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Research article

Multi-season environmental life cycle assessment of lemons: A case study in south Uruguay

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ABSTRACT

Lemons are a relevant agricultural commodity in Uruguay, mainly exported for fresh consumption. Food eco-labels are on the rise worldwide as consumers and authorities are increasingly demanding them. However, there is a lack of scientific studies estimating the environmental impacts of Uruguayan citrus production. This study aims to assess the environmental performance of lemon production in Uruguay taking into account inter-seasonal variability by applying the Life Cycle Assessment (LCA) methodology and following the Environmental Product Declarations (EPDs) guidelines. A cradle-to-farm gate assessment was carried out based on both mass and spatial functional units. Primary data was gathered from a representative orchard of the region for four harvest seasons (2016–2020). Environmental impact categories recommended by EN 15804 + A2 standard were assessed. Specifically, blue water scarcity was assessed using the AWARE method. In addition, human and freshwater ecotoxicity were assessed using USEtox. Results show that on-field emissions and input production are critical for most of the categories assessed (on average, 84% CC, 88% Ac, 98% MEu, and 85% TEu), whereas blue water consumed for irrigation is the main hotspot in blue water scarcity (86%, on average). As expected, inter-seasonal impacts present higher variability when expressing results per tonne vs. per hectare because, although agricultural inputs applied are the same, climatic variability influences water requirements and also affects yield. Blue water scarcity exhibits the highest variability because water consumption depends strongly on agroclimatic conditions, mainly on rain and irrigated water and on water dynamics in soil. Nitrate leaching is a key emission for freshwater eutrophication and, to a minor degree, for climate change, which also depends on the water dose and timing, either from rain or irrigation. Optimising the N application is crucial to minimise on-field emissions, a hotspot in the present study. Along these lines, improved agricultural practices are suggested to enhance the environmental profile of Uruguayan lemons. Replacement or minimisation of the dose of certain inputs (e.g., copper oxide) through the implementation of complementary agricultural practices is suggested. Finally, up-to-date techniques to decrease blue water scarcity are proposed. Methodological recommendations for future studies include modelling N emissions using mechanistic models, incorporating potential reductions in N emissions due to certain agricultural practices, and harmonizing the methodology to quantify water consumption. This study sets a baseline LCA for Uruguayan citrus fruit production. It highlights inter-seasonal variability as an issue to be considered, even when agricultural practices do not change, and especially relevant in countries with high climatic variability like Uruguay. The study also provides scientific and quantitative evidence to support the environmental decisions of both citrus producers and consumers.

1. Introduction

Citrus is the most important fruit crop in Uruguay in terms of production, area, and economic contribution, with 218,671 t, 14,587 ha and 71,489 thousand dollars from exports in 2020, respectively, as well as concerns labour demand (19.000 workers) (Cardeillac Gulla et al., 2020; MGAP, 2021). Uruguayan citrus production is characterised by a few big orchards and many smallholdings. Eight companies concentrate 63% of citrus production and 62% of the productive area. Lemons mean almost a quarter of the national citrus production, with 51,619 tonnes produced in 2020, and 19% of the total citrus area, with 2,763 ha in total (MGAP, 2021). In addition, Uruguayan production is mainly devoted to

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fresh consumption, where 44% of the citrus production is exported, namely 82,000 tonnes in 2020. At the same time, Uruguay is responsible for 7.21% of total citrus fruit exports from South America (FAO, 2021), with the European Union and the United States of America as the main destinations (MGAP, 2021).

Governments and non-governmental organisations are nowadays fostering the use of food eco-labels. Consequently, there is a proliferation of methods for measuring the environmental performance of products and organisations. In particular, the so-called type III Environmental Product Declarations (EPDs), in compliance with the ISO 14025 standard, aimed to quantify the environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function. EPDs are created and registered in the framework of a programme, such as the International EPD® System, the world's first operational EPD programme, originally founded in 1998 as the Swedish EPD System by the Swedish Environmental Protection Agency and industry. More recently, European Commission (EC) released the Product Environmental Footprint - PEF (EC, 2021) as a standard methodology to assess the environmental impact of products. The former is now in a transition phase, exploring the possibility of integrating the PEF method into the EU Ecolabel criteria, hand in hand with other political actions to accelerate the shift to sustainable food systems, such as the Farm to Fork strategy (European Commission, 2020). Initiatives are also emerging in the USA, a great Uruguayan citrus importing country, such as the Sustainable Citrus Standard (Protected Harvest, 2019) promoted by the non-profit organisation Protected Harvest. This growing complexity of environmental labelling schemes has raised concerns, as these requirements could create difficulties for small and medium-sized enterprises in export markets. In addition, schemes could be misused to protect domestic producers, although according to the Technical Barriers to Trade Agreement of the World Trade Organization (WTO, 2015), they should not create barriers or disguised restrictions on international trade. However, new non-tariff barriers for products from other countries can arise, since importers will not be willing to "finance pollution" when they are making significant investments in this respect (Romero, 2003). In a few words, sustainable consumption is undoubtedly gaining momentum and ecolabels can nudge consumers towards more sustainable food choices (Potter et al., 2021). Meanwhile, the Uruguayan citrus sector is mainly focused on improving productive growth, varietal diversification and fruit quality while shyly becoming aware of the environmental impacts associated with intensive fruit production. Therefore, a detailed analysis of the environmental impacts of citrus fruit farming can constitute a milestone, helping to prioritise actions to improve the environmental profile of the product and promote its commercialisation in increasingly demanding markets.

Life Cycle Assessment (LCA) is a widely accepted methodology to quantitatively evaluate the environmental impact of products across the agri-food chain, in general, and the agricultural production systems, in particular (Martin-Gorriz et al., 2020). Its main challenge lies in the reproducibility and comparability of the results. To handle this issue, in recent years, guidelines have been developed to assist practitioners. Among them, the Product Category Rules (PCRs) provide the rules, requirements, and guidelines for developing the abovementioned EPDs for a specific product category, allowing for comparisons within the same product group (EPD, 2022a). Similarly, the PEF initiative of the EU proposes a multi-criteria measure for the calculation of the environmental footprint of goods or services. These are complemented by the Product Environmental Footprint Category Rules (PEFCRs) that provide further specifications at the level of a specific product category (EC, 2021).

LCA has been used to determine the environmental profile of citrus grown in different countries, mainly in the Mediterranean region, mostly oranges in Italy (Lo Giudice et al., 2013; Nicolo et al., 2017; Pergola et al., 2013) and Spain (Martin-Gorriz et al., 2020; Ribal et al., 2009, 2019). Other studies have been developed more recently, specifically oranges in Mexico (Bonales-Revuelta et al., 2022) and lemons in Argentina (Machin Ferrero et al., 2021, 2022). Overall, although these studies do not always use the same impact assessment methods or assess the same impact categories, they all highlight the environmental burdens related to fertilisers as concerns. Both their manufacturing and on-field emissions stemming from their application are particularly relevant, as well as irrigation and machinery operations, as highlighted in Cabot et al. (2022). In Uruguay, the LCA tool has been shyly used over the years in the agri-food sector. The published studies focus mainly on the evaluation of a single indicator (e.g. carbon footprint or water footprint), and the productive chains analysed are mostly livestock (Becona et al., 2014; Picasso et al., 2014), dairy (Lizarralde et al., 2014), and annual crops such as maise, soybean, or sorghum (Darré et al., 2019; Bustamante Silveira, 2020). The citrus fruit sector in Uruguay is committed to a mature and conscious analysis of the impact it generates on the environment; therefore, it will require scientific evidence to sustain key decisions. To the best of the authors' knowledge, there is a lack of scientific analysis of the associated environmental impacts. The goal of this study is to carry out an environmental assessment of Uruguayan lemons production, to identify the environmental hotspots in the farming stage and propose improvements. In particular, this study aims at setting up a baseline LCA for Uruguayan citrus fruits, involving the quantification of the environmentally relevant flows of lemon production in Uruguay using several environmental indicators.

