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# From farm accountancy data to environmental indicators: Assessing the environmental performance of Spanish agriculture at a regional level

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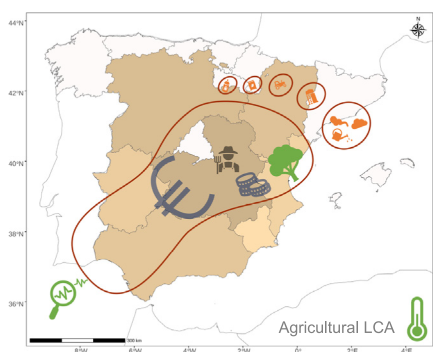
## HIGHLIGHTS

- Regionalised impacts of agriculture are assessed using farm accountancy data.
- Net value added is a suitable functional unit to compare agricultural products.
- Impacts expressed per mass and economic functional units are compared.
- Environmental impacts are offset proportionally by the economic goal sought.
- Many herbaceous holdings show consistent negative net value added.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Understanding the environmental impacts of current agricultural practices is a starting point for transitioning towards sustainable agriculture, which is a goal to be achieved by the European Union. This study aims to provide a set of environmental impact indicators with which to assess and compare the environmental performance of a broad group of agricultural reference holdings at the Spanish NUTS 2 level. A life cycle assessment approach based on statistical data on farm accountancy is applied. The unit of analysis is a reference holding on which a specific crop is grown in a NUTS 2 and follows a specific management system (open-field irrigated, open-field rainfed, or greenhouse). The system boundaries are set at the farm gate, and the impact results are expressed per 1 € of net value added. For most reference holdings, the EF scores per net value added are similar regardless of their EF scores per kg commodity, suggesting a correspondence between the use of resources and the economic results. The environmental footprint is clustered into four groups. The first one accounts for 78 % of the sample and represents the holdings with the lowest impact (between $9.7\cdot10^{-5}$ and $2.88\cdot10^{-3}$ EF score$\cdot NVA_{fc}{}^{-1}$); the second cluster groups seven reference holdings (3 herbaceous and 4 Mediterranean perennial crops) with an environmental footprint of between $3.04\cdot10^{-3}$ and $9.01\cdot10^{-3}$ EF score$\cdot NVA_{fc}{}^{-1}$; the third group comprises four irrigated herbaceous crops holdings with the highest impact (between $1.37\cdot10^{-2}$ and $2.13\cdot10^{-2}$ EF score$\cdot NVA_{fc}{}^{-1}$); and the last group corresponds to the holdings with economic losses (mostly herbaceous and two Mediterranean perennial crops). This research highlights the challenge of improving the competitiveness and profitability of Spanish farming. In this way, agricultural practices that generate environmental impacts without achieving their economic goals would be avoided.

## 1. Introduction

Not only must agriculture respond to its primary function of supplying food, but also has to adapt to the social and economic needs of the region,

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as well as to the environmental challenges that societies face. As a fundamental link of the food chain, it causes both positive (e.g. soil functionality improvement, carbon sequestration) and negative (e.g. pollution of soil, air, and freshwater) externalities on the environment (Chen et al., 2014; Pajewski et al., 2020). In fact, most of the negative environmental loads of the food chain are associated with the agricultural stage (Djekic et al., 2018; Pandey et al., 2011; Ribal et al., 2019).

Through the European Green Deal (EC, 2023a), two strategies are set out that address agriculture, namely Farm-to-Fork and Biodiversity 2030. These strategies seek to reduce the use of pesticides and the excess of nutrients in the environment (EC, 2023b, 2020) by promoting precision agriculture, organic farming, and agroecology (EC, 2019). Consequently, the new CAP 2023–27 aims to contribute to the Green Deal goals and the current challenges of European agriculture by reinforcing the support to smaller farms and offering greater flexibility for the state members to adopt those measures which best fit their local conditions (EUCO, 2023). The CAP goals are adapted to Spanish agriculture by means of the Spanish CAP Strategic Plan (MAPA, 2023a). As far as environmental sustainability is concerned, in addition to the mitigation of and adaptation to climate change, the Spanish Plan highlights the need to promote efficient irrigation and improve soil quality (MAPA, 2023a). Hence, understanding the environmental impacts of agriculture is a starting point for transitioning towards sustainable systems, and a basis for contrasting the results of future policies to enhance agricultural sustainability.

Life cycle assessment (LCA), described in the environmental management standards ISO 14040 and 14044 (ISO, 2006a,b, 2017), is the most widely used methodology with which to assess the negative environmental impacts of anthropogenic activities (Hélias et al., 2022), such as agriculture, and is a valuable tool to support sustainable transitions (Sala et al., 2021). The vast body of literature on agricultural LCAs shows that the decision context, the functional unit (FU), and the representativeness of the inventory data are critical issues. The ILCD Handbook (EC-JRC, 2010) defines four potential decision contexts (A, B, C1, or C2) not always explicit in agricultural case studies; however, the definition of the decision context is crucial as it determines the modelling framework for the life cycle inventory (LCI), either attributional or consequential. The FU must adequately represent the system's functions, especially in comparative studies (Djekic et al., 2018; O et al., 2023; Ponsioen and van der Werf, 2017). Four types of FU are used in agricultural LCAs (Alhashim et al., 2021; Notarnicola et al., 2015), based on the mass of the product (M-FU), area of land occupied (A-FU), nutritional criteria (N-FU), or economic parameters (E-FU). These FUs work similarly in identifying hotspots (O et al., 2023), although in comparative LCAs, their performance may vary (Cerutti et al., 2013; Notarnicola et al., 2015). M-FU (e.g. 1 kg of a commodity) is the most commonly used (Cerutti et al., 2014, 2013; Djekic et al., 2018), and indicates the impacts per weight of a desired output without accounting for its quality (O et al., 2023). A-FU (e.g. 1 ha) expresses the impacts per unit of land required to grow a product and allows the farm management intensity to be assessed (Mouron et al., 2006a). N-FU (e.g. 1 kg protein) gathers the properties of agricultural commodities as a nutrient source; however, foods provide an array of macro and micronutrients, and the key nutrients can substantially differ from product to product, making comparisons difficult (e.g. oranges are a source of fibre and vitamin C and olives of fat). E-FU (e.g. 1 € income) uses an economic or financial indicator to relate the impacts (Cerutti et al., 2014; O et al., 2023). It makes it feasible to integrate the quantity and quality of a product in a single FU, broadly representing the function of agricultural commodities as economic goods and being appropriate for comparative LCAs (Mouron et al., 2006a; Ponsioen and van der Werf, 2017; Van Der Werf and Salou, 2015). The main disadvantage of E-FU concerns the uncertainty associated with the economic context, which can be mitigated by considering several years (Cerutti et al., 2014; Mouron et al., 2006a). Ponsioen and van der Werf (2017) recommend reporting the value of the economic indicator and the environmental impacts per M-FU when using E-FUs.

Regionalised LCAs should be promoted in the agricultural context since policies to achieve sustainable agriculture must be developed at the regional level and adapted to its opportunities and constraints (Benoît et al., 2012; Pradeleix et al., 2022). Regionalised LCAs pose a challenge regarding the accuracy and representativeness of the inventory analysis (Avadí et al., 2016; Pradeleix et al., 2022). Different approaches to obtaining the activity data may be found in the literature; although those based on primary sources represent greater accuracy, they require significant efforts to acquire representativeness. Avadí et al. (2016) developed a regionalized inventory combining the calculation of LCAs at the farm level from a representative sample, followed by a principal component analysis to develop farm typologies. Avadí et al. (2018) constructed virtual representative farms using regional statistics, representing the dominant farm types of a given region. Pradeleix et al. (2022) proposed an approach based on Agrarian System Diagnosis; whereas Jan et al. (2012), Dolman et al. (2014), and Sinisterra-Solís et al. (2023a, 2023b) used Farm Accountancy Data Network (FADN) as the main data source for the development of the LCIs.

Several studies assess Spanish agriculture at the regional level. Aguilera et al. (2015a, 2015b) estimated the global warming potential of representative herbaceous and fruit tree crops, both conventional and organic, using average data from personal interviews with farmers. Ribal et al. (2017) assessed orange production in the Valencia region (Spain); they elicited the activity data from a broad survey of farmers and applied a bootstrap technique to obtain confidence intervals of the average impact scores. Martin-Gorriz et al. (2020) evaluated the impacts of fruit and vegetables in the Region of Murcia (Spain) using representative data from agricultural information systems and other literature sources to develop the LCI. Sinisterra-Solís et al. (2023a, 2023b) proposed an approach to account for the impacts of representative holdings at the NUTS 2 level using the annual studies of costs and incomes of agricultural holdings, the so-called ECREA database (MAPA, 2023b). To validate their approach, they estimated the impacts of tomatoes and oranges and compared their results with the literature in the same NUTS 2.

To the authors' knowledge, a comprehensive environmental assessment at a NUTS 2 level in Spain applied to a broad group of crops is not found in the literature. Understanding the importance of data generation, this study aims to account for the environmental impacts and compare the environmental performance of a broad group of agricultural reference holdings at the Spanish regional level (i.e. NUTS 2). The EF has been selected for comparison purposes because it is a comprehensive indicator. To capture both the temporal variability and that of the management practices, data from an 8-year period (from 2010 to 2017) have been used. These indicators can serve as a basis for a comparison with those resulting from the application of future policies supporting the transition to sustainable agriculture within the framework of the CAP 2023–27.

## 2. Materials and methods

This study corresponds to an attributional LCA, which considers a type C accounting decision-context according to the ILCD Handbook (EC-JRC, 2010), where regionalised LCIs are developed using ECREA-FADN data and other representative secondary sources (i.e. official statistics) to estimate representative activity data for farming typologies (reference holdings) at the NUTS 2 level. The approach developed by Sinisterra-Solís et al. (2023a, 2023b) to account for the environmental impacts of Spanish agriculture at the NUTS 2 level is used. ECREA-FADN is a non-standardised Spanish FADN that reports farm activity accountancy in the Spanish regions in greater detail than in the RECAN, the Standardised Spanish FADN (MAPA, 2023c, 2008).

