Journal of Cleaner Production 486 (2025) 144556

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

An integrated approach of carbon footprint calculation for agricultural sector through smart-farming

Dimitrios E. Tsesmelis [a,b,c,*], Ippokratis Gkotsis [a,c], Christos Saltogiannis [b,c], Spyridon Reppas [c], Stavros Panagakis [c], Efthimios Zervas [b]

[a] Department of Agriculture, University Campus Messolonghi, University of Patras, 30200, Greece
[b] Laboratory of Technology and Policy of Energy and Environment, School of Applied Arts and Sustainable Design, Hellenic Open University, 26335, Patras, Greece
[c] Division of Technology Products and Services, NEUROPUBLIC S.A., Methonis 6, 18545, Piraeus, Greece

ARTICLE INFO

Handling Editor: Jian Zuo

Keywords:
Smart farming
Carbon footprint
LCA
Agriculture sustainable development
Agricultural sector

ABSTRACT

Agricultural production and, by extension, the agri-food sector, significantly contribute to the greenhouse effect, as farming practices and inputs are among the main sources of greenhouse gas emissions (GHG). However, through the Smart Farming approach and the equipment and tools it entails, the reduction of the crops' carbon footprint becomes increasingly feasible, and this is what the current study supports and aims to highlight. Therefore, the carbon footprint of three of the most important agricultural products in the Mediterranean (Olive, Orange and Grape) is examined in crops that have been supported by Smart Farming equipment and models, in order to compare the results with those of respective ones that follow conventional farming methods. The Life Cycle Analysis (LCA) tool (ISO 14040, 14044 and 14067) along with the most suitable emissions factors are employed to ensure the validity pf the process. The results reveal a carbon footprint between 0.400 and 0.520 per kg of olive fruits grown through Smart Farming methods, between 0.180 and 0.290 for oranges and between 0.190 and 0.290 for grapes. On the other hand, conventional applications have presented an increased trend. These findings highlight the efficiency of Smart Farming in minimizing resource use and emissions, offering a pathway toward more sustainable agricultural practices.

1. Introduction

For 2019, 22% of global emissions were due to the Agriculture, Forestry and Other Land Use (AFOLU) economic sector while the largest percentage of it derives from the cultivation of crops and livestock (Intergovernmental Panel on Climate Change (IPCC), 2022). This percentage reveals a dynamic contribution of the sector to the overall greenhouse gas phenomenon and shows an increasing trend, as much as the application of conventional farming techniques and practices are favored (Leip et al., 2015). At a political level in the European Union, targets for reducing GHG are set through the European Green Deal. This agreement aims to reach net-zero balance with a time horizon of 2050 for the entire economic and productive spectrum of the EU (Directorate-General for Research and Innovation (European Commission), 2021). The agricultural sector is to be fully harmonized and drafted with the political imperatives of the institution of the EU as well. Among other things, those imperatives promote environmentally friendly crop management practices, while ensuring quality and safety for the products destined for the consumer (Wrzaszcz and Prandecki, 2020). In order to implement the above, food production is called upon to move into a new phase, including the implementation of innovative actions, which will be based on the holistic digital transformation of the management of agricultural holdings, thus integrating Smart Farming and digitization systems into the entire agri-food model (Bronson, 2018; Gardezi et al., 2024; Prutzer et al., 2023). Therefore, the agricultural sector, through the Common Agricultural Policy (CAP), aims to become more sustainable (economically and environmentally), so as to avoid wasting natural resources, such as soil and water (Barral and Detang-Dessendre, 2023).

In an era characterized by alarming rates of natural resource depletion and soil erosion deriving from the traditional agricultural practices, the advent of Smart Farming stands as a game-changing solution, poised to address these pressing issues (Lamboll et al., 2017). With climate change's pervasive impacts and the ever-mounting global demand for food, it is of major importance to redefine the approach by which agriculture is managed (Karavitis et al., 2020; Phelan et al., 2022;

* Corresponding author. Department of Agriculture, University Campus Messolonghi, University of Patras, 30200, Greece.
E-mail address: tsesmelis@upatras.gr (D.E. Tsesmelis).