Data representativeness is a critical issue when performing LCAs of fruit production, and specially LCAs of perennial crops. Farming is especially sensitive to spatio-temporal differentiation not only due to the practices implemented according to the crop growth stages, but also to the inherent variability in farm management practices (Raschio et al., 2018). Thus, both temporal and geographical representativeness are particularly considered in the present study. The first by gathering data corresponding to four crop seasons, following the recommendations of Bessou et al. (2016) and Cerutti et al. (2014). The second by selecting a representative real orchard as recommended by Cabot et al. (2022) when a great number of orchards cannot be sampled. The studied orchard is located in the south of the country, where lemons production for fresh fruit exportation is concentrated, with 52% of the total production in 2018 (MGAP, 2019). Specifically, the selected cultivars "Lisbon" and "Fino" are two of the most cultivated varieties in Uruguay for fresh consumption (MGAP, 2019). In addition, the orchard belongs to one of the eight aforementioned largest producing and exporting companies, and the agricultural practices follow the Global GAP certification system for exportation (GLOBALG.A.P., 2022). This is the dominant certification for fruits, and citrus in particular, commercialised in both the United States and Europe (Mook and Overdevest, 2021), the leading destination of Uruguayan citrus, and therefore the most widely used by exporting companies in Uruguay (Caputi and Montes, 2010). The GLOBALG.A.P. Integrated Farm Assurance (IFA) standard for fruits covers all stages of production, from preharvest activities such as soil management and plant protection product application.

2. Materials and methods

This study follows the LCA methodology based on ISO standards (ISO, 2006a, 2006b; ISO, 2017; ISO, 2020a; ISO, 2020b) using GaBi software (Sphera Solutions GmbH, Leinfelden-Echterdingen, Germany). In addition, the PCR 2019:01 V1.01 for fruits and nuts (EPD, 2019) and the International EPD framework guided most of the methodological choices adopted, specifically as concerns the functional unit, system boundaries and impact assessment. A mass functional unit was considered, and most of the attributional processes of the upstream and core processes were included. In addition, the impact categories reported in the results also correspond to those suggested in the PCR (EPD, 2019). While this study does not constitute an EPD of Uruguayan lemons, following these guidelines facilitates comparability with studies undertaken under the auspices of the PCRs.

2.1. System description

The selected orchard is representative of Uruguayan fresh lemon production for export (mostly located in the south), with middle-aged trees and follows standard integrated production practices. It has a total surface of 243.51 ha with lemon and mandarin; of these, 6.26 ha correspond to lemon trees of the 'Lisbon' and 'Fino' cultivars planted in the same year (2008), with a density of 516 trees·ha^{-1} (3230 trees in total). The orchard is located in Kiyú, in San José Department, south of Uruguay. According to IPCC (2006), this region has a warm temperate moist climate, which corresponds to a subtropical humid zone. For the studied harvest seasons (from 2016 to 2020), and based on data from the nearest weather station, the average annual rainfall was 1010 mm, and the average temperature was 17.0 °C. A minimum temperature of −2.4 °C was recorded in August 2018, and a maximum of 37.9 °C in January 2016 (INIA-GRAS, 2022). As to soil characteristics, according to CONEAT classification, it is a 10.8 b soil, whose geological material corresponds to silt clay sediments of brown colour and normally with calcium carbonate concretions (INIA-GESIR, 2022). The dominant soils are Brunosols/Vertisols corresponding to Hapludert (Vertisols) in the USDA classification and Vertisol Rúptico Lúvico in the DSA-MGAP classification (INIA- SIGRAS, 2022).

Different operations are carried out during each cropping season, beginning immediately after the previous harvest (usually August) and ending with the next harvest (July). Fertilisation is generally carried out from September to December. All pesticides are applied via foliar, as some of the fertilisers, the rest are applied by fertigation. The pesticides are applied from September to November, except for cuprous oxide, which application extends until May. Their main objective is combating pests such as insects or mites and fungi such as Colletotrichum, scabies, botrytis, canker, and melanosis, among others. A tractor, with 44.1 kW of power at rated speed and 1800 rpm rated speed, is employed for input application, pruning, shredding pruning debris, and transporting orange bins. Drip irrigation is performed from September to March, coinciding with the most significant water demand in spring-summer, by using an electric pump fed from an underground well of approximately 30 m depth. As mentioned, lemons for export are harvested in July; they are picked by hand and then quickly transported to packinghouses, where the fruit is packaged according to the quality requirements at the destination.

2.2. Life cycle assessment

2.2.1. Functional unit and system boundaries

Two functional units (FUs) are adopted in this study. From a product perspective and related to eco-labelling purposes (e.g. EPD, PEF), a mass-based FU (1-tonne lemon · season^{-1}) is chosen according to the above-mentioned PCR (EPD, 2019). In addition, a land-based FU (1 ha · season^{-1}) is selected to consider land use intensity and to take into account the provision of ecosystem services. By using these FUs, both overvaluation of resource use efficiency and displacement of environmental impacts are avoided (Cerutti et al., 2011). It must also be noted that these two FUs are also used in LCAs of citrus fruits (Alishah et al., 2019; Pergola et al., 2013; Ribal et al., 2017; Yan et al., 2016; Yang et al., 2020). The system boundaries are set from cradle to farm gate (Fig. 1). The stages taken into consideration are the production of fertilisers and pesticides, their transport to the orchard and their application, the use of machinery for agricultural practices (including fuel production), and irrigation (including electricity production for the irrigation pump). The manufacturing of capital goods such as tractors is not included because they have a long life and are used on successive seasons within the same farm, which implies an intensive use, thus the environmental load allocated to the FU is negligible. Furthermore, Frischknecht et al. (2007) showed that the production of capital goods for agriculture has a non-significant contribution to most of the impact categories, except for cumulative energy demand.

As regards the temporal system boundaries, a farming season is assessed, beginning in August, immediately after the previous harvest, and ending with the lemon harvest in July. In addition, to analyse the variability of the impact results over time and following the recommendations of Bessou et al. (2016) and Cerutti et al. (2014), four farming seasons corresponding to the years 2016–2020 have been taken into account.

2.2.2. Life cycle inventory (LCI)

Information on the agricultural practices, yields, the type and dose of inputs applied, together with their origin, the amount of water for irrigation, and fuel for machinery, was obtained from direct interviews with the agronomist responsible for the orchard. Agroclimatic parameters used to calculate water consumption were retrieved from INIA agroclimatic data bank (INIA-GRAS, 2022), namely maximum, minimum, and average temperatures, wind speed, average relative humidity, effective precipitation and heliophany.

Relevant background processes were mostly taken from Ecoinvent 3.8. Database (Moreno Ruiz et al., 2021; Wernet et al., 2016). However, some specific processes were taken from GaBi v.10 (Sphera Solutions GmbH, 2022) database, namely the electricity mix in Uruguay and the transoceanic transport, which are not available in Ecoinvent 3.8. The irrigation pump and the tractor were retrieved from GaBi v.10 database too because processes are parametrised, which allows specific data of the orchard to be used (e.g. well depth, tractor nominal power, etc.). These processes were then used to develop reference LCI datasets for the LCA models, as explained below. Metadata for these reference LCIs is described in Table S1.

2.2.2.1. Input production and transportation. Default processes from

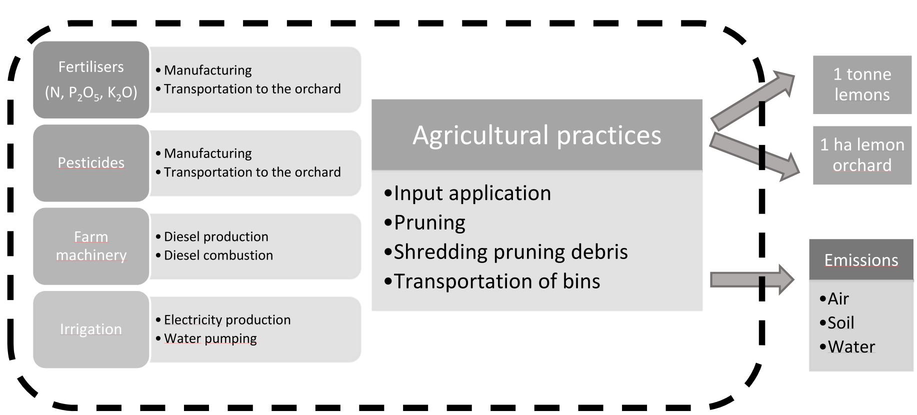

Fig. 1. System boundaries showing the life cycle stages included in the LCA of Uruguayan lemons.