### *2.1. Context of the study*

Reference holdings configured from ECREA-FADN are the unit of analysis of this study. For each crop under a particular management system in a specific NUTS 2, ECREA-FADN gathers annual information on the average financial results of a group of farms (e.g. income, expenses and profit indicators) together with the description of the agricultural practices and some activity data (e.g. amount of macronutrient supplied, yield), which represent a reference holding. In particular, the ECREA-FADN compiled in the "Dbi1_ECREA" dataset in Sinisterra-Solís et al. (2023b) was used. This dataset collects data from 200 reference holdings from 2010 to 2017, the most up-to-date in ECREA-FADN when this study was developed, representing 64 crops in 9 of the 17 NUTS 2 of the Spanish territory (MAPA, 2023b).

An ID variable was created to name the reference holdings assessed, as detailed in Table 1, which consists of four items separated by hyphens. The first item is an acronym that groups the reference holdings according to the type of crops in the ECREA-FADN classification (i.e. fruit tree, herbaceous, Mediterranean perennial, and vegetables crops). The second corresponds to the crop's name, the third to the management system used, and the last to the NUTS 2.

To account for the temporal variability, following Cerutti et al. (2014), those reference holdings with data for four or more years are considered in this study, resulting in a total of 140 reference holdings. As explained in Sinisterra-Solís et al. (2023a), not all the reference holdings were analysed since the source used to estimate the consumption of pesticides (MAPA, 2021) only provides data for some of the crops gathered in ECREA-FADN; thus, 115 of the 140 reference holdings were included in the study. Table 2 shows the number of reference holdings that make up the sample in each NUTS 2, and the number of reference holdings assessed and excluded; in addition, the studied crops are detailed, as are the management systems (greenhouse, irrigated open-field and rainfed open-field) used in each NUTS 2. The supplementary material (T-1 in SM-1) provides information about the yield, average farm area and the number of years with data of the reference holdings to be analysed.

To give an idea of the representativeness of the study, the percentage of the agricultural surface area analysed in each NUTS 2 has been identified (Fig. 1) by linking the reference holdings analysed in this study with the agricultural surface area of the corresponding NUTS 2, excluding the fallow surface area (MAPA, 2023d). Specifically, the sample assessed for each NUTS 2 represented 87.59 % of the agricultural surface area of *Castilla-La Mancha* (CM); 79.14 % of *Castilla y León* (CL); 74.91 % of *Aragón* (AR); 71.06 % of *Andalucía* (AN); 65.99 % of *Extremadura* (EX); 61.54 % of *Comunidad Valenciana* (VC); and 52.22 % of *Murcia* (MC).

In addition, the representativeness of this study regarding the production of the 42 crops considered for the year 2017 is shown in T-3 (SM-1). According to production statistics from MAPA, 2023e, most of the crops (28) in the NUTS 2 assessed represent more than 56 % of the total Spanish production of the crop in that very year. Nine of the assessed crops (olive, olive for oil, orange, strawberry, watermelon, sunflower, durum wheat and tomato) represent more than 90 % of the total production. For eighteen of the crops, this representativeness is between 57 % and 87 % (e.g. oat, almond, wine grape, barley and soft wheat). In thirteen crops, the cover is lower than 46 % and lower than 15 % in five (apple, extra early potato, cherry, cauliflower and cabbage). Still, this last group is not relevant with respect to the surface area cultivated in Spain. Finally, it must be highlighted that production data for persimmon were not found in the MAPA, 2023e. Other representative crops in some of the studied NUTS 2 are outside ECREA-FADN and have, thus, not been included. Both these crops and those excluded due to the above criteria are shown in T-2 in SM-1.

**Table 1**
Name and acronym, in parentheses, of the items assigned to the ID variable of the analysed reference holdings.

Type of crop:
Fruit trees (Fr); Herbaceous (He); Mediterranean perennials (Me); Vegetables (Ve).
Crop:
Apple (App); Apricot (Apr); Cherry (Che); Lemon (Lem); Mandarin (Man); Melon (Mel); Nectarine (Nec); Orange (Ora); Peach (Pea); Pear (Per); Persimmon (Pers); Plum (Plu); Barley (Bar); Durum wheat (Dwh); Oat (Oat); Rye (Rye); Sunflower (Sun); Soft wheat (Swh); Triticale (Tri); Almond (Alm); Olive (Ol); Olive for oil (Olo); Wine grape (Wgr); Artichoke (Art); Broccoli (Bro); Cabbage (Cab); Cauliflower (Cau); Celery (Cel); Chard (Cha); Courgette (Cou); Cucumber (Cuc); Extra early potato (Eep); Garlic (Gar); Lettuce (Let); Midseason potato (Mpo); Onion (Oni); Pepper (Pep); Pepper for paprika (Ppe); Strawberry (Str); Tomato industry (Toi); Tomato (Tom); Watermelon (Wat).
Management system:
Irrigated open field (IO); Rainfed open field (RO); Irrigated greenhouse (IG).
*NUTS 2:*
*Aragón* (AR)*; Región de Murcia* (MC)*; Comunidad Valenciana* (VC)*; Extremadura* (EX)*; Andalucía* (AN); *Castilla-La Mancha* (CM)*; Castilla y León* (CL).

### 2.2. System boundaries and functional unit

The approach applied was restricted to the farming stage; thus, the system boundaries were set at the farm gate, including all the relevant stages from the production of agricultural inputs to the farm gate (Fig. 2). As explained in Sinisterra-Solís et al. (2023a), the transport of agricultural inputs was not taken into account because its environmental loads are not relevant.

The definition of the FU is critical since it can dramatically influence the LCA results and their interpretation, especially in comparative studies. Thus, the FU should pertinently represent both the qualitative and quantitative issues of the function of the system under study from the perspective of the information user, that is, the stakeholders of the supply chain (Hauschild et al., 2018). In this study, an E-FU is used because, as commented on in Section 1, it allows for the comparison of commodities with different physical and nutritional features. In particular, considering that this study aims to generate data to be potentially used by policymakers (target audience), the net value added (NVA) is used. Specifically, the NVA at factor cost generated per kg of commodity ($NVA_{fc}$) has been chosen to represent the economic results of the holdings, without considering government interventions, such as taxes and subsidies; this expresses the endogenous holdings' capacity to generate value added. Hence, the environmental impacts are expressed per 1 € $NVA_{fc}$. $NVA_{fc}$ is calculated as the difference between the output value and that of the intermediary consumption (Eq. (1)) reported in ECREA-FADN and in line with (MAPA, 2019).

$$NVA_{fc} = \frac{gi + in - dc - mc - ci - bc - oc - ac}{y} \quad (1)$$

where $gi$ is the gross income and $in$ is the damage insurance compensation, and the remaining variables of the numerator represent the intermediary consumption: $dc$ is the direct cost, $mc$ is the machinery cost, $ci$ is the capital insurance cost, $bc$ are the maintenance costs, $oc$ are other costs, and $ac$ is the amortisation of non-current assets. These variables are originally expressed at nominal prices per hectare and year, and they are thus converted to actual prices to disregard the inflation effect. In particular, the income ($gi$ and $in$) and cost ($dc$, $mc$, $ci$, $cb$, $oc$ and $ac$) variables have been adjusted on the basis of the price indices received and paid by farmers, taking 2010 as the base year (MAPA, 2023f, 2023g). In addition, they are divided bythe yield per hectare ($y$) of the respective year to obtain the $NVA_{fc}$ per kg commodity. Following the recommendation of Ponsioen and van der Werf (2017), the impacts per M-FU (1 kg of commodity) and the $NVA_{fc}$ scores are provided in the SM.

### 2.3. Inventory data

The activity data for the life cycle inventory (LCI) of each reference holding (i.e. input consumption and on-field emissions) were estimated following Sinisterra-Solís et al. (2023a) from ECREA-FADN data, other official sources and the scientific literature gathered in Sinisterra-Solís et al. (2023b).

According to Notarnicola et al. (2015), the commodity's mass was the reference unit of analysis at the inventory level and the inputs and emissions were expressed per 1 kg of agricultural commodity (SM-2). Therefore, the impacts were calculated per 1 kg of the commodity and subsequently divided by their respective $NVA_{fc}$ to estimate the impacts per 1 €.

### 2.4. Impact categories and impact assessment methods

Following the EU recommendations for the measurement of environmental performance, the most up-to-date version of its method (EF v3.0)