https://doi.org/10.1016/j.jclepro.2024.144556
Received 5 March 2024; Received in revised form 2 December 2024; Accepted 20 December 2024
Available online 25 December 2024

Phillips and Ilcan, 2003; Tsesmelis et al., 2019, 2022a). The current study attempts to highlight the degradation of the resources to which conventional agricultural practices led, as well as the immediate need for the utilization of modern technologies that can emerge as a strong ally of the farmer (Rehman et al., 2017). By conducting a thorough research in the relevant scientific publications, it is easy to discern the transformative potential that the Smart Farming practices can deliver (Moysiadis et al., 2021). Through the application of carbon footprint calculation, this study will attempt to highlight the beneficial presence of modern technologies in the field, in an effort to troubleshoot one of the leading environmental puzzles (Adamides et al., 2020).

In the current case study, crop management practices applied by the producers to the selected agricultural lands and crops, have been digitally recorded by them. For the cultivation of these lands, consultation as well as digital tools of Smart Farming have been received, implemented and used. Then, the carbon footprint of their crops was performed, separately for each parcel and for different calendar periods. To ensure the validity of the methodology on a theoretical as well as on a practical level, a literature review was carried out, and a study of similar applications of LCA demonstrating the use of emission factors to calculate the carbon footprint of a product in agriculture based on the same international standards (ISO 14067), was conducted. In addition, attention was paid to publications related to the categories of inputs to be examined (Fan et al., 2022; Jaiswal and Agrawal, 2020; Pelletier, 2014). Then, the above results were compared with respective ones obtained from the cultivation of plots that followed conventional agricultural practices, are located within a radius of 1 km away from the original ones, have a similar size and in which the exact same varieties are grown.

The scope of this current effort is to a) identify and evaluate the emissions per crop case, in order to discover possible weak links in the processes used and pave way for improvement (Holka et al., 2022; Karwacka et al., 2020) and b) to make comparisons between the results from smart and conventional farming practices in order to cross check whether the original hypothesis is valid. If this is confirmed, the study then contributes to the identification and the imperative need for transition towards an agriculture of low and zero GHG, while ensuring the safety and quality of the food produced as mandated by the European Green Deal (Directorate-General for Research and Innovation (European Commission), 2021). This will have been achieved if the individual objectives concerning the reduced use of resources in each of the agricultural activities implemented have been achieved too. Below are mentioned the means of Smart Farming technology that were utilized in the plots of all different crops where smart farming practices were applied, and the way they served to achieve the individual goals.

1) Agrometeorological stations and soil moisture sensors for irrigation management and formulas to ensure the optimal use of water during irrigation.

Fig. 1. Study area with six plots in three different areas (Kavala, Larissa and Argos).

2) Plant protection formulas for risk assessment in order to ensure the optimal use of plant protection products in terms of their quality and quantity.
3) Fertilization balance – soil samples to ensure the nutritional products through the findings generated and the literature reviewed.

2. Materials and methods

2.1. Study area

All three crops under study are found within the administrative boundaries of Greece (Fig. 1). Geographically the country is located Southeast of Europe, and it is one of the landlocked countries surrounding the Mediterranean Sea. The main geophysical features of it are its mountainous topography that prevails inland, the long coastline (14,000 km) and the large number of islands that its seas surround (up to 3000 in total) (Tsesmelis et al., 2021). Since the climate is a typical Mediterranean one, the highest amount of precipitation – mostly rainfall – takes place between October and March, while the average annual rainfall varies from 350 mm to 2150 mm. The summer season is generally dry throughout the whole country (Fassouli et al., 2021; Karavitis et al., 2011, 2012, 2014, 2012; Stathopoulos et al., 2018; Tsesmelis et al., 2021, 2022b). Olive cultivation is one of the most historically representative crops of the Greek territory, with beneficial effects at an ecological and economic level (Loukas and Krimbas, 1983; Migliorini et al., 2018).