Ecoinvent 3.8. Database (Moreno Ruiz et al., 2021; Wernet et al., 2016) were chosen for fertiliser production. Those fertilisers not found in the database were modelled as standard NPK fertilisers, considering their respective fertiliser units, as N, P_2O_5 and K_2O. The production of a corrective foliar fertiliser with a high concentration of zinc and the production of gibberellic acid (a growth regulator) could not be modelled due to a lack of data. However, it must be noted that the doses applied are low.

Data on pesticide manufacturing was taken from Ecoinvent 3.8 (Moreno Ruiz et al., 2021; Wernet et al., 2016). considering their active substance, as follows. First, the production process corresponding to the active principle was searched for, if it was not available in the commercial databases mentioned above, the chemical group of the pesticide was considered. In case the compound was not found, then the pesticide production was modelled as the generic "pesticide production" process from Ecoinvent 3.8. As can be seen in Table S1, only mancozeb, paraffinic oil and cuprous oxide could be modelled directly, whereas pyraclostrobin and pyriproxyfen were modelled considering their corresponding chemical group and the rest as generic pesticides. The transportation of all the agricultural inputs entailed the transfer by ship and lorry, except for those products that could be transported exclusively by land, for which a lorry with 16–32 metric tonne payload was considered. For all of them, one-way transport was modelled by using the corresponding Ecoinvent 3.8 (Wernet et al., 2016) and GaBi (Sphera Solutions GmbH, 2022) processes (Table S1). The distances travelled were obtained from Searates (2022) (Table S2).

2.2.2.2. Emissions from fertiliser and pesticide application. To model direct and indirect N_2O emissions, the Tier 1 IPCC Guidelines (IPCC, 2006) and the subsequent refinement (IPCC, 2019) were used, inasmuch as they are more recent than those suggested by the PCRs for fruits and nuts (EPD, 2019). IPCC (2019) considers the climate in the region of study and the type of fertiliser, which in this case study correspond to wet climate and synthetic fertiliser, respectively. NH_3 and NO_x were modelled following the EMEP/EEA guidebook (EEA, 2019), an updated version of the EEA (2013) proposed in the PCRs for fruits. In particular, NH_3 emissions were estimated following a Tier 2 approach, considering normal soil pH (7.0 or below) and temperate climate. A Tier 1 emission factor was used for NO_x emissions since the EMEP/EEA guidebook (EEA, 2019) does not propose a Tier 2 emission factor. Nitrate (NO_3^-) leaching was estimated with the Tier 2 model SQCB-NO_3 (Emmenegger et al., 2009), which represents an improvement of the IPCC emission factor proposed in the PCRs (EPD, 2019). Specifically, the model considers climatic parameters, namely precipitation, soil and crop characteristics and data related to agricultural practices, as described below. Precipitation values were obtained from the nearest meteorological station, INIA Las Brujas, located in the Canelones department, 36 km away from the studied orchard (INIA-GRAS, 2022). The clay content of the soil was obtained by taking into account the soil type according to USDA classification (Vertisols) and using the table proposed by Emmenegger et al. (2009). The nitrogen content in soil organic matter was estimated using the equation and standard values proposed in the SQCB-NO_3model. The depth of the roots was retrieved from Goñi and Otero (2009). As to the absorption of nitrogen by the crop, values from Gambetta et al. (2021) for Uruguayan citrus fruits were used. Data on the agricultural practices (irrigation, N supply from fertilisers) were obtained from interviews with the agronomist responsible for the orchard. In line with the recommendations of the PCRs (EPD, 2019), phosphate (PO_4^{3-}) leaching was estimated with the SALCA-P model (Nemecek et al., 2019), considering the P_2O_5 content of each fertiliser used.

Primary emissions from pesticide application were calculated following PestLCI Consensus V.1.0 (Fantke et al., 2017), which estimates the fraction of pesticide emitted to the environmental compartments, namely air, field soil surface, crop leaf surface and off-field surface (freshwater and natural soil). It is a consensus model that takes into account several parameters to make a better approximation of the primary distribution of the pesticides. In particular, the model considers the crop type, dose applied, fraction of pesticide intercepted by the leaves -which depends on the stage of the crop- and the application method considering drift reductions. It also accounts for the surface area of the orchard and whether there is a buffer zone (location and width).

2.2.2.3. Water use, energy, and blue water consumption for irrigation. The amount of irrigated water per season was primary data provided by the farmer (see Table 1). The electricity consumption for irrigation (Table 1) was estimated by using the GaBi process "Irrigation pump generic", employing as inputs the amount of water irrigated for each season (1069.77 mm on average) and the depth of the well (30 m). Default values for the nominal operating pressure (3 bar) and the efficiencies of the power unit (0.9), pumping (0.8) and irrigation (1.0) were used.

The blue water consumption for irrigation was estimated according to Allen et al. (1998). The method is based on a soil balance in the root zone considering the evapotranspiration under water stress conditions:

$$D_{r,i} = D_{r,i\text{-}1} - P_{eff,i} - I_i - CR_i + ET_{c,i} + DP_i \qquad (1)$$

In the following paragraphs, the parameters involved in equation (1) are explained together with the methods or data sources used for their estimation. The subscript "i" refers to daily values.

$D_{r,\ i}$ and $D_{r,i\text{-}1}$ refer to moisture depletion in the root zone (mm). Initial $D_{r,i\text{-}1}$ was considered zero since it is assumed that the analysis starts after heavy rain or irrigation which means that, according to Allen et al. (1998), the moisture content in the root zone is close to field capacity and $D_{r,i\text{-}1} \approx 0$.

$P_{eff,i}$ is the effective precipitation (mm), retrieved from INIA Las Brujas meteorological station (INIA-GRAS, 2022).

Some previous concepts must be defined to estimate I_i (net layer of irrigation on the day i that infiltrates the soil, mm). The first corresponds to the readily available (extractable) water from the soil root zone (RAW, mm), which is the maximum fraction of the total available water the crop can extract from the root zone without experiencing water stress. The second is moisture depletion in the root zone (D_r), defined as the amount of water missing with respect to the field capacity. Taking as a premise that irrigation is not necessary as long as the crop has readily available water in the soil to consume, the following assumption is made; in the event that the value of the initial moisture depletion in the root zone minus the effective precipitation of that day (which is considered to occur at the beginning of the period) is greater than the RAW value, the dose of irrigation water (I_i) needed to reach the field capacity is ($D_{r,i\text{-}1}$ - $P_{eff,i}$) is applied. Otherwise, the crop is not irrigated.

To calculate the RAW, the total water available in the root zone of the soil (TAW, mm) and the average fraction of the total water available in the soil that can be depleted from the root zone before moisture stress (p_i) were calculated, as follows:

$$RAW_i = p_i \cdot TAW \qquad (2)$$

$$TAW = 1000 \cdot (\theta_{FC} - \theta_{WP}) \cdot Z_r \qquad (3)$$

Where θ_{FC} is the moisture content at field capacity ($m^3 \cdot m^{-3}$) and θ_{WP} is the moisture content at permanent wilting point ($m^3 \cdot m^{-3}$), both values retrieved from INIA-GESIR (2022) for CONEAT 10.8 b soils; Zr is the root depth (m), retrieved from Goñi and Otero (2009). The p_i-value for citrus fruits was calculated according to Allen et al. (1998) as:

$$p_i = 0.4 + 0.04 \cdot (5 - ET_{c,i}) \qquad (4)$$

$ET_{c,i}$ is the crop evapotranspiration on the day i (mm) and its calculation is detailed below.

CR^i is the capillary rise from the groundwater table on the day i (mm). It is assumed to be zero since the water table in Uruguay is more than 1 m below the root zone (Allen et al., 1998; Fan et al., 2013).

$ET_{c,i}$ was estimated by following FAO guidelines (Allen et al., 1998):

Table 1
Main inventory data for the lemon cultivation stage.