**Table 2**
Reference holdings at the NUTS 2 level in Spain with data available for four or more years.

| | AN | AR | CL | CM | EX | MC | VC | Total |
|---|---|---|---|---|---|---|---|---|
| Number of reference holdings | 24 | 20 | 21 | 24 | 15 | 15 | 21 | 140 |
| Number of reference holdings assessed | 20 | 16 | 10 | 21 | 13 | 15 | 20 | 115 |
| Number of reference holdings not assessed | 4 | 4 | 11 | 3 | 2 | 0 | 1 | 25 |
| Crop | | | | | | | | |
| *Fruit trees* | | | | | | | | *26* |
| Apple | | IO | | | | | | 1 |
| Apricot | | | | | | IO | IO | 2 |
| Carob[a] | | | | | | | RO | 1 |
| Cherry | | | | | | | RO | 1 |
| Persimmon | | | | | | | IO | 1 |
| Lemon | | | | | | IO | IO | 2 |
| Mandarin | | | | | | | IO | 1 |
| Nectarine | | IO | | | IO | IO | IO | 4 |
| Orange | IO | | | | | IO | IO | 3 |
| Peach | | IO | | | IO | IO | IO | 4 |
| Pear | | IO | | | | IO | | 2 |
| Plum | | | | IO | IO | IO | IO | 4 |
| *Herbaceous* | | | | | | | | *54* |
| Alfalfa[a] | | IO | RO, IO | | | | | 3 |
| Barley | | RO, IO | RO, IO | RO, IO | RO | | | 7 |
| Sugar Beet[a] | IO | | IO | | | | | 2 |
| Chickpeas[a] | | | RO | | | | | 1 |
| Rapeseed[a] | | | RO, IO | | | | | 2 |
| Corn[a] | IO | IO | IO | IO | IO | | | 5 |
| Cotton[a] | IO | | | | | | | 1 |
| Dried peas[a] | | RO | RO | RO, IO | | | | 4 |
| Durum wheat | RO | RO, IO | | | | | | 3 |
| Fodder corn[a] | | | IO | | | | | 1 |
| Forage vetch[a] | | | RO | | | | | 1 |
| Lentils[a] | | | RO | | | | | 1 |
| Oat | RO | | RO | RO | RO | | | 4 |
| Ryegrass[a] | | IO | | | | | | 1 |
| Rice[a] | IO | | | | IO | | | 2 |
| Rye | | RO | RO | | | | | 2 |
| Sunflower | RO | RO | RO, IO | RO | | | | 5 |
| Soft wheat | RO | RO, IO | RO, IO | RO | RO, IO | | | 8 |
| Triticale | | | | RO | | | | 1 |
| *Mediterranean perennials* | | | | | | | | *23* |
| Almond | | RO | | RO | | RO | RO, IO | 5 |
| Olive for oil | RO, IO | RO, IO | | RO, IO | RO, IO | | RO | 9 |
| Olive | RO, IO | | | | RO | | | 3 |
| Wine grape | IO | RO | RO | RO, IO | RO | | | 6 |
| *Vegetables* | | | | | | | | *37* |
| Artichoke | | | | | | IO | | 1 |
| Broccoli | | | | | | IO | | 1 |
| Cabbage | | | | IO | | | | 1 |
| Cantaloupe | RO, IO | | | IO | | IO | | 4 |
| Cauliflower | | | | IO | | | | 1 |
| Celery | | | | | | | IO | 1 |
| Chard | | | | IG | | | IG | 2 |
| Cucumber | IG | | | | | | | 1 |
| Garlic | | | | IO | | | | 1 |
| Lettuce | | | | | | IO | | 1 |
| Onion | | | | IO | | | IO | 2 |
| Pepper | IG | | | | | IG | IG | 3 |
| Pepper for Paprika | | | | | IO | | | 1 |
| Extra early potato | | | | | | | IO, IG | 2 |
| Midseason potato | | | IO | | | | | 1 |
| Strawberry | IG | | | | | | | 1 |
| Tomato industry | IO | | | | IO | | | 2 |
| Tomato | IG | | | IO, IG | | IG | IG | 5 |
| Watermelon | RO, IO | | | IO | | IO | IO | 5 |
| Courgette | IG | | | | | | | 1 |

AN: *Andalucía*; AR: *Aragón*; CL: *Castilla y León*; CM: *Castilla-La Mancha*; EX: *Extremadura*; MC: *Murcia*; VC: *Comunidad Valenciana*; RO: crop in rainfed system; IO: crop in irrigated system; IG: crop in greenhouse.
[a] Crops not assessed because the data on pesticide consumption were not found in the sources consulted.

when this study was developed (EC, 2023c) was used to estimate the environmental footprint indicator (EF) and the midpoint impact categories. In addition, the ReCiPe endpoint indicators v1.1 (Huijbregts et al., 2017) were calculated to provide decision-makers with a comprehensive environmental impact dataset considering the three levels of analysis.

### 2.5. Uncertainty modelling

As far as data availability is concerned, two sources of uncertainty are assessed. Firstly, the temporal variability has been addressed by considering various years, as recommended for agricultural LCAs (Cerutti et al.,

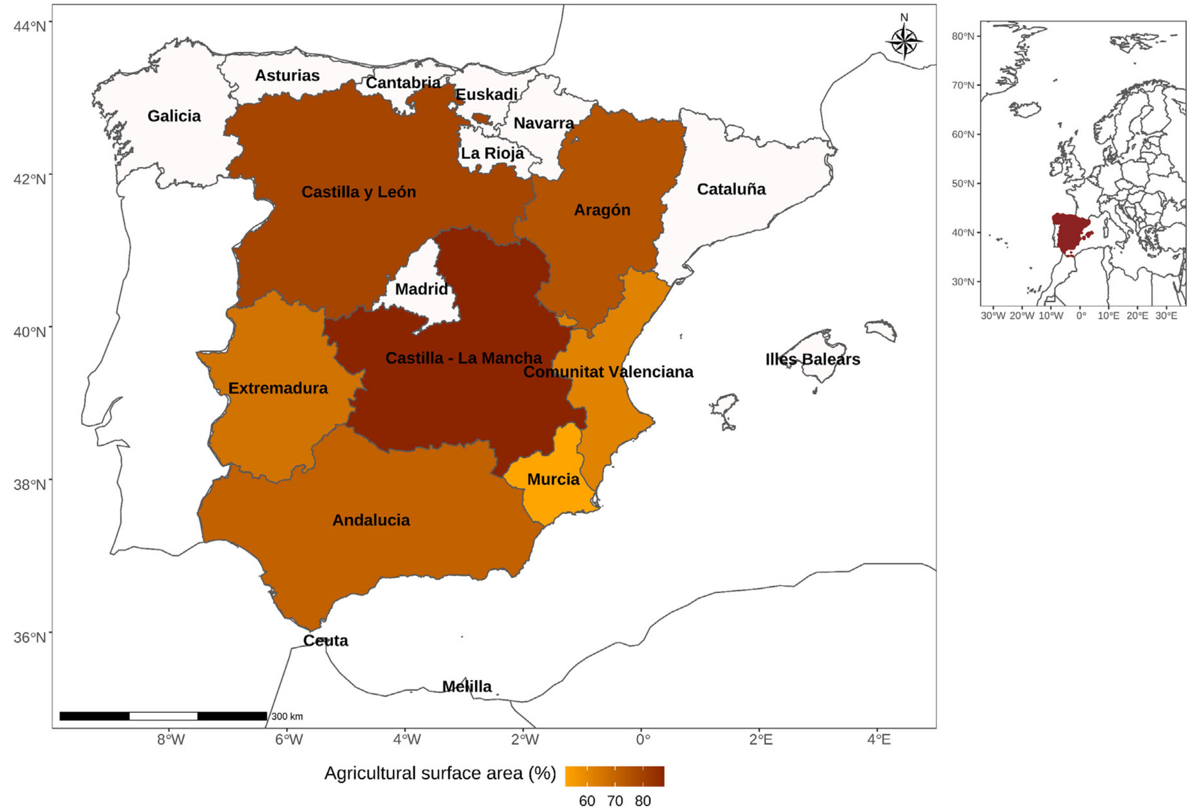


**Fig. 1.** Agricultural surface area (%) covered, excluding the fallow surface area, of the Spanish NUTS 2 represented in this study.

2014). It should be noted that cross-sectional variability (i.e. that from the holdings sample) is not considered as only average values are reported in ECREA (MAPA, 2023b). Secondly, the uncertainty associated with some input data was modelled as in Sinisterra-Solís et al. (2023b, 2023a), assuming non-parametrical distributions and considering 1000 simulations for each year assessed. Consequently, for each impact indicator, results were estimated as the median of the simulations for every year analysed, indicating its confidence interval (between 2.5 % and 97.5 % of the data). As the uncertainty of the impacts has been modelled from non-parametrical distributions in the input data, the results are assumed to be non-normally distributed.

### *2.6. Software and background processes databases*

The code files in the R programming language (R Core Team, 2021) and the dataset to estimate the environmental impacts of the reference holdings

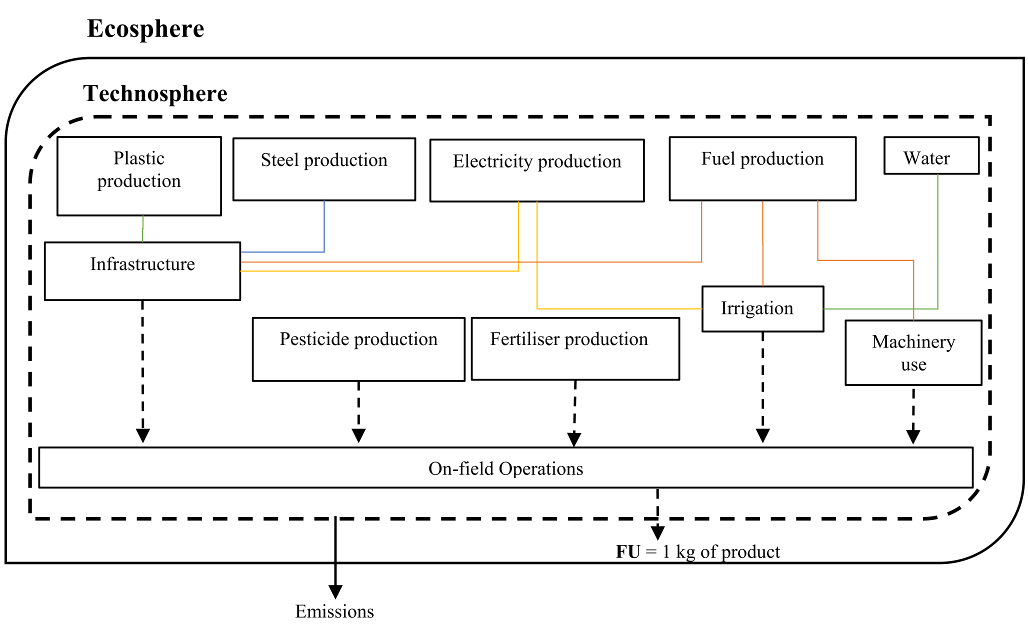


**Fig. 2.** System boundaries for the environmental assessment of the reference holdings assessed (Sinisterra-Solís et al., 2023a).

are presented in Sinisterra-Solís et al. (2023b). It must be remarked that in that publication, the unit environmental impacts associated with upstream processes were not reported in the respective file ("Dbi3_unit_impact") due to copyright issues; thus, when applying the code, the actual impact scores of upstream processes and the impact scores of on-field emissions from fertiliser application were included in the "Dbi3_unit_impact" file. These values were taken from Ecoinvent v3.8 (Wernet et al., 2016) and GaBi DB (SPHERA, 2022) databases using GaBi professional v10 software.

## 3. Results

The complete set of environmental impacts is shown in SM-3, where statistics of central tendency, dispersion and confidence are provided. In the following sections, descriptive statistics are used to develop a comparative analysis of the EF scores of the reference holdings.