The olive plots under study are located in Northern Greece and more specifically in the Prefecture of Kavala. Although the majority of olive crops in Greece are located in warmer southern parts of the country, the fact that it adapts and thrives in a wide variety of soils, even in areas considered unsuitable for other crops, offers the species the opportunity to appear in a variety of Mediterranean lands. For the same reason, the species contributes to the protection of vulnerable soils from erosion and desertification (Michalopoulos et al., 2020). Both plots that are examined are irrigated - through borehole - olive groves, with a 30-year-old underground irrigation system and a total coverage of 0.8 and 0.7 ha accordingly. The cultivated olive variety for both plots is "Chalkidiki", i.e., it belongs to the category of table use fruits. With regards to the plot into which a Smart Farming cultivation approach is applied the relevant practices and applications conducted by the olive grower concerned the calendar periods of 2020, 2021 and 2022, according to the records derived from the detailed digital record kept. The operations carried out by the producer were divided into the following categories: a) soil management operations, b) general cultivation care, c) irrigation, d) fertilizer applications, e) application of crop protection products and f) harvesting. The exact same categories of work were applied to the plot for which conventional cultivation methods are followed, however, for this particular plot there is only data available for the 2022 growing season. The total applications per activity and year are shown in Table 1.

Although the cultivation of citrus fruits has suffered and is still suffering a recession in recent years, it has always been a key source of production of Mediterranean diet products which are rich in nutrients and antioxidants (Mathioudakis et al., 2023). In Greece, according to the National Ministry of Rural Development and Food, it covers approximately 40,000 ha in area and produces approximately 1,000,000 tons of products annually (Ministry of Rural Development and Food, 2022). In the present study the cultivation of oranges of the variety "Newhall" in the area of the Argolis plain is examined. The plot on which Smart Farming practices were applied covers 0.32 ha while the corresponding one for the application of conventional agricultural practices is 0.4 ha wide. The following diagrams (Fig. 2) show the temperature and humidity curves during the years if the study, while the amount of rain and the corresponding evapotranspiration concerning the wider area of Argolis, are also shown. The same categories of work as those that took place inside the olive groves took place in both plots here as well, applied of course in correspondence with the needs presented by the plots of citrus cultivation.

Viticulture, whether it concerns wine or table grapes, is also one of the most characteristic crops of the Mediterranean as well as of Greece. Almost 90,000 ha are covered by vine cultivation in Greece while it produces more than 800,000 tons annually. Moreover, the importance and status of the wine industry in Greece has enhanced the interest in studies concerning the climatic characteristics of crop seasons, as well as the adaptation of crops to climate change data (Koufos et al., 2014). As far as the parcel plots under study is concerned, they both belong to the Prefecture of Larissa and the grape variety cultivated within their boundaries is called "Soultanina". Both parcels of land belong to the regional unit of Larissa and within their boundaries the grape variety called Sultanina is grown. The groups of work carried out differ in the two plots and in the growing seasons according to the needs that arose. Both plots were also at a fully productive age.

Table 1
Emission factors with the relevant references and Tier level.

Emission Source	Tier	References
Conventional Fuels (Manufacture/Use)	1	Gordillo et al. (2018) Masnadi et al. (2018) European Environment Agency (2023)
Electricity	2	European Environment Agency (2023)
Synthetic Fertilizers (Production)	1	Marinussen et al. (2012)
Plant Protection Products (Production)	1	Lal (2004)
Amortization of Equipment	2	Ministry of Rural Development and Food (2022) Nemecek and Kägi (2007) Rossignol (2020)
Application of Fertilizers	1	IPCC (2006)
Sequestration		
Land Use	2	Ministry of Environment and Energy (2023)

2.2. GHG emission calculations approach

Life Cycle Assessment (LCA) serves as a tool for evaluating the potential environmental impact of a product's entire life cycle, spanning from the acquisition of raw materials to the final disposal (Bhander et al., 2003; Joshi, 1999). One of its primary uses includes the assessment of environmental impacts of the manufacture, use and disposal of a product, related to climate change through greenhouse gas (GHG) emissions (Crettaz et al., 2015). LCA employs thorough surveys that consider all resources associated with all flows of a full-scale production system, enabling the quantification of not only GHG emissions, but also of various other environmental factors, such as acidification, eutrophication, and ecotoxicity (Huijbregts, 1999). Moreover, it offers a versatile range of strategies for analyzing and mitigating environmental impacts associated with specific processes or activities (Chauhan et al., 2011; Jeswani et al., 2010; Leip et al., 2015; Tsesmelis et al., 2021). The application of LCA in various industries, including energy and industrial processes, has been well-established and can offer significant advantages to the agricultural sector (Bevan, 2022; Hospido et al., 2010; Olmez et al., 2016).