LCI data	Unit	2016–2017	2017–2018	2018–2019	2019–2020	Average	Standard deviation
Yield	$tonne \cdot ha^{-1}$	47.0	55.0	49.0	66.0	56.0	9.5
Electricity consumption for irrigation	$kWh \cdot ha^{-1}$	21.0	37.5	26.4	87.8	43.1	30.5
Water withdrawal for irrigation	$m^3 \cdot ha^{-1}$	520.1	928.6	654.2	2176.2	1069.8	757.0
Rainfall water	$mm \cdot season^{-1}$	955.6	1062.6	1119.8	901.2	1009.8	99.4
Rainfall + irrigation water	$mm \cdot season^{-1}$	1007.6	1155.5	1185.2	1118.8	1116.8	77.7
Machinery use	$h \cdot ha^{-1}$	27.0	27.0	27.0	27.0	27.0	0.0
Diesel for machinery operations							
Application of inputs	$L \cdot ha^{-1}$	87.6	87.6	87.6	87.6	87.6	0.0
Pruning	$L \cdot ha^{-1}$	15.0	15.0	15.0	15.0	15.0	0.0
Crushing of pruning waste	$L \cdot ha^{-1}$	9.0	9.0	9.0	9.0	9.0	0.0
Harvest and transport of bins	$L \cdot tonne^{-1}$	1.8	1.8	1.8	1.8	1.8	0.0
Fertilisers							
Total N	$kg \cdot ha^{-1}$	203.1	203.1	203.1	203.1	203.1	0.0
Total P_2O_5	$kg \cdot ha^{-1}$	8.5	8.5	8.5	8.5	8.5	0.0
Total K_2O	$kg \cdot ha^{-1}$	142.8	142.8	142.8	142.8	142.8	0.0
NPK 30-0-0	kg · ha-1	677.0	677.0	677.0	677.0	677.0	0.0
Potassium chloride	kg · ha-1	235.0	235.0	235.0	235.0	235.0	0.0
Phosphoric acid	kg · ha-1	8.0	8.0	8.0	8.0	8.0	0.0
Zinc	kg · ha-1	2.0	2.0	2.0	2.0	2.0	0.0
NPK 0-40-20	kg · ha-1	8.9	8.9	8.9	8.9	8.9	0.0
Fungicides							
Difenoconazole	$kg \cdot ha^{-1}$	0.4	0.4	0.4	0.4	0.4	0.0
Pyrachlostrobin	$kg \cdot ha^{-1}$	0.3	0.3	0.3	0.3	0.3	0.0
Cuprous oxide	$kg \cdot ha^{-1}$	25.2	25.2	25.2	25.2	25.2	0.0
Mancozeb	$kg \cdot ha^{-1}$	3.2	3.2	3.2	3.2	3.2	0.0
Insecticides							
Pyriproxyfen	$kg \cdot ha^{-1}$	$3.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	$3.0 \cdot 10^{-2}$	0.0
Acetamiprid	$kg \cdot ha^{-1}$	0.3	0.3	0.3	0.3	0.3	0.0
Paraffinic oil	$L \cdot ha^{-1}$	50.7	50.7	50.7	50.7	50.7	0.0
Abamectin	$kg \cdot ha^{-1}$	$4.1 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	$4.1 \cdot 10^{-2}$	0.0
Growth regulator							
Gibberellic acid	$kg \cdot ha^{-1}$	0.2	0.2	0.2	0.2	0.2	0.0
On-field emissions							
Direct N_2O	$kg \cdot ha^{-1}$	5.1	5.1	5.1	5.1	5.1	0.0
Indirect N_2O (from NO_3^-)	$kg \cdot ha^{-1}$	3.5	3.9	4.0	3.8	3.8	0.2
Indirect N_2O (from NH_3)	$kg \cdot ha^{-1}$	0.3	0.3	0.3	0.3	0.3	0.0
NH_3 volatilised	$Kg\ ha^{-1}$	13.6	13.6	13.6	13.6	13.6	0.0
NO_2 volatilised	$Kg\ ha^{-1}$	8.1	8.1	8.1	8.1	8.1	0.0
NO_3^- leached	$kg \cdot ha^{-1}$	895.7	1013.2	1036.9	984.1	982.5	61.7
PO_4^{3-} leached	$kg \cdot ha^{-1}$	0.3	0.3	0.3	0.3	0.3	0.0

$$ET_{c,i} = Kc \cdot ET_{0,i} \tag{5}$$

Where $ET_{c,i}$ corresponds to the crop evapotranspiration ($mm \cdot day^{-1}$), Kc is the crop coefficient (dimensionless), and $ET_{0,i}$ is the reference crop evapotranspiration ($mm \cdot day^{-1}$). To obtain daily $ET_{0,i}$, climate data for the studied seasons from INIA Las Brujas meteorological station (INIA-GRAS, 2022) was used as an input for the Penman-Monteith equation (Allen et al., 1998). Then, by adding up those daily values, the monthly $ET_{0,m}$ (mm/month) values were calculated, which were subsequently multiplied by the monthly Kc for Uruguayan citrus fruits obtained from García Petillo and Castel (2007) to obtain $ET_{c,m}$ ($mm \cdot month^{-1}$). These authors performed a water balance considering the irrigation, effective precipitation, and parameters related to soil characteristics (drainage and variation in the soil water storage during the studied period) for a citrus orchard located at Kiyú, Uruguay. Finally, the monthly $ET_{c,m}$ ($mm \cdot month^{-1}$) values were added to obtain the $ET_{c,s}$ of the studied seasons ($mm \cdot season^{-1}$), as reported in Table S3.

DP_i is the water loss from the root zone by deep percolation on the day i (mm) after heavy rain or irrigation. It was calculated using equation (1), considering that the values of $D_{r,i}$ and CR_i are zero; this means that there is no moisture depletion in the soil root zone or capillary rise from the groundwater table after heavy rain or irrigation, thus equation (1) becomes:

$$DP_i = P_{eff,i} + I_i - ET_{c,i} - D_{r,i-1} \tag{6}$$

If the system is below its field capacity, this value is null.

2.2.3. Impact categories and impact assessment methods

As recommended by the PCRs for fruits (EPD, 2019), a default list of environmental performance indicators was accounted for, and the latest update of that list, made on 2022-03-29, was considered (EPD, 2022b). In this regard, the impact categories and the corresponding category indicators recommended by the EN 15804 + A2 standard were assessed, namely, climate change - CC (CO2 eq.), acidification - Ac (mol H+ eq.), freshwater eutrophication - FEu (kg P eq.), marine eutrophication - MEu (kg N eq.), terrestrial eutrophication - TEu (Mole of N eq.), photochemical ozone formation (impacts on human health) - POF hh (kg NMVOC eq.), ozone depletion - OD (kg CFC 11 eq.), resource use of minerals and metals - RU m (kg Sb eq.) and resource use of fossil resources - ADP f (MJ). The AWARE method (Boulay et al., 2018) was applied to assess blue water scarcity - BWS (m^3 eq.) as is the most up-to-date method also recommended for EPDs (EPD, 2022b). Specific monthly characterisation factors (CF) for the corresponding Uruguayan basin (Río de la Plata) were used to calculate the direct water consumption at the field. For indirect water consumption (i.e., inputs manufacturing, irrigation, electricity production and diesel production and combustion), the world average CF for non-agricultural activities ($CF = 20.30\ m^3\ eq. \cdot m^{-3}$) was selected, inasmuch as those processes are carried out in locations worldwide.

Besides the listed categories, toxicity impacts were assessed to address consumers' concerns about the widespread use of pesticides. USEtox 2.12 (Rosenbaum et al., 2008) was the method applied to assess freshwater ecotoxicity (CTUe) and human toxicity carcinogenic and non-carcinogenic (CTUh) because it is the most widely used method for agri-food LCAs as well as the recommended method by the ILCD

Handbook (Finkbeiner, 2011). Since there are no CFs available in USEtox 2.12 database for paraffinic oil, acetamiprid and pyraclostrobin, a literature search was carried out. Specifically, the CF for paraffinic oil was obtained from Juraske and Sanjuán (2011) and that for acetamiprid from Steingrímsdóttir et al. (2018). Human toxicity CF for Pyrachlostrobin was taken from Fantke and Jolliet (2016), and the one for ecotoxicity from Bennet (2012). As regards cuprous oxide and abamectin, the CFs for substances with similar characteristics, namely copper (II) and avermectin B1A, were used, respectively. According to the PCRs for fruits and nuts (EPD, 2019) and taking into account the EPD (2022b) guidelines, indicators for primary energy resources were also assessed following EN 15804 + A2.

3. Results and discussion

3.1. Environmental impacts and contribution analysis

Table 2 shows the impact results for each impact category and FU for all the periods assessed, together with the average value and the coefficient of variation (CV). The average contribution of the life cycle stages for the assessed seasons is represented in Fig. 2, whereas the average values and their standard deviation for both FUs are shown in Tables S4a and S4b.