### 3.1. Environmental footprint analysis

The median of the EF scores of the reference holdings is grouped in four panels according to the crop type (Fig. 3): fruit tree, herbaceous, Mediterranean perennial (almonds, olives and wine grapes) and vegetable crops. For interpretative convenience, the results are clustered into four groups. The first one shows the lowest EF (between $9.7 \cdot 10^{-5}$ and $2.88 \cdot 10^{-3}$ EF score·$NVA_{fc}^{-1}$), and is made up of 77.74 % of the sample, namely 11 herbaceous crops, 17 Mediterranean perennial crops, and all the fruit tree and vegetable crops. It is the most diverse group with a broad type of reference holdings showing a broad range of EF scores per kg commodity. The correspondence between the use of resources and the economic results is evident in this group; this is because, despite the wide range of EF scores per kg commodity, they converge when expressed per $NVA_{fc}$, which is the group with the narrowest dispersion in terms of the EF scores per $NVA_{fc}$. The second cluster presents an intermediate performance, between $3.04 \cdot 10^{-3}$ and $9.01 \cdot 10^{-3}$ EF score·$NVA_{fc}^{-1}$, and it is made up of 7 reference holdings (3 herbaceous and 4 Mediterranean perennial crops); whereas the third group includes 4 irrigated herbaceous crops (soft wheat and barley in AR, CM and CL) with the greatest impacts (between $1.37 \cdot 10^{-2}$ and $2.13 \cdot 10^{-2}$ EF score·$NVA_{fc}^{-1}$). In these last two clusters, it is possible to observe a high degree of dispersion both in the results per kg commodity and $NVA_{fc}$, suggesting there is less correspondence between the use of resources and the economic results. The fourth cluster is made up of 14 reference holdings (12 herbaceous and 2 Mediterranean perennial crops) which showed negative $NVA_{fc}$ (economic losses). Even though 86 % of this group corresponds to herbaceous crops in rainfed (12 reference holdings), irrigated soft wheat in EX and irrigated barley in CL were the most critical reference holdings because they exhibited the highest EF scores per loss of $NVA_{fc}$. In addition, it should be noted that the four oat holdings studied are included in the fourth cluster. The negative economic results of these reference holdings can be explained by the low land productivity (yield) of these crops in the corresponding NUTS 2, which was lower than the average Spanish yield for the same crops in the years analysed reported in FAO (2023).

Exploring the structure of the $NVA_{fc}$ (Fig. 4) can help to better understand the results. Fruit tree and vegetable crops show the best economic performance. In the fruit tree crops, intermediate costs, mainly those of fertilisers, and general direct costs are the ones with the greatest share, and for the vegetables group, seed costs and general direct costs predominate. Machinery (including fuel, maintenance, and the price of the outsourced service), amortisation and fertilisers are the most relevant operating costs through the holdings of herbaceous and Mediterranean perennial crops, and are relatively greater in those with a negative economic result. Another heading to be highlighted in the irrigated herbaceous crops with negative NVA is the direct general cost.

### 3.2. Contribution analysis

Generally speaking, the relative contribution of the life cycle stages analysed to the EF scores of the reference holdings substantially differ depending on the type of crop and management system (Fig. 5). The relative

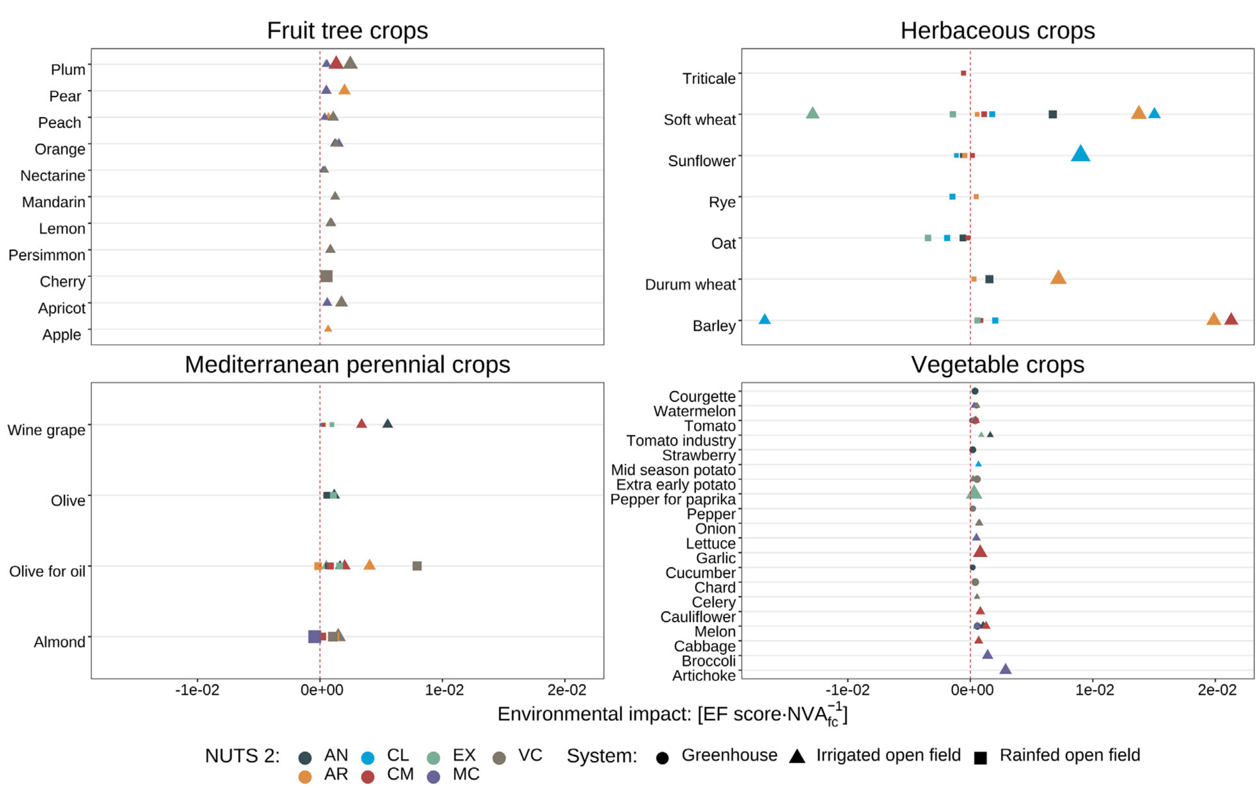


**Fig. 3.** Median environmental footprint scores of the reference holdings. The size of the symbol is proportional to the EF score per kg commodity.

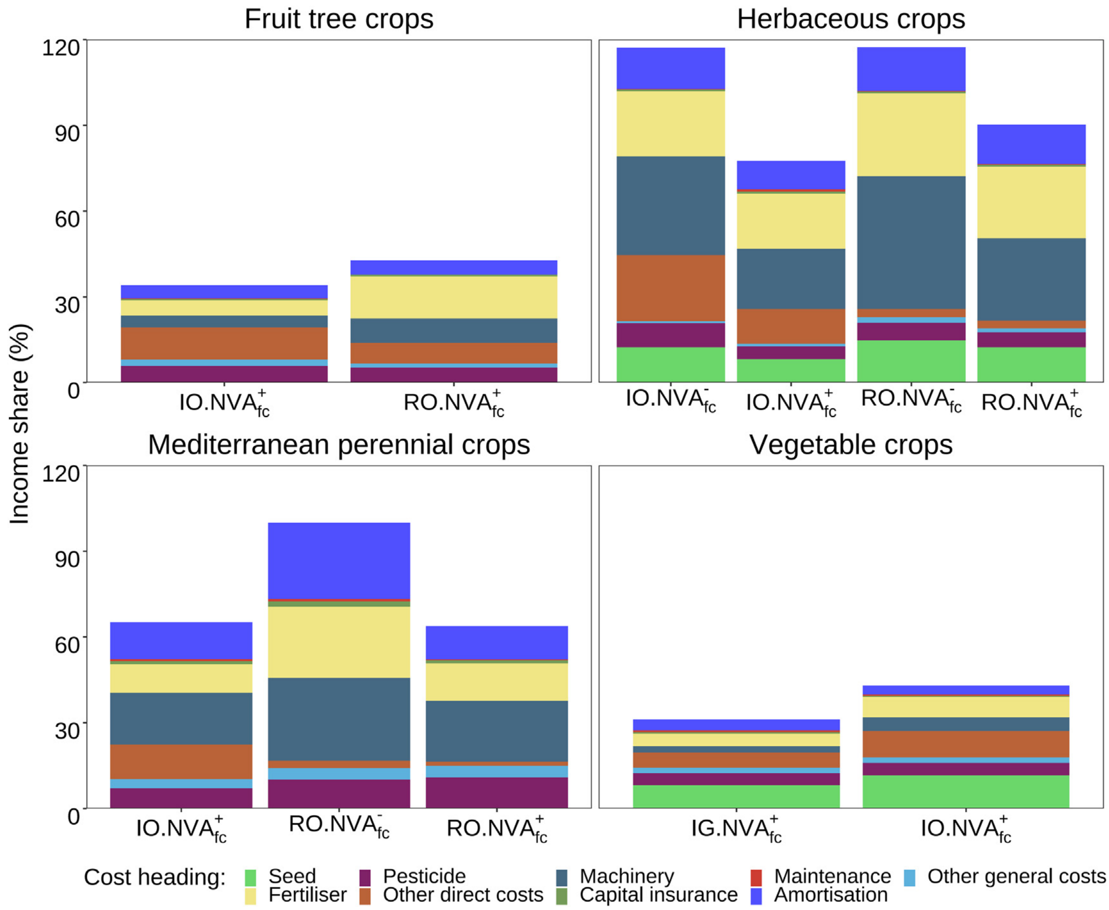


**Fig. 4.** Average structure of the intermediate costs of the reference holdings analysed. RO, IO and IG indicate rainfed and irrigated open field and greenhouse systems, respectively. + and - indicate positive and negative $NVA_{fc}$.

contribution of the stages in each NUTS 2 is similar, except in the case of the vegetable crops, where the share varies depending on the NUTS 2. It must also be noted that in the case of the irrigated fruit tree crops, the contribution of the on-field operation stage for the reference holdings in EX is greater than in the remaining NUTS 2. As for the herbaceous crops, no differences can be found between the relative contribution of the stages of the reference holdings with positive and negative $NVA_{fc}$.

