distribution and storage	3,78E-01	94,4	4,60E-01	81,9	5,60E-02	4,04E-01
Transport	2,41E-01	60,2	2,39E-01	42,5	2,88E-02	2,10E-01
Refrigeration electricity	1,37E-01	34,2	2,21E-01	39,3	2,72E-02	1,94E-01
6. Use	2,31E-02	5,77	2,16E-03	0,39	4,50E-04	1,71E-03
Electric energy	2,24E-02	5,60	1,78E-03	0,32	2,18E-04	1,56E-03
Water use	1,94E-04	0,05	5,65E-05	0,01	1,65E-05	3,99E-05
Water waste	5,00E-04	0,12	3,26E-04	0,06	2,15E-04	1,11E-04
7.1. End of life food waste	−1,66E-03	−0,41	4,43E-02	7,87	3,68E-02	7,51E-03
Transport	1,80E-03	0,45	1,92E-04	0,03	1,76E-05	1,75E-04
Compost	−5,50E-03	−1,37	9,67E-03	1,72	6,88E-03	2,80E-03
Energy recovery	−1,20E-03	−0,30	6,63E-04	0,12	6,90E-05	5,94E-04
Landfill	3,24E-03	0,81	3,38E-02	6,00	2,98E-02	3,94E-03
7.2. End of life packaging waste	8,00E-04	0,20	5,58E-02	9,91	2,98E-02	2,61E-02
Transport	4,10E-03	1,02	1,12E-04	0,02	1,03E-05	1,02E-04
Energy recovery	−3,90E-03	−0,97	1,76E-02	3,12	1,11E-02	6,45E-03
Recycle	−1,20E-03	−0,30	–	–	–	–
Landfill	1,80E-03	0,45	3,81E-02	6,77	1,87E-02	1,95E-02
Total Downstream	**4,00E-01**	**44,56**	**5,62E-01**	**52,54**	**1,23E-01**	**4,39E-01**

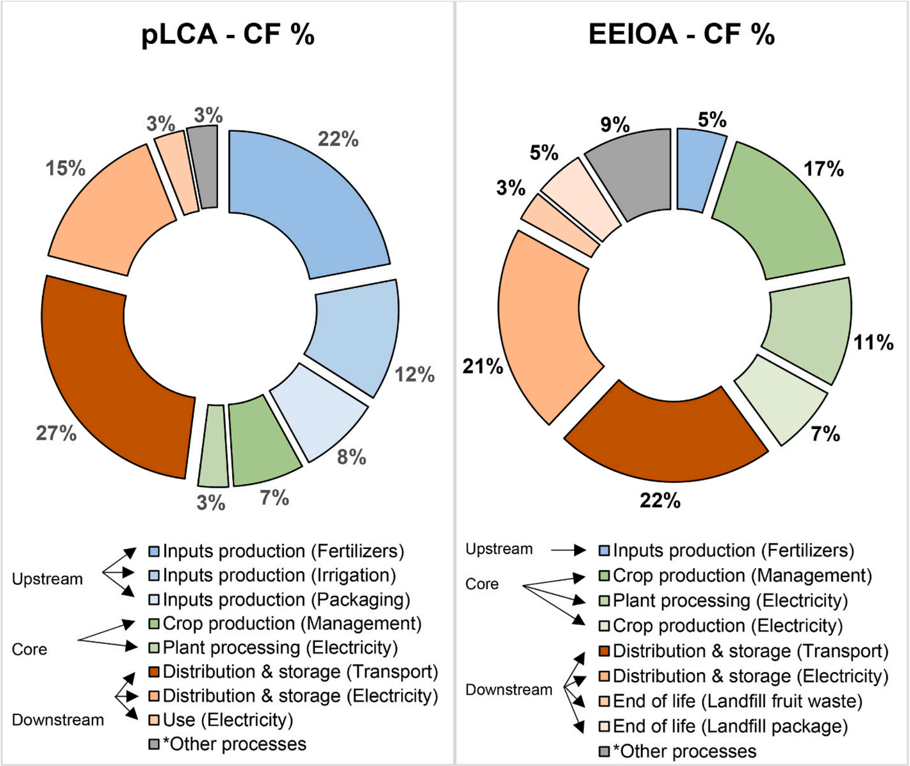


Fig. 2. Comparison between methods of the processes with the highest percentage contribution in the carbon footprint throughout the life cycle. *Other processes are the contribution of the group of unspecified processes whose individual contribution to the carbon footprint is less than 3%.

ratio of 1.22 for Euro Wood pallet, and by Castellani (Castellani et al., 2019) with a ratio of 1.12 for the system household consumption in Europe (Table 1).