Regarding the relative contribution of different cradle to farm gate stages, on-field emissions from fertilisers is the dominant contributor to climate change (55–56% of the total impact, depending on the season), followed by fertilisers production (13–14%). Specifically, the production of NPK 30-0-0 and its subsequent N_2O emissions represent the main hotspots. Marine eutrophication is also led by on-field emissions from fertilisers (97–98%), while freshwater eutrophication is dominated by the production of both pesticides (71%) and fertilisers (20%). On-field emissions from fertilisers, in particular NH_3 and NO_2, together with machinery operations, are the stages with the greatest weight on terrestrial eutrophication (75% and 11%, respectively). Blue water consumption for irrigation is the main contributor to blue water scarcity, with an average of 86% and ranging from 75 to 91%, depending on the season. As to the categories related to resource depletion, the main contributor to fossil use is fertiliser production (57%), followed by machinery operations (23%). Pesticide production (91%) -mostly copper oxide-is the main hotspot detected regarding mineral and metals use. In the acidification category, field emissions -mainly NH_3 and NO_2- and pesticide production are the main contributors, with 61% and 16% of total impacts, respectively. POF is dominated in equal parts by machinery operations and NO_2 field emissions (33% each). In OD, the stage that impacts the most is input production (82% fertilisers and 12% pesticides).

When analysing the results of toxicity-related categories, pesticide production means 90% of total ET, 50% of HTc and 63% of HTnc, being copper pesticides the ones with the highest impact scores. Other two relevant stages in this impact category are fertiliser production (10% of total ET and 45–46% of HTc) and the emissions stemming from pesticide application (26% HTnc). Among the pesticides used, and considering the quantity applied, cuprous oxide, mancozeb, difenoconazole, and abamectin exhibit the highest values in ecotoxicity. Cuprous oxide, acetamiprid, pyraclostrobin and abamectin have the highest scores in human toxicity (Table S5). Despite the different origins of the agricultural inputs, their transportation does not represent a hotspot for any of the impact categories analysed, as most of the distances are covered by ship, an efficient transport which generates lower impacts than trucks (Wernet et al., 2016; Sphera Solutions GmbH, 2022).

Average results and standard deviations of resource use indicators (renewable and non-renewable primary energy resources) can be found in Tables S6a and S6b. The stage with the greatest impact on renewable and non-renewable energy is fertiliser production, with 38–43% (depending on the season) and 57%, respectively, mainly due to the production of NPK 30-0-0. As to renewable energy, pesticide production -especially copper oxide- and machinery operations, with a similar proportion of 23–26%, are other impacting stages. The second most impacting stage in the category of non-renewable energy is machinery operations (23%).

3.2. Inter-seasonal variability of impacts

To evaluate the inter-seasonal variability of the results, for each cropping season, the coefficient of variability (CV, %) (Table 2) and the ratio "impact value in the season/mean impact value" were calculated for each impact category and FU. By plotting this ratio (Fig. 3), it is possible to observe how the values for each season and impact category are distributed with respect to the mean.

When the impact categories are expressed per ha, inter-seasonal variability of most impact categories is low, with CVs close to 0%, mainly because of the uniformity of agricultural practices since the applied inputs are the same (see Table 1). Only the irrigation water requirements, which depend on agroclimatic conditions, and

Table 2
Impact results per cropping season, average impacts, and coefficient of variation (CV) of cradle to farm gate lemon cultivation in Uruguay.

	FU = 1ha						FU = 1 tonne					
Impact category	2016 2017	2017 2018	2018 2019	2019 2020	Average	CV (%)	2016 2017	2017 2018	2018 2019	2019 2020	Average	CV (%)
Climate change (kg CO_2 eq.$\cdot$FU^{-1})	4870.1	5009.7	5035.2	4985.4	4975.1	1	103.6	91.1	102.8	75.5	93.2	14
Ozone depletion (kg CFC-11 eq.$\cdot$FU^{-1})	$2.0 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	$2.0 \cdot 10^{-4}$	0	$4.3 \cdot 10^{-6}$	$3.7 \cdot 10^{-6}$	$4.2 \cdot 10^{-6}$	$3.1 \cdot 10^{-6}$	$3.8 \cdot 10^{-6}$	14
Acidification (Mole of H^+ eq.$\cdot$FU^{-1})	77.0	77.0	77.0	77.0	77.0	0	1.6	1.4	1.6	1.2	1.4	15
Freshwater eutrophication (kg P eq.$\cdot$FU^{-1})	1.3	1.3	1.3	1.3	1.3	0	$2.8 \cdot 10^{-2}$	$2.4 \cdot 10^{-2}$	$2.7 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$2.4 \cdot 10^{-2}$	15
Marine eutrophication (kg N eq.$\cdot$FU^{-1})	212.8	239.3	244.6	232.6	232.3	6	4.5	4.4	5.0	3.5	4.3	14
Terrestrial eutrophication (Mole of N eq.$\cdot$FU^{-1})	290.3	290.3	290.3	290.4	290.3	0	6.2	5.3	5.9	4.4	5.4	15
Photochemical ozone formation, human health (kg NMVOC eq.$\cdot$FU^{-1})	24.6	24.6	24.6	24.6	24.6	0	0.5	0.4	0.5	0.4	0.5	15
Resource use, mineral and metals (kg Sb eq.$\cdot$FU^{-1})	0.3	0.3	0.3	0.3	0.3	0	$6.5 \cdot 10^{-3}$	$5.6 \cdot 10^{-3}$	$6.3 \cdot 10^{-3}$	$4.7 \cdot 10^{-3}$	$5.8 \cdot 10^{-3}$	15
Resource use, fossils (MJ$\cdot$FU^{-1})	$3.6 \cdot 10^{4}$	$3.6 \cdot 10^{4}$	$3.6 \cdot 10^{4}$	$3.6 \cdot 10^{4}$	$3.6 \cdot 10^{4}$	0	772.3	660.1	740.8	550.5	680.9	15
Ecotoxicity (CTUe$\cdot$FU^{-1})	$8.2 \cdot 10^{7}$	$8.2 \cdot 10^{7}$	$8.2 \cdot 10^{7}$	$8.2 \cdot 10^{7}$	$8.2 \cdot 10^{7}$	0	$1.7 \cdot 10^{6}$	$1.5 \cdot 10^{6}$	$1.7 \cdot 10^{6}$	$1.2 \cdot 10^{6}$	$1.5 \cdot 10^{6}$	15
Human toxicity, cancer (CTUh$\cdot$FU^{-1})	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-4}$	0	$4.7 \cdot 10^{-6}$	$4.0 \cdot 10^{-6}$	$4.5 \cdot 10^{-6}$	$3.4 \cdot 10^{-6}$	$4.2 \cdot 10^{-6}$	14
Human toxicity, non-canc. (CTUh$\cdot$FU^{-1})	$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	$3.1 \cdot 10^{-3}$	0	$6.6 \cdot 10^{-5}$	$5.7 \cdot 10^{-5}$	$6.4 \cdot 10^{-5}$	$4.7 \cdot 10^{-5}$	$5.8 \cdot 10^{-5}$	15
Blue water scarcity (m^3eq.$\cdot$FU^{-1})	$6.9 \cdot 10^{3}$	$7.7 \cdot 10^{3}$	$2.9 \cdot 10^{3}$	$7.9 \cdot 10^{3}$	$6.4 \cdot 10^{3}$	37	147.3	140.8	59.4	119.8	116.8	34