For this present report, the process of conducting an LCA was based in established standards that were developed by the ISO series (ISO 14040 to ISO 14044), while, in order to complete the methodology of the study in terms of calculating the carbon footprint of a product, the research process was also based on the standards of ISO 14067 (Finkbeiner et al., 2006; ISO (International Organization for Standardization), 2018, 2006a, 2006b). These standards provide comprehensive guidance on the objectives and implementation of LCA, while offering a detailed description of the assessment's four primary steps (Azapagic and Clift, 1999; Sharif and Hammad, 2019). It initiates with a) the definition of goals and scope, followed by b) the Life Cycle Inventory

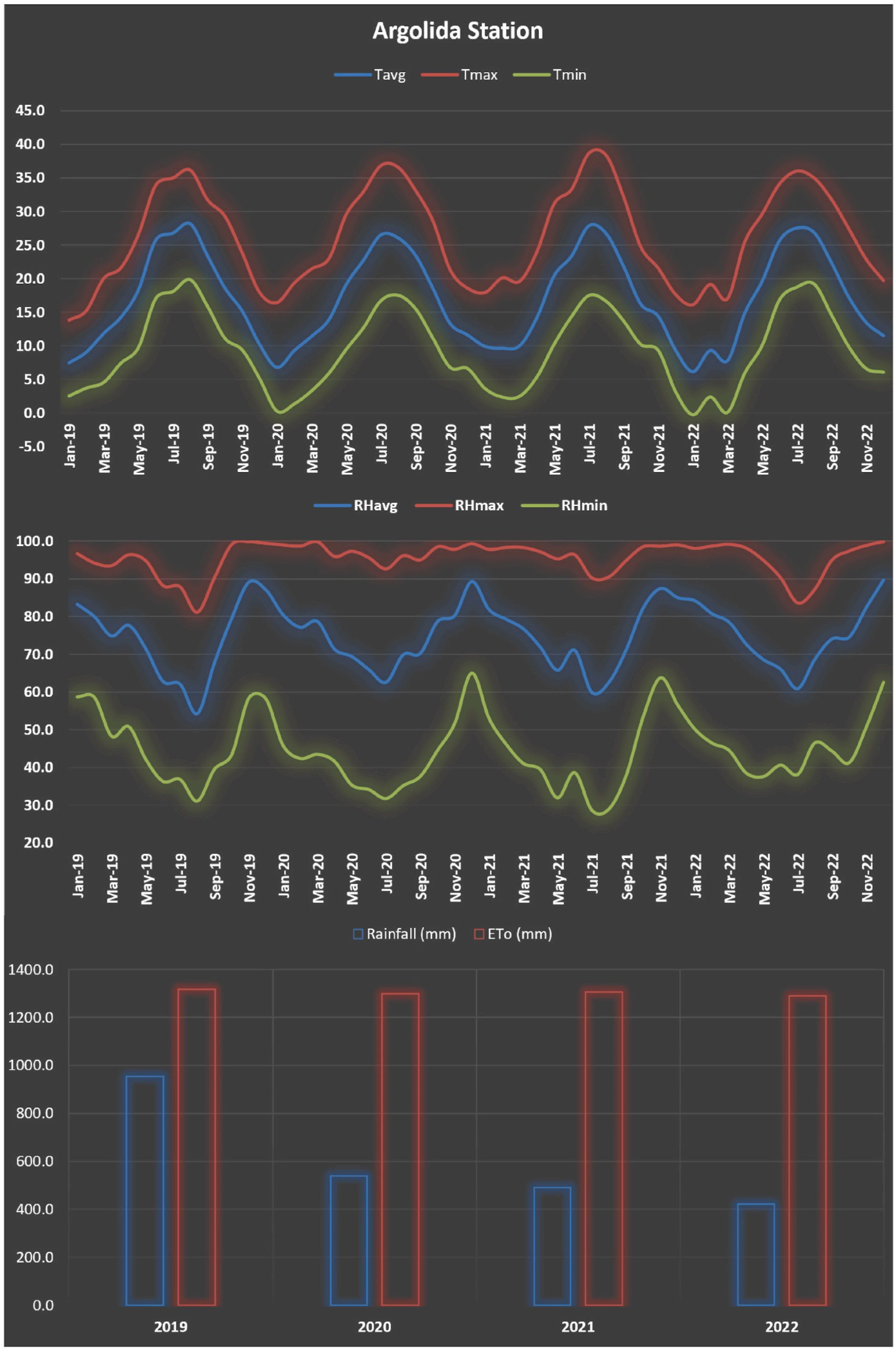

Fig. 2. Climatic parameters in Argolida Station (2019–2022).

(LCI), c) Life Cycle Impact Assessment (LCIA), and d) the subsequent interpretation of results. Fig. 3 shows all emission categories that have been considered during this particular study.

The LCA scope in the present study covered the process from cradle-to-farm gate of all different crops examined. The relevant functional unit is 1 kg of product (prd) for each different crop respectively. The system boundary – which is the one that defines the processes and input/output components that are taken into account in the LCA - starts from the extraction of raw materials, continues with the manufacture/preparation and transport of the necessary system inputs, and extends to the execution of the cultivation activities and the crop yield, from which the final product is obtained (Fig. 4). The placement of the system boundaries must be carried out correctly, as it is one of the basis for the success of the obtained results (FAO, 2017; Matthews et al., 2008).

Any primary data, from whatever different source may come from, should be clearly and accurately recorded in a work journal, by the respective producer. In general, a work journal should consist of three different parts. In the first one, the information regarding the "identity" of the parcel plot should be recorded in detail. This information usually concerns the name of the producer, the location, the type of the crop and the variety, the area measured in hectares, the date of the first establishment (for perennial crops), the source of water and the irrigation method used. The second is the one in which inputs are also clearly and accurately recorded. For each of them, it is essential to record the type, the amount of application and the composition, the day and time as well as the method of application if this is necessary. The last part of the