Regarding the differences between methods by stage, the core stage presents the greatest difference with an EEIOA/pLCA ratio of 4.38, which includes a 4.13 ratio for crop production and a 5.04 ratio for plant processing. The stage with the smallest difference between methods is in the downstream stage with an EEIOA/pLCA ratio of 1.40. However, Exiobase does not consider any sectors for recyclable packaging, so a ratio of −100 is associated to the end-of-life substage of organic waste and packaging. Therefore, although the total CF estimated by both methodologies is similar, there are significant differences at the stage and substage level.

Fig. 2 shows the processes with the highest contribution in the CF in each method throughout the life cycle stages. The processes that are not presented are those that have a contribution of less than 3% or are not considered by the methodology. Both methodologies agree that transport and the electricity for refrigeration in the distribution & storage substage are main contributors to CF with a 42–43% of the total.

In the pLCA, the upstream stage generates a contribution to the CF of 42.5% (irrigation system 12.5%, fertilizers 22%, packaging 8%). Process-based analysis provides greater detail than EEIOA in upstream inputs production, taking into account the irrigation system, packaging and crop management. This also includes detailed contribution information from phytosanitation, fertilization and electric energy. This detailed description is a very useful advantage for pLCA (a bottom up methodology) in order to identify materials or processes with high emissions, consequently replacing them with environmentally friendlier ones.

EEIOA computes a contribution of the core stage to CF of 38.2%. This is mainly due to crop management and the electric energy for crop production, together with electric energy and workers for plant processing. The gap in CF emissions between the core-stage process-based analysis (10.6%) and EEIOA (38.2%) stems primarily from crop management and electrical power use. EEIOA also includes emissions from hiring permanent and temporary labour (1.86% and 4.44%) and production insurance (2.47%), which are represented in the total value chain of nectarine that the pLCA does not consider and that correspond to 8.77% of the total HR in EEIOA. The CF difference between methods without considering personnel, workers and services is 8% (0.977 kg CO_2 eq EEIOA vs 0.899 kg CO_2 eq pLCA).

The limitations present in the study are mainly derived from the nature and representativeness of the EEIOA methodology, and the limited disaggregation of economic sectors, which do not necessarily represent the situation for specific materials and processes. EEIOA databases are not updated frequently (the EXIOBASE database used in this investigation describes data from 2015), and therefore does not reflect changes in the economic structure of regions or trends in the emissions intensity of different sectors. In recent years, a decreasing trend has been observed in GHG emissions from all sectors in the EU (EEA, 2020), which may result in differences with respect to the pLCA methodology.

3.2.4. Uncertainty assessment

To support the robustness of the pLCA CF results, an uncertainty analysis has been carried out (Fig. 3). The life cycle analysis performed indicates that the average value of the carbon footprint is 0.828 kg CO_2 eq per FU. The uncertainty analysis shows that the median is 0.824 kg CO_2 eq per FU, which is very similar to the average, indicating that the distribution of the data is quite symmetrical. The standard deviation is ±0.041 kg CO_2 eq per FU and the coefficient of variation is 4.95%, indicating that the data are quite homogeneous and therefore the mean of 0.828 kg CO_2 eq per FU is representative. The standard error of the average is only 1.45 g CO_2 eq per FU, and the 95% confidence interval has a lower limit of 0.76 kg CO_2 eq per FU and an upper limit of 0.919 kg CO_2 eq per FU. These results are within the range (0.22–2 kg of CO_2 eq) found in previous studies carried out on peaches (Vinyes, Ingrao, Frankowska).