Irrigation is the most influential stage in the EF scores of the reference holdings of fruit tree and vegetable crops, followed by on-field operations and infrastructure. In contrast, the stages of fertiliser and pesticide production were those that contributed the least to the EF. It must be noted that due to the relatively high amount of fertilisers applied or the lower irrigation dose, the stages contributing the most in some fruit tree and vegetable reference holdings were on-field operation (e.g. Fr_Pea_IO_EX, Fr_Nec_IO_EX, Ve_Eep_IO_VC and Ve_Mpo_IO_CL) and infrastructure (namely Ve_Eep_IG_VC, Ve_Cha_IG_VC and Ve_Cha_IG_CM). In addition, irrigation was not influential in Fr_Che_RO_VC because it was the only rainfed reference holding of fruit tree crops; therefore, the stage that contributed the most to its EF was that of on-field operation.

Different patterns are observed for the reference holdings corresponding to Mediterranean perennial and herbaceous crops. On the one hand, similar to fruit tree and vegetable crops, irrigation, on-field operation and infrastructure were the stages with the greatest share for the irrigated reference holdings, with irrigation being the most influential stage. Secondly, the on-field operation had the greatest share in the rainfed reference holdings, although fertiliser production and machinery were also relevant. The sunflower reference holdings were an exception to this (He_Sun_RO_AN, He_Sun_RO_AR, He_Sun_RO_CL and He_Sun_RO_CM), in which the use of machinery was the stage with the highest share; this can be explained by the low contribution of on-field operation, due to the low quantity of fertilisers applied in these holdings.

### 3.3. Implications of the selection of the functional unit

The environmental performance of the reference holdings as EF score per euro of $NVA_{fc}$ is compared versus that expressed per kg of commodity since it is the most commonly used in agricultural LCAs. Rankings are developed in descending order for each crop, since M-FU only works if comparing the environmental impacts of similar products. The rankings of the impacts of the reference holdings using both FUs are shown in SM-3, while Fig. 6 shows the differences in the ranking position when the EF score is expressed per M-FU instead of E-FU.

It can be observed that 54 % of the holdings do not change their ranking positions when using a M-FU, whereas the remaining 46 % show a shift of a different order of magnitude. In particular, in the groups of fruit tree and vegetable crops, most of the holdings keep their position in the ranking (80.77 % and 70.27 %, respectively). In the case of herbaceous and Mediterranean perennial crops, only 26.67 % and 30.43 % of the holdings keep their position, and some of the holdings of these two groups exhibit a marked shift in the ranking. For instance, of the eight holdings growing soft wheat in the herbaceous crop group, He_Swh_IO_EX shifts its position in the ranking by 88 %; it has the greatest impact when the scores are expressed per E-FU and the second best when using M-FU. Of the five holdings growing almonds in the Mediterranean perennial crops, the worst performance is that of the one in Murcia (Me_Alm_RO_MC) with the E-FU and the best is with the M-FU. These findings once more confirm the influence of the FU in the results when comparative LCAs are developed.

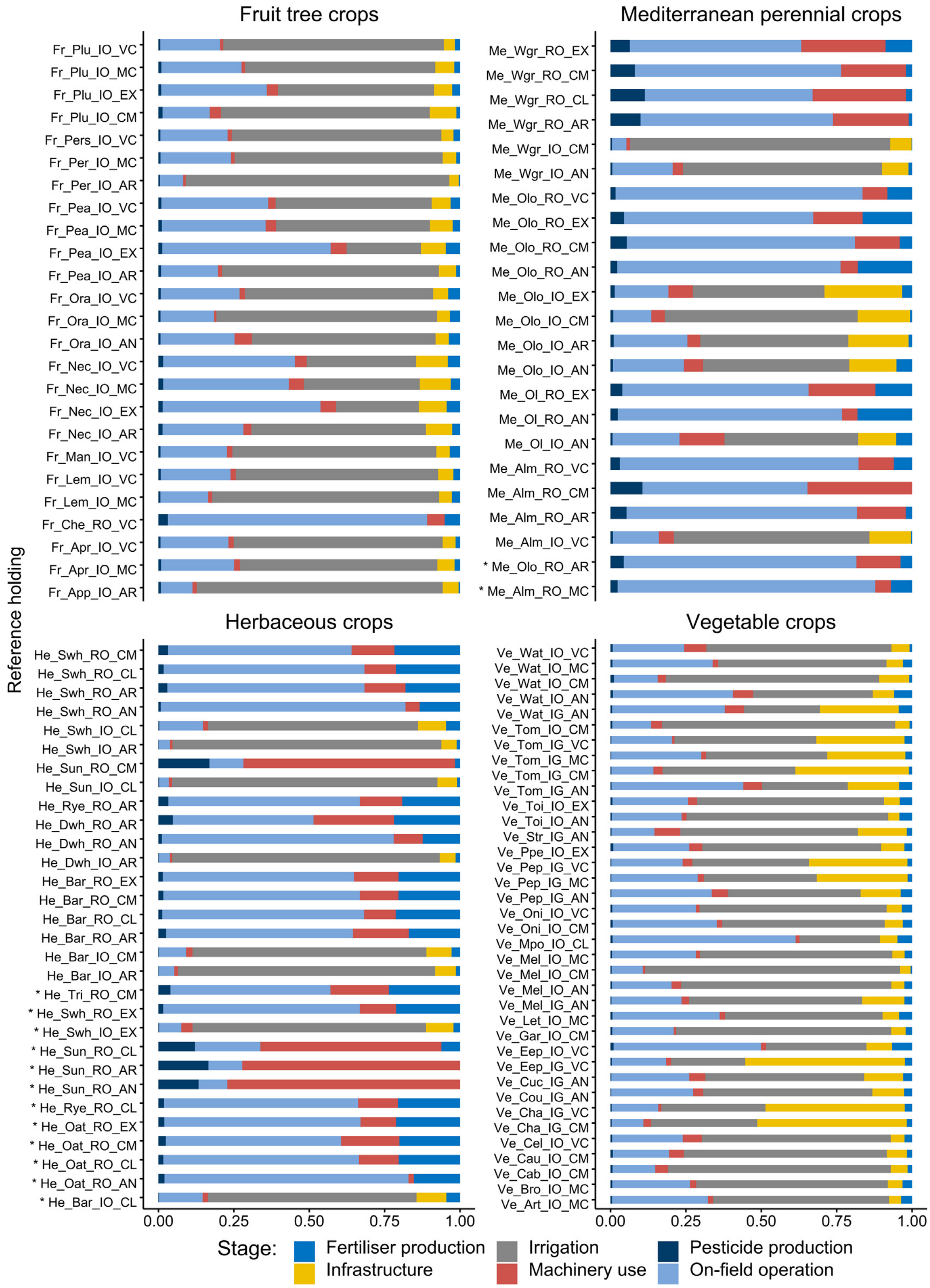


**Fig. 5.** Relative contribution of life cycle stages to the environmental impacts of the reference holdings at the Spanish NUTS 2 level in the period 2010–2017. Acronyms of the y-axis are depicted in the SM-1. The reference holdings with negative NVA are highlighted with *.

In this study, the economic value added is the FU used, as policymakers are the potential target audience of the accounted impacts; however, other economic and financial indicators can better represent the E-FU depending on the target audience. For instance, in some studies aimed at farmers, the receipts have been used as FU (Cerutti et al., 2013; Mouron et al., 2006a, 2006b); nevertheless, the use of profit-based indicators (e.g., Earnings Before Interest Taxes Depreciation and Amortisation-EBITDA) can be a better methodological choice, since they relate the environmental impacts with the economic goal sought by the farmers. If customers were the target audience, a suitable FU should represent the money paid by a customer to obtain goods or services, such as the price, which was the FU used by Van Der Werf and Salou (2015) and O et al. (2023).

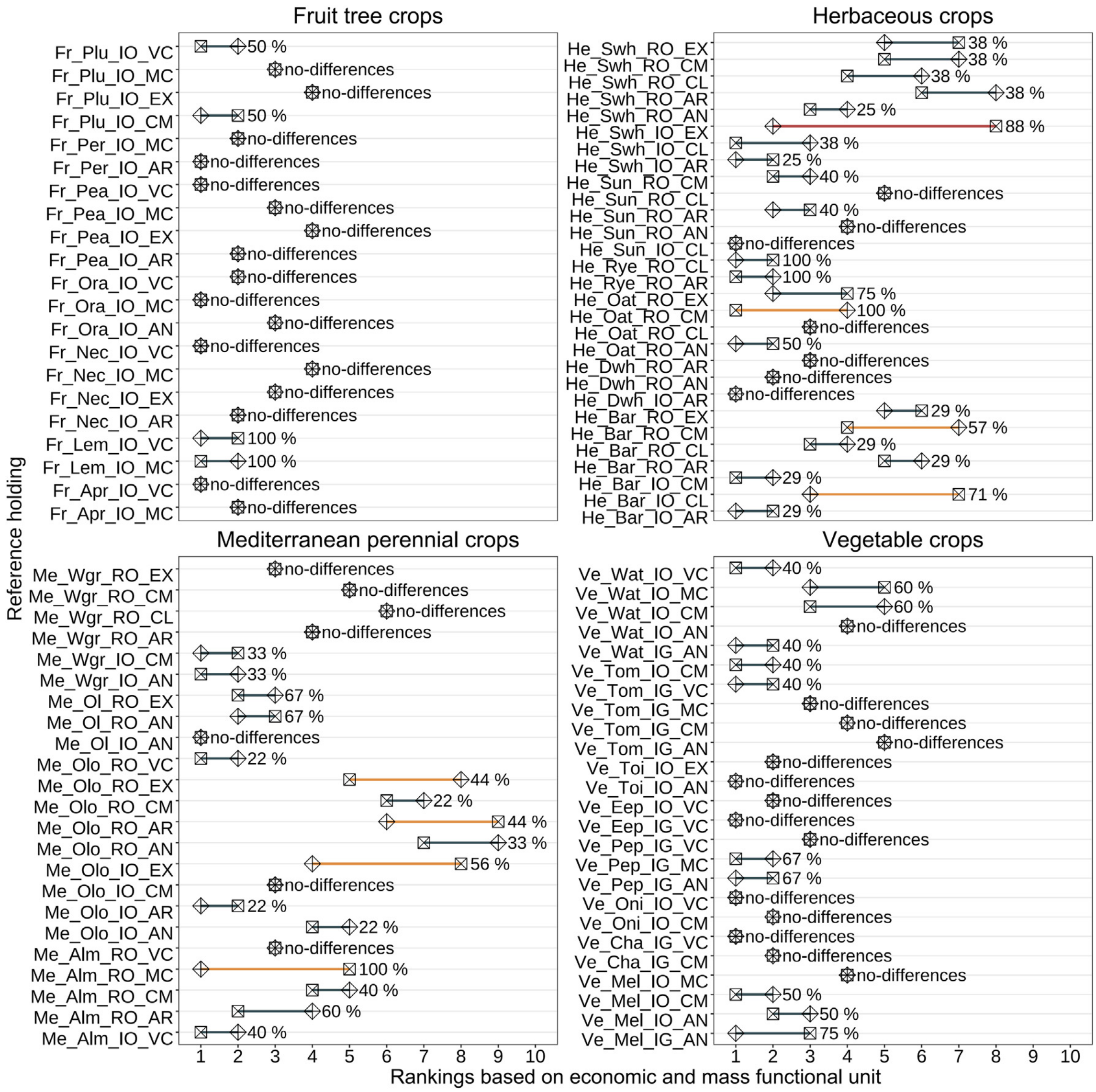


**Fig. 6.** Ranking in descending order of the environmental footprint performance using 1 € of net value added (square) versus 1 kg commodity (rhombus) as functional unit.