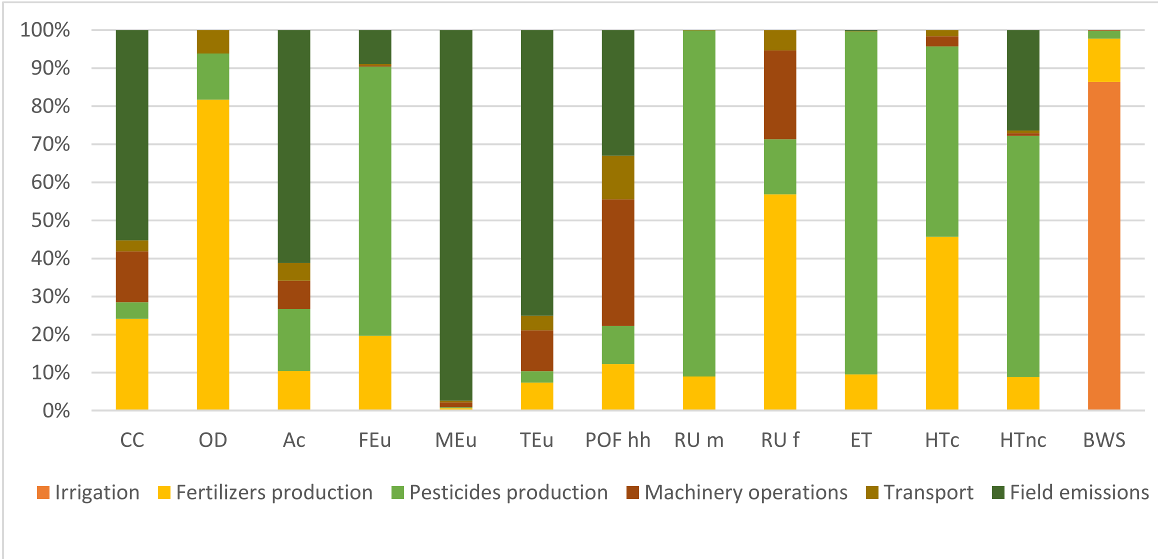

Fig. 2. Average percent contribution of the life cycle stages to the environmental footprint of Uruguayan lemons, per tonne of lemon and per ha. Climate Change (CC), Ozone Depletion (OD), Acidification (Ac), Freshwater eutrophication (FEu), Marine eutrophication (MEu), Terrestrial eutrophication (TEu), Photochemical ozone formation impacts on human health (POF hh), Resource use - mineral and metals - (RU m), Resource use - fossils - (RU f), Ecotoxicity (ET), Human toxicity - cancer (HTc), Human toxicity - non-cancer (HTnc), Blue water scarcity (BWS). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

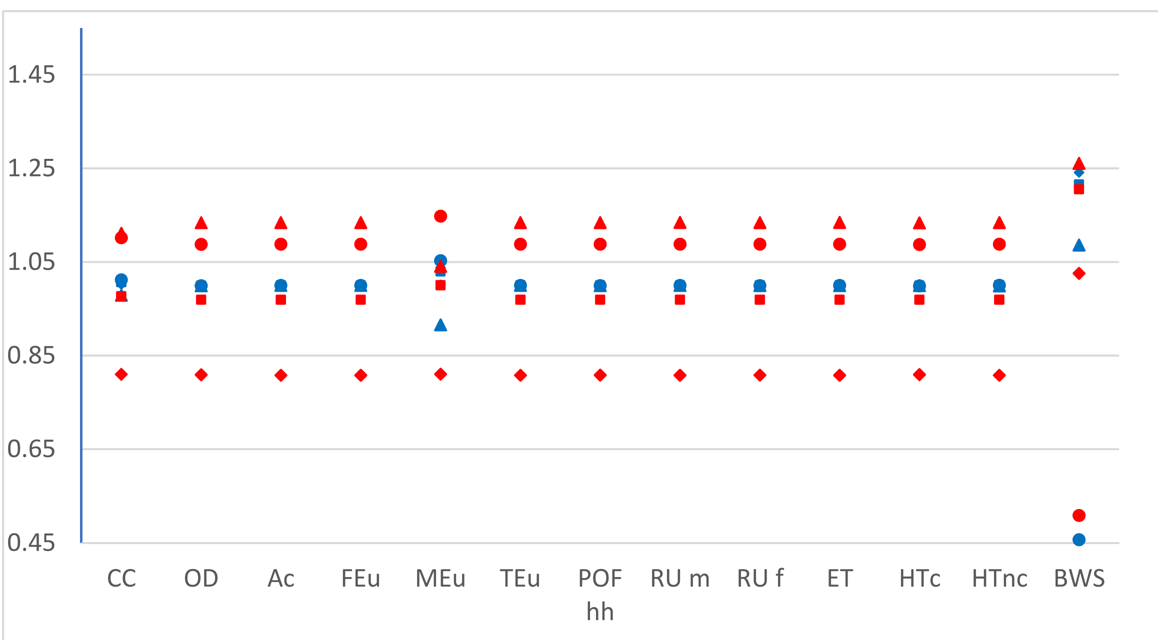

Fig. 3. Relative variability of the impact values of Uruguayan lemons with respect to the mean for the studied seasons. Red symbols represent results per tonne of product, and blue symbols results per hectare of the orchard. ▲ 2016–2017, ■ 2017–2018, ● 2018–2019 ◆ 2019–2020. Climate Change (CC), Ozone Depletion (OD), Acidification (Ac), Freshwater eutrophication (FEu), Marine eutrophication (MEu), Terrestrial eutrophication (TEu), Photochemical ozone formation, human health (POF hh), Resource use - mineral and metals - (RU m), Resource use - fossils - (RU f), Ecotoxicity (ET), Human toxicity - cancer (HTc), Human toxicity - non-cancer (HTnc), Blue water scarcity (BWS). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

consequently the energy needed for irrigation, change. In fact, the only categories that have a CV greater than 0% are BWS, MEu and CC, with 37%, 6% and 1%, respectively (Table 2). The high CV of BWS can be explained by the dependence of the crop's water demand on climatic parameters (mostly precipitation, relative humidity, wind, and temperature), which vary notably from year to year in Uruguay. In turn, the BWS impact also depends on the monthly scarcity CF of the basin, also influencing the variability of the results. The maximum and minimum BWS are detected for 2019–2020 and 2018–2019, respectively. Specifically, the value for 2018–2019 is the one that contributes the most to the great inter-season CV of this impact per ha, since it is approximately 60% lower than the values obtained for the remaining seasons. When observing in detail the monthly water consumption from November to March (the months with the greatest CFs for the studied basin), the season 2018–2019 exhibits the lowest water consumption (51% of total consumption). On the contrary, in 2019–2020, the water consumed in those months is the greatest (100%), which could explain the CV values obtained.

When analysing the inter-season variability per ha of MEu and CC, it must be borne in mind that on-field emissions is the stage that mostly influences those impact categories, with 97–98% and 55–56%, respectively, as commented in Section 3.1. Specifically, the higher inter-season variability of MEu (Fig. 3) mainly depends on NO_3^- leaching, which varies along the cropping seasons since it depends on both precipitation and irrigation, which usually vary from season to season. The extreme values of NO_3^- leached correspond to the seasons 2018–2019 and 2016–2017, where the sum of 'irrigation + rainfall' is maximum (1185.2 mm) and minimum (1007.6 mm), respectively (see Table 1). N_2O emissions dominate the CC category; these include direct and indirect N_2O emissions. The former are constant for all crop seasons since they depend on the amount of fertiliser applied, and the latter depends on NH_3 and NO_x emissions to air and on NO_3^- leached to groundwater. NH_3 and NO_x emissions are also constant for all the crop seasons assessed since they also depend on the amount of fertiliser applied. Hence, NO_3^- leaching is again the main source of variation for this impact, which depends on the above-mentioned variable factors. The greatest CC value thus corresponds to 2018–2019, with 5035.16 CO_2 eq.·ha^{-1}, and the lowest to 2016–2017, with 4870.1 CO_2 eq.·ha^{-1} (Table 2). It should be noted that these maximum and minimum CC values are not so different since there is not a direct relation between CC and NO_3^- leaching, as in the case of MEu. Finally, it should also be remarked that for the remaining categories in which on-field emissions is a relevant stage (61.15% of total Ac, 75.06% of TEu, 32.98% of POF hh), the CV is low (Table 2). The principal explanation lies in the main emissions that influence each of them. In particular, for Ac and TEu, NH_3 and NO_2 are the most influencing emissions, while NO_2 affects POF hh values. These emissions are constant for all the seasons studied since they depend directly on the amount of N applied, which was the same.

An interesting point to be raised is that the Uruguayan data used in this case study reveal an average annual N loss by NO_3^- leaching of 221.6 kg N · ha^{-1}, higher than the amounts of N applied with the fertiliser (203.1 kg N · ha^{-1} on average). This implies that a large part of the applied N fertiliser would be lost through leaching and that there is also a loss of N draining from the soil content. The model used in the present study (SQCB-NO_3 model) does not consider the day the fertiliser is applied, either the rain or irrigation days, which could directly influence the results. In turn, it neither considers the type of crop nor its N absorption dynamics. Using methodologies that contemplate these parameters would conduct to different and more accurate results. Along these lines, Pittelkow et al. (2016), who study the sustainability of the rice intensification process in Uruguay, point out that losses due to NO_3^- leaching depend on climatic factors and crop management, which have a great space-time variability, directly affecting the leaching rates. This highlights the importance of considering several harvest seasons, as in the present case study. The use of mechanistic models is recommended to quantify these emissions, considering the weight that NO_3^- leaching has, mainly in the MEu category but also in the CC category.