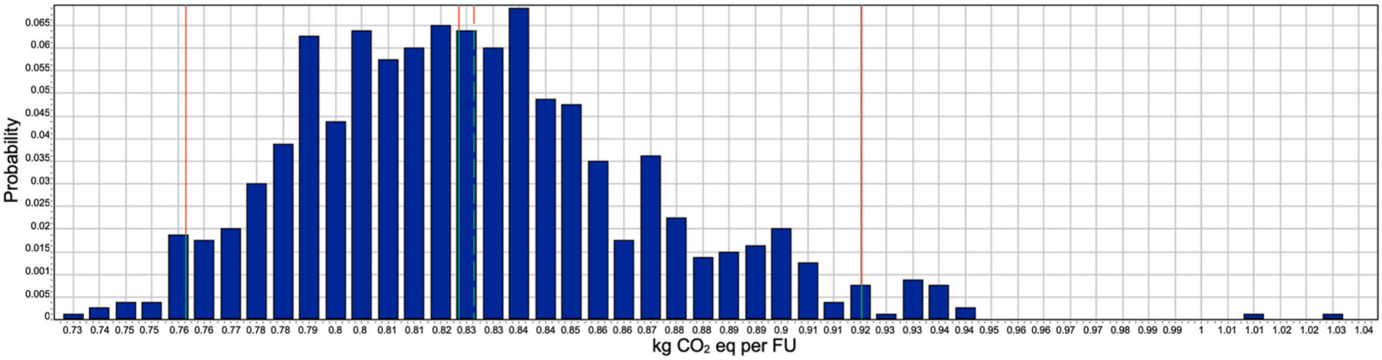


Fig. 3. Histogram of the probability distribution of the carbon footprint in kg CO_2 eq per functional unit, resulting from performing an uncertainty analysis. The red vertical solid lines at the ends show the limits of the 95% confidence interval.

4. Conclusions

The CF analysis of nectarine production yielded total emissions of 1.07 kg CO_2 eq per FU for the EEIOA and 0.899 kg CO_2 eq per FU for the pLCA, resulting in a 1.19 EEIOA/pLCA ratio. While this difference might seem acceptable, it is a matter of concern that this is in fact caused by trade-offs between larger discrepancies operating in opposite directions in the stages that make up the product life cycle. CF emissions calculated by pLCA were significantly higher than those determined by EEIOA in the upstream stage (primarily fabrication of inputs utilized for fertilization and packaging materials) (0.23 EEIOA/pLCA ratio), while the opposite was observed in the analysis of the core stage (nectarine production and processing) (4.38 EEIOA/pLCA ratio). Differences in the downstream stage were less notable (mainly distribution and storage, and EoL phase) (1.40 EEIOA/pLCA ratio). Economic-based inputs, used in EEIOA (such as labour, insurance and other service costs) and unaccounted for in pLCA, may be partly responsible for such divergences, while others should be linked to differences in the impact assessment procedures followed by each of these methodologies. These results raise some doubts about the potential of EEIOA and calls for further research on the validity, complementarity and the application domains of these methodologies.

Both modelling approaches agree in identifying distribution and refrigerated storage (in downstream stage) as the life cycle processes that contribute the most to GHG emissions of the nectarines. This calls for the implementation of policy and actions aimed at promoting the consumption of seasonal and local fruit. Additional measures should address the use of renewables in the electricity mix consumed during refrigerated storage, efficiency in the consumption of crop inputs (e.g., through the use of precision agriculture) and packaging materials.

CRediT authorship contribution statement

Pablo Núñez-Cárdenas: Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Guillermo San Miguel:** Conceptualization, Methodology, Software, Validation, Investigation, Writing – review & editing, Visualization, Supervision. **Brigitte Báñales:** Methodology, Software, Formal analysis, Data curation. **Sergio Álvarez:** Methodology, Software, Validation, Writing – review & editing, Visualization, Supervision. **Belén Diezma:** Conceptualization, Methodology, Software, Validation, Investigation, Writing – review & editing, Visualization, Supervision. **Eva Cristina Correa:** Conceptualization, Validation, Investigation, Writing – review & editing, Visualization, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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