### *3.4. Adverse economic results versus negative environmental consequences*

The results of this study show that 14 of the 115 reference holdings assessed presented consistent economic losses over the years analysed. Spanish agriculture is framed in a competitive market economy, where many farmers provide the same commodities, making substitutions between them feasible. Taking this into account, it is debatable whether, even under a weak vision of sustainability, where the substitution of natural capital for manufactured is allowed (Hediger, 1999; López Pardo, 2012), it is convenient to support the adverse effects on the environment of the holdings with negative economic results. Assuming that these losses are not due to an inconsistency derived from working with average data from ECREA-FADN, since information on its distribution and dispersion is not provided, the continuation of the economic activity of these holdings can be justified for different reasons: among others, cultural aspects, the opportunity cost of the land, the fact that agriculture is often developed as a secondary activity, and in some cases because of subsidy collections. However, nowadays most of the subsidies are decoupled from yield and linked to meet eco-conditionality. It must be noted that agriculture contributes to fixing the population in the so-called "emptied regions", a decisive problem in some Spanish NUTS 2, and also in other southern countries of the EU (EUROSTAT, 2022; Newsham and Rowe, 2023). These positive externalities should be weighed through a comprehensive cost-benefit analysis.

In this case study, most of the holdings showing consistently negative output correspond to herbaceous crops, which should facilitate the implementation of standard measures to face this issue. As commented on in Section 3.1, machinery and fertiliser present the greatest share in the herbaceous group. To improve the performance of these crops, political decisions aimed at achieving an efficient use of agricultural inputs are needed in line with objective 1 of the Spanish CAP Strategic Plan.

### *3.5. Assessing the representativeness of the results*

The data sources used to configure the life cycle inventories of the reference holdings in the Spanish NUTS 2 can be considered representative of the regional and technical levels of the crops analysed. Even with this, the relationship between the average surface area of the reference holdings and their environmental impacts needs to be analysed to know whether the impact scores can be used to assess the environmental impacts of the crops without considering the farm size. If no significant correlation between the two variables is found, it can be assumed that the estimated scores can represent the environmental damages of farms regardless of their surface area, suggesting that there is no differential impact as a result of the size effect. As shown in Fig. 7, no correlation between the average size of the reference holding and the EF scores is observed for the four types of crops, which supports the idea that the environmental performance of the reference holdings estimated in this study was not affected by the size of the reference holdings. Therefore, as long as the opposite is not proven, the impact results of this study can be used as a reference for a specific crop in a NUTS 2 in Spain, regardless of the size of the holdings.

## 4. Discussion

The impacts accounted for in this study are subject to two kinds of limitations: the LCA approach and the data source used. Regarding the LCA approach, it should be remarked that this study corresponds to a C decision context in which purely descriptive accounting is considered (EC-JRC, 2010). In particular, a retrospective analysis is carried out, in which the performance of alternative systems in recent years is assessed. Along these lines, the C decision context works as the starting point to understand the context of a system and not as the definitive source to develop recommendations and decisions with future implications, which should be supported by A or B decision contexts; that is, a consequential LCA. Nevertheless, these results can be used to identify hotspots where measures to support sustainable agriculture should be applied, and can also be used as a basis for comparison with those resulting from the implementation of the new CAP. In addition, political measures could be suggested, whose consequences should be assessed by applying a consequential LCA. Analogously to how financial accounting is used in the calculation of income taxes, environmental impact accounting from a C decision context could be the basis for calculating environmental taxes. Even though median EF scores are analysed descriptively in Section 3, future inferential analyses would allow their monitorisation over the years, assessing the relation with the structural factors (such as yield and price of commodities). In addition, it should be noted that the calculated impacts can be used as input data in both explained and predictive studies based on historical data.

As to the data source used, although ECREA-FADN is open to the seventeen Spanish NUTS 2, consistent data for only seven of them were available in the years analysed (i.e. Andalucía, Aragón, Castilla y León, Castilla-La Mancha, Extremadura, Murcia and Comunidad Valenciana), and some relevant crops were not accounted for in some NUTS 2 (e.g. corn in AN, AR, CL, CM and EX; and olive and wine grapes in MC and VC), due to the reasons reported in Section 2.1. Yet, it does not provide information regarding the structure of the data (e.g. dispersion, distribution), and the technological itineraries of the farms are poorly described as there is no data on the surface area of the surveyed holdings, type of farming system (conventional, organic) or irrigation system (sprinkler, drip irrigation); thus, it is assumed that the reference holdings follow conventional farming practice, which is the prevailing type in Spanish agriculture. Along these lines, increasing the NUTS 2 and crops represented, improving ECREA reports with statistics on the distribution and dispersion of the quantitative data together with a systematisation of the description of the management practices followed in the reference holdings would increase the reliability and representativeness of the database and, therefore, that of the results obtained.

The new version of ECREA (MAPA, 2023c) has recently been developed based on the RECAN database, where anonymised microdata of the farms surveyed can be accessed. Microdata implies greater detail, mitigating the loss of information due to third-party data processing. In this way, the development of the ECREA-FADN from the RECAN increases the representativeness of the data and, together with the transition of existing FADN to the Farm Sustainability Data Network (FSDN) proposed by the EU (EC, 2023d), represents a relevant effort to improve the estimation of the environmental impacts of agricultural systems from this data source.

In the transition to a FSDN, the synergy between governmental institutions and researchers in the field of agricultural sustainability must be promoted to obtain a FSDN that satisfies the demand for research data. This data could be the basis for further studies; for instance, to improve the regionalisation of agricultural LCIs and to develop the social life cycle assessment or life cycle costing of representative agricultural commodities. On the other hand, decisions aimed at the opening up of accessibility to detailed data in other official statistics and at facing up to the challenge of digitalisation of Spanish agriculture may help to develop more comprehensive R-LCAs.

Methodological efforts in the application of R-LCAs should address representativeness and accuracy not only as concerns activity data but also in

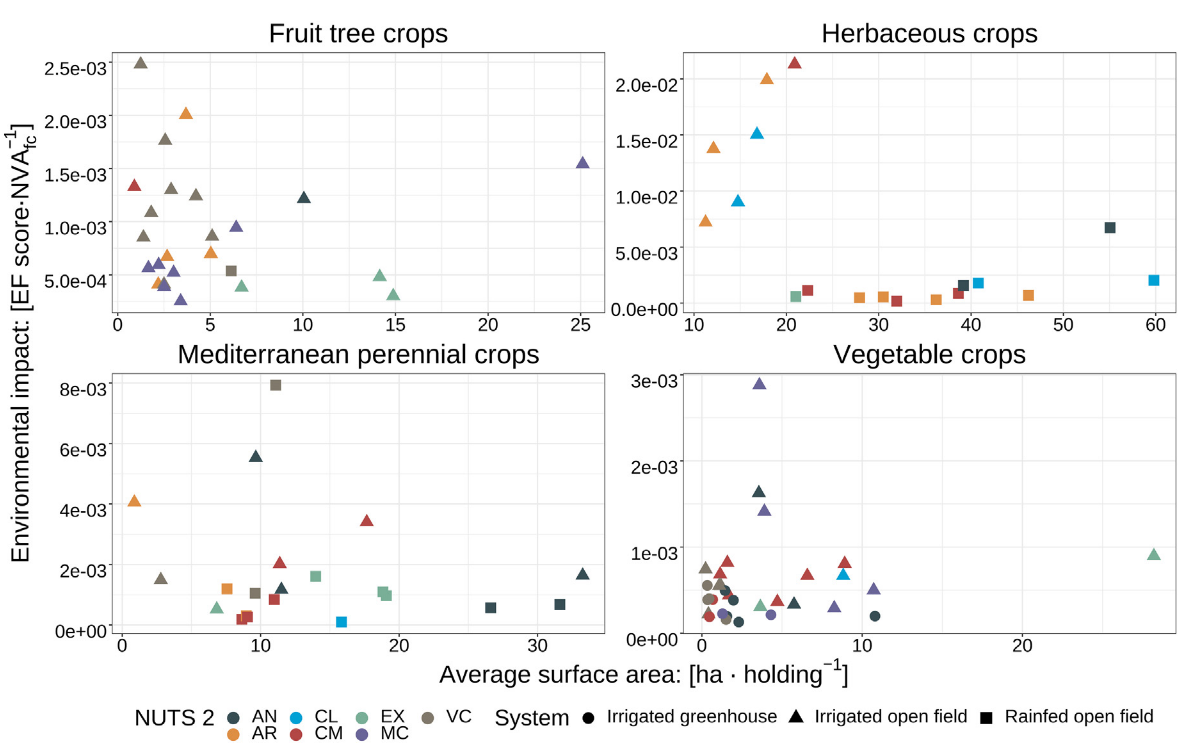


**Fig. 7.** Environmental footprint per 1 € of net value added versus the surface area of the farms.

terms of the emissions factors: for instance, the metanalysis of Cayuela et al. (2017) compile emission factors for $N_2O$ for Mediterranean cropping systems. The use of regionalised impact assessment methods is also recommended, such as IMPACT World+ (Bulle et al., 2019), LC-Impact (Verones et al., 2020), or AWARE (Boulay et al., 2018; Boulay and Lenoir, 2020).