As expected, when expressing data per tonne, a greater variability is observed (Table 2), with CVs around 15%, except for BWS, which registered a 34% variation (Fig. 3). This highlights the strong relationship between impacts and yield, which depends on both climatic variables (e.g. rainfall, temperature-frost damage, irradiance, relative humidity), as well as on the agricultural practices (e.g. pruning, management of yield alternation, harvest time). The greatest variability ratios for all the impact categories per tonne, except MEu, correspond to those obtained in 2016–2017 (season with the lowest yield, 47 tonnes ·ha^{-1}), while the lowest are the ones for 2019–2020 (season with the greatest yield, 66 tonnes ·ha^{-1}), with BWS being an exception, showing the lowest ratio in 2018–2019. The greatest variability ratio obtained for MEu corresponds to 2018–2019, in which the sum of 'irrigation + rainfall' was greater, and not to 2016–2017, where the yield is the lowest (see Table 1). This reinforces the importance of the amount of water added to the crop for this impact category. As to BWS, 2016–2017 is the only period in which there is an inverse relationship between the impact score and the yield, as the yield was minimum, whereas the impact was the greatest. Along these same lines, 2017–2018 and 2019–2020 have similar water consumption values. Therefore, the main difference in the BWS values obtained (15% lower in 2019–2020) is explained by the yield (17% greater in that period). The BWS value obtained for 2018–2019 is the lowest (Table 2), mainly because the blue water consumption is also the lowest (Table S3). This can be explained by the fact that the rainfall value was the greatest in that period (1119.8 mm, Table 1), where 48% of the total rain is concentrated from November to March, when the crop water demand is the highest. Consequently, the crop consumed the rainwater retained in the soil (green water) instead of consuming the blue water from irrigation, generating a lower BWS impact. These results strongly highlight the relevance of including several years in LCAs of perennials, particularly in countries with highly variable climate conditions (e.g. precipitation).

3.3. Sensitivity analysis

A sensitivity analysis is carried out in which a supposedly key inventory parameter is changed to verify the changes in the scores of the impact categories. Three parameters are chosen to perform the analysis: the yield, the amount of irrigated water and the rate of N fertiliser applied. The first two are chosen because they are highly variable from year to year, and the third since, although it does not vary in the case study, both its production and on-field emissions are detected as hotspots.

Yield variation affects all the impact categories when using 1 tonne as FU. Specifically, a 20% reduction in yield increases the results of all impact categories by 25%, whereas a 20% increase in the yield decreases all impacts by 17%. When the results per ha are analysed, the variation in the amount of irrigation water slightly changes the CC and MEu results. Halving the amount of irrigated water reduces CC by 1% and MEu by 5%, and doubling it increases the CC by 2% and the MEu by 8%. The N rate applied affects the stages of fertiliser production, transportation, and field emissions; therefore, varying N rate mainly affects TEu, Ac, OD and CC. TEu and Ac are shown to be more sensitive to on-field emissions, while OD and CC are more sensitive to fertiliser production. Specifically, a 20% increase in the N rate increases TEu by 15%, Ac by 13%, OD by 12% and CC by 11%, whereas a 20% decrease in the N rate decreases TEu by 17%, Ac by 15%, OD by 14%, and CC by 12%.

The results show the influence of the different parameters on the impact scores depending on the selected FU. Maximising the yield of the process results in lower environmental impacts when a mass FU is selected. When a spatial FU is selected, the importance of minimising the amount of N added and, to a lesser extent, the amount of irrigated water stands out.

3.4. Comparison with other studies

In this section, this study's cradle to farm gate impacts of lemon cultivation are compared with those from available literature, focusing on CC, FEu, and MEu, together with the water consumption-related impact, which differs depending on the case study analysed (see Table S7). It must be noted that, considering that the yields of lemon crops are usually higher than those of 'sweet' citrus fruits (oranges or mandarins), the comparison is carried out with three available studies on lemon (Machin Ferrero et al., 2021, 2022; Martin-Gorriz et al., 2020) and one study on generic citrus fruit (Yang et al., 2020).

When using a mass-based FU, the CC value obtained for Uruguayan lemons was 0.093 CO_2 eq.·kg^{-1}, around two (0.196 CO_2 eq.·kg^{-1}) and four (0.380 CO_2 eq.·kg^{-1}) times lower than in Machin Ferrero et al. (2022) and Martin-Gorriz et al. (2020), respectively. These differences could be related to the lower yield reported in both studies, 29.5 tonnes·ha^{-1} in Martin-Gorriz et al. (2020) and 32.5 tonnes·ha^{-1} in

Machin Ferrero et al. (2022) vs 56.0 tonnes·ha^{-1} in this study. In addition, it must be noted that different emission factors are used to estimate N_2O emissions, namely Martin-Gorriz et al. (2020) use 0.01 kg N_2O–N·kg N^{-1} (IPCC, 2006), 0.067 kg N_2O–N·kg N^{-1} (Renouf, 2006) is used in Machin Ferrero et al. (2022), and 0.016 kg N_2O–N·kg N^{-1} (IPCC, 2019) is used in the present study. On-field emissions are the hotspot in this category in the present study and also in Machin Ferrero et al. (2022). As seen, those authors used a greater emission factor which, together with their lower yield, could explain their greater CC impact result. In the study of Martin-Gorriz et al. (2020), the main hotspot is fossil fuel combustion, contrasting with the great relevance of on-field emissions in the present study. The rationale behind these results could lie on the one hand, in the amount of diesel used for field operations in Martin-Gorriz et al. (2020), which is double (535.0 vs 216.0 L ha^{-1}), increasing the weight of this stage in the total CC. On the other hand, the lower weight of the on-field emissions stage in their study can be explained by the 10% lower total N added (182.0 vs 203.1 kg N · ha^{-1}) and the lower emission factor used to estimate N_2O emissions, as commented above. Yang et al. (2020) show CC values seven times greater than those for Uruguay, also identifying on-field emissions as the most impactful stage. The differences are mainly explained by the greater amount of N applied (234% more) and the crop yield (approximately 50% lower).

Regarding water scarcity, especially relevant in agricultural LCAs (Payen et al., 2018), it must be highlighted that the methodologies and inputs used for its quantification greatly influence the results. In the present study, a value of 0.103 m^{3}eq.·kg^{-1} is obtained using the AWARE methodology, where the monthly water consumed by the crop, calculated as explained in Section 2.2.2.3, is then multiplied by the corresponding monthly CF. Only Machin Ferrero et al. (2021) assess this impact with the same methodology, although their result is 0.359 m^{3}eq.·kg^{-1}, that is, almost 3.5 times higher. This could be partially explained by the lower yield obtained for Argentinian lemons (42% lower). Likewise, it must be borne in mind that both the inventory input and CFs are different. In the Argentinian study, the irrigation water (102.94 m^3·tonne^{-1}) is multiplied by the average CF corresponding to the months in which the crop is irrigated (3.40 m^{3}eq.·m^{-3}); both values are about twice greater than those used in the present case study. In case that the average irrigation water (18.64 m^3·tonne^{-1}) and the average CF (1.70 m^{3}eq.·m^{-3}) for the irrigation months were used to calculate BWS, as in the Argentinian study, the final BWS value of the present study would be 54% lower. Therefore the difference with respect to Machin Ferrero et al. (2021) would be even greater. In sum, although both studies use the AWARE consensus method, BWS results are drastically influenced by both the water input and the CFs used. The value obtained by Machin Ferrero et al. (2022) is ten times lower than that obtained in the present case study. However, as previously stated, direct comparisons are not possible since they use the Swiss Ecological Scarcity Method (Frischknecht et al., 2006), which proposes regionalised factors according to water pressure categories.