## 5. Conclusions

A set of indicators suitable for the purposes of comparing the recent environmental performance of reference holdings at the Spanish NUTS 2 level has been obtained. One strength of these indicators is that they have been developed for a broad group of reference holdings using the same data source, that is, avoiding bias resulting from the use of diverse sources. The analysis of the EF scores helped to identify how, in most of the reference holdings, the environmental impacts were proportionally compensated for by the economic goal sought. This was not the case for most of the reference holdings of herbaceous and some Mediterranean perennial crops, in which, neither was the economic goal achieved (negative NVA) nor did the greater use of resources in the irrigated reference holdings necessarily lead to a higher yield and better economic performance, but instead increased the environmental impact. The existence of holdings with a recurrent negative contribution to the gross domestic product highlights one of the main challenges of Spanish agriculture: how to improve competitiveness and return (MAPA, 2023a). Following this study's findings, policies addressing a more efficient use of fertilisers and machinery are needed to improve the return and the environmental performance of the reference holdings, particularly in the cases of herbaceous and Mediterranean perennial crops. In particular, farm subsidies to improve the digitalisation and the development of precision farming can help to make an efficient use of the resources, such as fertilisers and machinery use; this is a valuable effort towards achieving sustainable agriculture.

In this study, the NVA is the E-FU used to compare the environmental performance of different agricultural commodities. In addition, considering that economic decisions around the supply chains is the main source of environmental impacts, E-FUs relate the environmental impacts more precisely than other options. In this context, impacts expressed on M-FU should be seen as an intermediate item to obtain impacts expressed on E-FU, which is helpful for results interpretation.

The availability of quantitative indicators is essential in decision-making towards achieving agricultural sustainability. The EU and the scientific community have robust methodologies for quantifying environmental indicators at the midpoint and a comprehensive environmental footprint indicator. Applying these methodologies to economic activity links methodological advances in science to society's needs for decision-making and policy development based on scientific arguments.

## CRediT authorship contribution statement

**Nelson Kevin Sinisterra-Solís:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft. **Neus Sanjuán:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Javier Ribal:** Conceptualization, Methodology, Software, Writing – review & editing. **Vicent Estruch:** Formal analysis. **Gabriela Clemente:** Conceptualization, Formal analysis, Writing – review & editing.

## Data availability

Data will be made available on request.

## Declaration of competing interest

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

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164937.

## References


Aguilera, E., Guzmán, G., Alonso, A., 2015a. Greenhouse gas emissions from conventional and organic cropping systems in Spain. I. Herbaceous crops. Agron. Sustain. Dev. 35, 713–724. https://doi.org/10.1007/S13593-014-0267-9.

Aguilera, E., Guzmán, G., Alonso, A., 2015b. Greenhouse gas emissions from conventional and organic cropping systems in Spain. II. Fruit tree orchards. Agron. Sustain. Dev. 35, 725–737. https://doi.org/10.1007/S13593-014-0265-Y.

Alhashim, R., Deepa, R., Anandhi, A., 2021. Environmental impact assessment of agricultural production using LCA: a review. Climate 9, 164. https://doi.org/10.3390/CLI9110164 2021, Vol. 9, Page 164.

Avadí, A., Nitschelm, L., Corson, M., Vertès, F., 2016. Data strategy for environmental assessment of agricultural regions via LCA: case study of a French catchment. Int. J. Life Cycle Assess. 21, 476–491. https://doi.org/10.1007/S11367-016-1036-6.

Avadí, A., Corson, M.S., van der Werf, H.M.G., 2018. Modelling environmental effects of selected agricultural management strategies with regional statistically based screening LCA. Int. J. Life Cycle Assess. 23, 12–25. https://doi.org/10.1007/S11367-017-1300-4.

Benoît, M., Rizzo, D., Marraccini, E., Moonen, A.C., Galli, M., Lardon, S., Rapey, H., Thenail, C., Bonari, E., 2012. Landscape agronomy: a new field for addressing agricultural landscape dynamics. Landsc. Ecol. 27, 1385–1394. https://doi.org/10.1007/S10980-012-9802-8.

Boulay, A.M., Lenoir, L., 2020. Sub-national regionalisation of the AWARE indicator for water scarcity footprint calculations. Ecol. Indic. 111, 106017. https://doi.org/10.1016/J.ECOLIND.2019.106017.

Boulay, A.M., Bare, J., Benini, L., Berger, M., Lathuillière, M.J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A.V., Ridoutt, B., Oki, T., Worbe, S., Pfister, S., 2018. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). Int. J. Life Cycle Assess. 23, 368–378. https://doi.org/10.1007/S11367-017-1333-8.

Bulle, C., Margni, M., Patouillard, L., Boulay, A.M., Bourgault, G., De Bruille, V., Cao, V., Hauschild, M., Henderson, A., Humbert, S., Kashef-Haghighi, S., Kounina, A., Laurent, A., Levasseur, A., Liard, G., Rosenbaum, R.K., Roy, P.O., Shaked, S., Fantke, P., Jolliet, O., 2019. IMPACT World+: a globally regionalized life cycle impact assessment method. Int. J. Life Cycle Assess. 24, 1653–1674. https://doi.org/10.1007/S11367-019-01583-0.

Cayuela, M.L., Aguilera, E., Sanz-Cobena, A., Adams, D.C., Abalos, D., Barton, L., Ryals, R., Silver, W.L., Alfaro, M.A., Pappa, V.A., Smith, P., Garnier, J., Billen, G., Bouwman, L., Bondeau, A., Lassaletta, L., 2017. Direct nitrous oxide emissions in Mediterranean climate cropping systems: emission factors based on a meta-analysis of available measurement data. Agric. Ecosyst. Environ. 238, 25–35. https://doi.org/10.1016/J.AGEE.2016.10.006.

Cerutti, A.K., Bruun, S., Donno, D., Beccaro, G.L., Bounous, G., 2013. Environmental sustainability of traditional foods: the case of ancient apple cultivars in Northern Italy assessed by multifunctional LCA. J. Clean. Prod. 52, 245–252. https://doi.org/10.1016/J.JCLEPRO.2013.03.029.

Cerutti, A.K., Beccaro, G.L., Bruun, S., Bosco, S., Donno, D., Notarnicola, B., Bounous, G., 2014. Life cycle assessment application in the fruit sector: State of the art and recommendations for environmental declarations of fruit products. J. Clean. Prod. 73, 125–135. https://doi.org/10.1016/J.JCLEPRO.2013.09.017.

Chen, Q., Sipiläinen, T., Sumelius, J., 2014. Assessment of agri-environmental externalities at regional levels in Finland. Sustainability 6, 3171–3191. https://doi.org/10.3390/SU6063171 2014, Vol. 6, Pages 3171-3191.

Djekic, I., Sanjuán, N., Clemente, G., Jambrak, A.R., Djukić-Vuković, A., Brodnjak, U.V., Pop, E., Thomopoulos, R., Tonda, A., 2018. Review on environmental models in the food chain - current status and future perspectives. J. Clean. Prod. 176, 1012–1025. https://doi.org/10.1016/J.JCLEPRO.2017.11.241.

Dolman, M.A., Sonneveld, M.P.W., Mollenhorst, H., De Boer, I.J.M., 2014. Benchmarking the economic, environmental and societal performance of Dutch dairy farms aiming at internal recycling of nutrients. J. Clean. Prod. 73, 245–252. https://doi.org/10.1016/J.JCLEPRO.2014.02.043.

EC, 2019. Communication from the Commission to the European parliament. The European Council, the Council, the European Economic and Social Committee and the Committee of the Regions the European Green Deal.

EC, 2020. European commission (EC). Biodiversity strategy [WWW Document]. https://commission.europa.eu/document/984adc41-3b34-4a33-9844-3cfeebdd81b7_en. (Accessed 29 March 2023).

EC, 2023a. European Commission. A European green deal [WWW Document]. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en. (Accessed 31 August 2022).

EC, 2023b. European Commission. Farm to fork strategy [WWW Document]. https://food.ec.europa.eu/horizontal-topics/farm-fork-strategy_en. (Accessed 31 August 2022).

EC, 2023c. European Commission. European platform on life cycle assessment. Environmental footprint [WWW Document]. https://eplca.jrc.ec.europa.eu/EnvironmentalFootprint.html. (Accessed 12 May 2022).

EC, 2023d. European Commission. Farm accountancy data network (FADN) [WWW Document]. https://agriculture.ec.europa.eu/data-and-analysis/farm-structures-and-economics/fadn_en. (Accessed 25 January 2023).

EC-JRC, 2010. European Commission -joint research centre institute for environment and ustainability. International Reference Life Cycle Data System (ILCD) Handbook -General guide for Life Cycle Assessment -Detailed guidance, First. ed. Publications Office of the European Union, Luxembourg https://doi.org/10.2788/38479.

EUCO, 2023. European Council (EUCO). Common agricultural policy - Consilium [WWW Document]. https://www.consilium.europa.eu/en/policies/cap-introduction/. (Accessed 30 March 2023).

EUROSTAT, 2022. Urban-rural Europe - Demographic developments in rural regions and areas - Statistics Explained [WWW Document]. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Urban-rural_Europe_-_demographic_developments_in_rural_regions_and_areas#Depopulation_of_rural_regions.2Fpopulation_change_due_to_migration. (Accessed 26 April 2023).

FAO, 2023. Food and Agriculture Organization of the United Nations. FAOSTAT. Food and agriculture data [WWW Document]. https://www.fao.org/faostat/en/#home. (Accessed 1 December 2023).

Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I., 2018. Life Cycle Assessment. Theory and Practice, Life Cycle Assessment: Theory and Practice. Springer.

Hediger, W., 1999. Reconciling “weak” and “strong” sustainability. Int. J. Soc. Econ. 26, 1120–1144. https://doi.org/10.1108/03068299910245859.

Hélias, A., van der Werf, H.M.G., Soler, L.-G., Aggeri, F., Dourmad, J.-Y., Julia, C., Nabec, L., Pellerin, S., Ruffieux, B., Trystram, G., 2022. Implementing environmental labelling of food products in France. Int. J. Life Cycle Assess. 27:7 (27), 926–931. https://doi.org/10.1007/S11367-022-02071-8 2022.

Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147. https://doi.org/10.1007/S11367-016-1246-Y.

ISO, 2006a. ISO 14044:2006(en), Environmental management — Life cycle assessment — Requirements and guidelines.

ISO, 2006b. ISO 14040:2006(en), Environmental Management — Life Cycle Assessment — Principles and Framework.

ISO, 2017. Environmental management - Life cycle assessment - Requirements and guidelines - Amendment 1 (ISO 14044:2006/Amd 1:2017).

Jan, P., Dux, D., Lips, M., Alig, M., Dumondel, M., 2012. On the link between economic and environmental performance of Swiss dairy farms of the alpine area. Int. J. Life Cycle Assess. 17, 706–719. https://doi.org/10.1007/S11367-012-0405-Z.

López Pardo, I., 2012. Sostenibilidad “débil” y “fuerte” y democracia deliberativa: el caso de la Agenda 21 Local de Madrid.

MAPA, 2008. Ministerio de Agricultura, Alimentación y Medio Ambiente de España (MAPA). Red Contable Agraria Nacional (RECAN). Recan (Nota metodológica hasta ejercicio contable 2008) [WWW Document]. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/economia/red-contable-recan/. (Accessed 4 May 2023).

MAPA, 2019. Ministerio de Agricultura, Alimentación y Medio Ambiente de España (MAPA). Red Contable Agraria Nacional (RECAN). IME-Red Contable Agraria Nacional (RECAN) [WWW Document]. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/economia/cuentas-economicas-agricultura/#ancla4. (Accessed 4 May 2023).

MAPA, 2021. Ministerio de Agricultura, Pesca y Alimentación de España. Estadística Anual de Consumo de Productos Fitosanitarios y Estadística Quinquenal de Utilización de Productos Fitosanitarios En La Agricultura. Encuesta de Utilización de Productos Fitosanitarios, 2019. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/estadisticas-medios-produccion/fitosanitarios.aspx.

MAPA, 2023a. Ministerio de Agricultura, Alimentación y Medio Ambiente de España (MAPA). El Plan Estratégico de la PAC de España [WWW Document]. https://www.mapa.gob.es/es/pac/post-2020/plan-estrategico-pac.aspx. (Accessed 29 March 2023).

MAPA, 2023b. Ministerio de Agricultura, Pesca y Alimentación. Estudios de costes de explotaciones agrícolas [WWW Document]. https://www.mapa.gob.es/es/ministerio/servicios/analisis-y-prospectiva/ECREA_Informes-Agricolas.aspx. (Accessed 31 August 2022).

MAPA, 2023c. Ministerio de Agricultura, Pesca y Alimentación de España. Subdirección General de Análisis, Prospectiva y Coordinación, Subsecretaría. ECREA 2.0.: Estudios de costes y rentas de las explotaciones agrarias [WWW Document]. https://www.mapa.gob.es/es/ministerio/servicios/analisis-y-prospectiva/ECREA.aspx. (Accessed 25 January 2023).

MAPA, 2023d. Ministerio de Agricultura, Pesca y Alimentación. Encuesta sobre Superficies y Rendimientos Cultivos (ESYRCE). Encuesta de Marco de Áreas de España. [WWW Document]. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce/. (Accessed 10 November 2022).

MAPA, 2023e. Ministerio de Agricultura, Alimentación y Medio Ambiente de España. Índices y precios percibidos agrarios. Resultados en base 2010 [WWW Document]. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/economia/precios-percibidos-pagados-salarios/precios-percibidos-por-los-agricultores-y-ganaderos/default.aspx. (Accessed 27 April 2023).

MAPA, 2023f. Ministerio de Agricultura, Alimentación y Medio Ambiente de España. Índices y precios pagados agrarios. Resultados en base 2010 [WWW Document]. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/economia/precios-percibidos-pagados-salarios/precios-pagados-por-los-agricultores-y-ganaderos/default.aspx. (Accessed 27 April 2023).

MAPA, 2023g. Ministerio de Agricultura, Alimentación y Medio Ambiente de España. Superficies y producciones anuales de cultivos. Superficie de cultivos y producciones. Cultivos y producciones 2017 [WWW Document]. https://www.mapa.gob.es/es/estadistica/temas/publicaciones/anuario-de-estadistica/2018/default.aspx?parte=3&capitulo=07. (Accessed 26 May 2023).

Martin-Gorriz, B., Gallego-Elvira, B., Martínez-Alvarez, V., Maestre-Valero, J.F., 2020. Life cycle assessment of fruit and vegetable production in the Region of Murcia (south-east Spain) and evaluation of impact mitigation practices. J. Clean. Prod. 265, 121656. https://doi.org/10.1016/J.JCLEPRO.2020.121656.

Mouron, P., Nemecek, T., Scholz, R.W., Weber, O., 2006a. Management influence on environmental impacts in an apple production system on Swiss fruit farms: combining life cycle assessment with statistical risk assessment. Agric. Ecosyst. Environ. 114, 311–322. https://doi.org/10.1016/J.AGEE.2005.11.020.

Mouron, P., Scholz, R.W., Nemecek, T., Weber, O., 2006b. Life cycle management on Swiss fruit farms: relating environmental and income indicators for apple-growing. Ecol. Econ. 58, 561–578. https://doi.org/10.1016/J.ECOLECON.2005.08.007.

Newsham, N., Rowe, F., 2023. Understanding trajectories of population decline across rural and urban Europe: a sequence analysis. Popul. Space Place 29, e2630. https://doi.org/10.1002/PSP.2630.

Notarnicola, Bruno, Tassielli, Giuseppe, Renzulli, Pietro A., Giudice, Agata lo, Notarnicola, B., Tassielli, G., Renzulli, P.A., Giudice, A. lo, Giudice, A. lo, 2015. Life Cycle Assessment in the agri-food sector: an overview of its key aspects, international initiatives, certification, labelling schemesand methodological issues. Life Cycle Assessment in the Agri-food Sector. 1–56. https://doi.org/10.1007/978-3-319-11940-3_1.

O, N.C., Pak, S.C., Ri, R.J., Han, H.I., 2023. Life cycle-carbon footprints for environmental performance/labeling of crop-based food products: analyses of complementary functional units and hotspots. Int. J. Environ. Sci. Technol. 20, 2375–2388. https://doi.org/10.1007/S13762-022-04174-Z.

Pajewski, T., Malak-Rawlikowska, A., Gołębiewska, B., 2020. Measuring regional diversification of environmental externalities in agriculture and the effectiveness of their reduction by EU agri-environmental programs in Poland. J. Clean. Prod. 276, 123013. https://doi.org/10.1016/J.JCLEPRO.2020.123013.

Pandey, D., Agrawal, M., Pandey, J.S., 2011. Carbon footprint: current methods of estimation. Environ. Monit. Assess. 178, 135–160. https://doi.org/10.1007/S10661-010-1678-Y.

Ponsioen, T.C., van der Werf, H.M.G., 2017. Five propositions to harmonize environmental footprints of food and beverages. J. Clean. Prod. 153, 457–464. https://doi.org/10.1016/J.JCLEPRO.2017.01.131.

Pradeleix, L., Roux, P., Bouarfa, S., Bellon-Maurel, V., 2022. Multilevel environmental assessment of regional farming activities with Life Cycle Assessment: Tackling data scarcity and farm diversity with Life Cycle Inventories based on Agrarian System Diagnosis. Agric. Syst. 196, 103328. https://doi.org/10.1016/J.AGSY.2021.103328.

R Core Team, 2021. R: A Language and Environment for Statistical Computing.

Ribal, J., Ramírez-Sanz, C., Estruch, V., Clemente, G., Sanjuán, N., 2017. Organic versus conventional citrus. Impact assessment and variability analysis in the Comunitat Valenciana (Spain). Int. J. Life Cycle Assess. 22, 571–586. https://doi.org/10.1007/S11367-016-1048-2.

Ribal, J., Estruch, V., Clemente, G., Fenollosa, M.L., Sanjuán, N., 2019. Assessing variability in carbon footprint throughout the food supply chain: a case study of Valencian oranges. Int. J. Life Cycle Assess. 24, 1515–1532. https://doi.org/10.1007/S11367-018-01580-9.

Sala, S., Amadei, A.M., Beylot, A., Ardente, F., 2021. The evolution of life cycle assessment in European policies over three decades. Int. J. Life Cycle Assess. 26, 2295–2314. https://doi.org/10.1007/S11367-021-01893-2.

Sinisterra-Solís, N.K., Sanjuán, N., Ribal, J., Estruch, V., Clemente, G., 2023a. An approach to regionalise the life cycle inventories of Spanish agriculture: monitoring the environmental impacts of orange and tomato crops. Sci. Total Environ. 856, 158909. https://doi.org/10.1016/J.SCITOTENV.2022.158909.

Sinisterra-Solís, N.K., Sanjuán, N., Ribal, J., Estruch, V., Clemente, G., 2023b. Dataset to monitor regionalised environmental impacts of the main agricultural products in Spain. Data Brief 46, 108883. https://doi.org/10.1016/J.DIB.2023.108883.

SPHERA, 2022. GaBi Databases & Modelling Principles.

Van Der Werf, H.M.G., Salou, T., 2015. Economic value as a functional unit for environmental labelling of food and other consumer products. J. Clean. Prod. 94, 394–397. https://doi.org/10.1016/J.JCLEPRO.2015.01.077.

Verones, F., Hellweg, S., Antón, A., Azevedo, L.B., Chaudhary, A., Cosme, N., Cucurachi, S., de Baan, L., Dong, Y., Fantke, P., Golsteijn, L., Hauschild, M., Heijungs, R., Jolliet, O., Juraske, R., Larsen, H., Laurent, A., Mutel, C.L., Margni, M., Núñez, M., Owsianiak, M., Pfister, S., Ponsioen, T., Preiss, P., Rosenbaum, R.K., Roy, P.O., Sala, S., Steinmann, Z., van Zelm, R., Van Dingenen, R., Vieira, M., Huijbregts, M.A.J., 2020. LC-IMPACT: a regionalized life cycle damage assessment method. J. Ind. Ecol. 24, 1201–1219. https://doi.org/10.1111/JIEC.13018.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21, 1218–1230. https://doi.org/10.1007/S11367-016-1087-8.