As to the eutrophication-related categories, the methodologies used in Martin-Gorriz et al. (2020) and Yang et al. (2020) do not discern between freshwater and marine, thus, direct comparisons cannot be made. Regarding FEu, in the present study, the production of pesticides, namely copper production, is a relevant stage, similar to that described in Machin Ferrero et al. (2022, 2021), who also do discriminate between MEu and FEu, obtaining lower values, although of the same order of magnitude. As to MEu, in the present case study, almost all the impact is attributed to on-field emissions (97–98%). In this respect, Machin Ferrero et al. (2022) emphasise that, since Tucumán is in an endorheic basin, and the water has not outflow to the ocean, the impact on MEu due to local on-field emissions is meaningless. Accordingly, the values obtained in the Argentinian study are one order of magnitude lower than those of the present case study, which makes sense considering that on-field emissions (a highly impactful stage in our research) has no weight in their result.

Regarding the categories not included in Table S7, for Uruguayan lemons, freshwater ecotoxicity is dominated by pesticide production, mainly copper oxide. The Argentinian studies also highlight pesticide production as a critical point: the production of glyphosate (which is not used in the present study) and the production of copper oxide are highlighted in Machin Ferrero et al. (2021), and the production of copper oxide and abamectin in Machin Ferrero et al. (2022). Regarding human health toxicity, copper oxide production resulted the most relevant stage in this study, agreeing with Machin Ferrero et al. (2022). These observations make clear that the production of pesticides, especially copper oxide, a widespread fungicide, is a hotspot for lemons production in the region. As to mineral depletion, pesticide production is also the stage that contributes the most, as observed by Machin Ferrero et al. (2022) and Martin-Gorriz et al. (2020).

3.5. Gap for improvement

In this section, recommendations to improve the environmental performance of Uruguayan lemons are proposed, mainly focusing on farm management practices. The results obtained show that on-field emissions from fertilisers are one of the main hotspots for lemon production in Uruguay, in addition to the production of pesticides and fertilisers. Therefore, the reduction of the environmental impacts should undoubtedly include a revision of this aspect, where the cycle of N is particularly relevant. It is important to highlight that, in the studied orchard, some practices aimed at the reduction of N emissions are already carried out. Firstly, the N fertiliser applied contains a urease inhibitor and DMPP, which decrease the activity of nitrifying bacteria and reduce N emissions. Secondly, cover crops are also used, a widespread practice in Uruguayan citrus orchards, which consists of growing vegetation between the rows of trees to minimise N losses due to leaching (Sanz-Cobena et al., 2014). In addition, drip irrigation is a practice that tends to minimise N_2O and NO_3^- emissions. Nevertheless, the reduction of N emissions as a consequence of these practices was not quantified since the methods used have no available emission factors linked, and it is thus an interesting point to be addressed in future studies.

The optimisation of N application is strongly linked to crop nutrition management, which is fundamentally based on the synchronisation of fertilisation with plant demand and, therefore, with crop physiology. To this end, a detailed study of the mineral N pool available should be carried out, considering the plant demand according to the physiological stage, the N available in the root zone and that released from applied fertilisers (Skiba et al., 1997). Two useful tools to optimise N application are the Normalized Difference Vegetative Index (Pettorelli, 2013) and the use of Site-Specific Nutrient Management (Buresh and Witt, 2007). The former takes into account the greenness of the leaves combined with previous yield data to design successive split fertiliser applications. The latter considers several factors to calculate the optimum level of N to be applied. In the case of citrus fruits, the selection of rootstocks more efficient in absorbing N during the production cycle could be another interesting option (Morales Alfaro et al., 2021). The selection of the type of fertiliser to be applied appears as a different approach to mitigate on-field emissions. Many authors recommend the incorporation of slow-release forms of N, among them solid organic fertilisers (Cayuela et al., 2017) and fertilisers covered with low permeability materials (Mahmud et al., 2021; Skiba et al., 1997). The incorporation of organic mulches, that is, material spread on the soil surface as a covering (e.g. bark, straw, senescent leaves), comes as a compelling alternative to minimise N losses. Mulch has a high carbon/nitrogen ratio and little available N; therefore, it can trap the residual N present in the soil (Carranca et al., 2018). Lastly, ecological ditches are an innovative strategy to minimise emissions. These are designed to absorb nutrients that otherwise would be lost through surface runoff and make those nutrients available for root uptake or be incorporated into microbial metabolites (Mahmud et al., 2021).

Another alternative to minimise on-field emissions is the optimisation of the irrigation regime (amount, moment, and irrigation technique). Drip irrigation, used in this case study, tends to minimise N_2O production by denitrification and NO_3^- leaching (Cayuela et al., 2017; Sanz-Cobena et al., 2017). Subsurface drip irrigation is an even better technology in terms of minimising emissions. As well, the implementation of fertigation at night hours, when evapotranspiration is reduced, can also reduce losses due to N volatilisation (Denmead et al., 2020).

The selection of the agricultural inputs to be applied is another opportunity for improvement since the manufacture of pesticides and fertilisers is a hotspot for several impact categories. In this respect, the selection of an alternative to copper oxide, as well as practices oriented to reducing pathogen inoculum in the field (pruning, organic mulches, and removing old twigs, among others), would have significant repercussions on the results. Despite the great impact of fertiliser production, their replacement is more complex as they are crucial for crop growth, although optimisation of the N cycle following the previous recommendations would contribute to minimising their use.

It must be taken into account that Uruguay is a country with a baseline water stress lower than 10% (World Resources Institute, 2019). Therefore, there is enough water available for agricultural use and recommendations to decrease BWS should be thus oriented to the optimisation of the ratio "irrigation dose/crop yield" in the months of greatest scarcity in the basin. Optimising irrigation through the use of up-to-date technologies that minimise unproductive evaporation from the soil and thus reduce water consumption could be a relevant mitigation strategy. Advanced irrigation scheduling or deficit irrigation, which is based on the application of lower amounts of water than those needed by the crop, increases water productivity while maintaining acceptable crop yields (García-Tejero et al., 2012). The aforementioned organic mulch also reduces irrigation requirements, as it increases soil moisture retention. As well, the use of nets to cover the crop decreases irrigation requirements since it reduces the impact of the wind on the crop while increasing the humidity of the surrounding air (Wachsmann et al., 2014). Those authors suggest that the use of nets could also increase the yield, with the subsequent effect on the impacts per mass unit.

4. Conclusions and future challenges

The environmental performance of lemon production in Uruguay was assessed by performing an LCA, revealing key process hotspots. The relevance of including several seasons in the analysis is evidenced, especially under highly variable climatic conditions and even with constant agricultural practices. On-field emissions from fertilisers, input production, and water consumption for irrigation are the main hotspots found, therefore, recommendations oriented to those stages have been proposed.

Results reaffirm the usefulness of considering different FUs for a more complete system analysis. As expected, inter-season variability is greater when results are expressed per unit of mass as, in this study, where the inputs applied are the same across the analysed seasons, yield greatly depends on agroclimatic variables. When expressing the results per ha, the inter-seasonal variability of MEu and CC and their dependence on nitrate leaching are evidenced. BWS shows the greatest inter-seasonal variability, mainly due to the dependence of the crop's water demand on climatic parameters, which are highly variable in Uruguay. This impact depends as well on the basin's monthly scarcity CF, also influencing the variability of the results.

The results obtained are similar and even lower, especially for CC and BWS, than those presented in other LCAs of lemon reviewed. The need to harmonise the method to quantify the water consumed by the crop must be emphasised, since this strongly influences the result of the BWS category when using the AWARE methodology. Given the importance of N emissions, the use of mechanistic models to quantify them is recommended. The quantification of the reduction of environmental impacts due to the measures already established in the orchards (e.g. use of urease inhibitors, cover crops, drip irrigation) is an interesting point to be addressed in future studies.

The present study is the first approach to quantify the environmental impacts of citrus fruit production in Uruguay. It highlights inter-seasonal variability as an issue to be considered, even when agricultural practices do not change from one season to another, which is especially relevant in countries with high climatic variability like Uruguay. The case study provides scientific and quantitative evidence to support both citrus producers and consumers when making decisions to increase the environmental performance of citrus production, in line with the Sustainable Development Goals (SDGs), in particular SDG-12.

Credit author statement

Multi-season environmental life cycle assessment of lemons: a case study in South Uruguay, María Inés Cabot: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Investigation. Neus Sanjuán: Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing, Joanna Lado: Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing.

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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

Supplementary data to this article can be found online

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Appendix A. Supplementary data

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