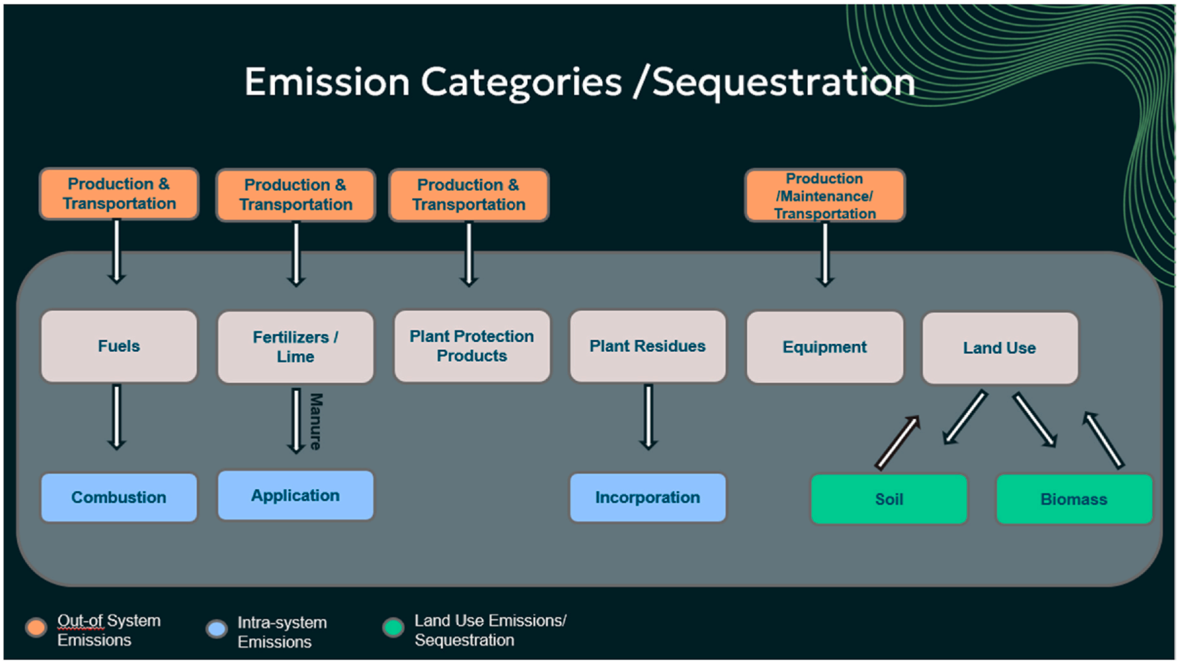

Fig. 3. All emission and sequestration parameters considered.

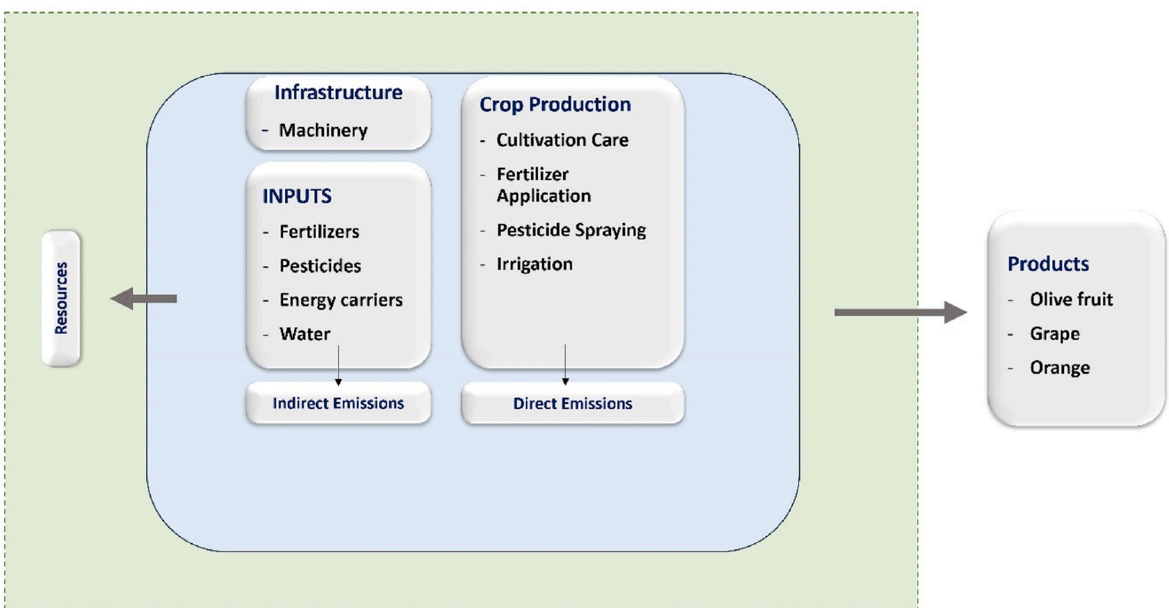

Fig. 4. Schematic representation of the Assessment's system boundary (adapted from FAO, 2017; FAO, 2017)).

journal concerns the post-collection data relevant to transport, storage and/or packaging of the final product. This latter part does not take place in this current assessment, as it is a cradle to farm-gate study. The different categories of inputs considered are shown in Fig. 4 and are further analyzed below. Table 1 shows the literature sources from which the emission factors were derived to apply the carbon footprint calculation methodology.

2.3. Smart farming approach

Smart Farming is an approach to agricultural production management that helps farmers make the best possible decisions about their crop, based on modern technologies, data, and research results (Tomar and Kaur, 2021). Practically, it could be said that it allows the farmer to know when to irrigate and the necessary quantity, the optimum time and applications against pests and diseases, or the type of fertilizer their crop needs. In short, the farmers reduce production costs and improve their harvest, thus increasing their profit (Güven et al., 2023). The environmental benefits from reduced inputs (agrochemicals and irrigation water etc.) and the product added value gained, attract the interest of retail buyers and consumers (Dong, 2021; Paleari et al., 2024). In this study gaiasense smart-farming system is utilized. The digital means of gaiasense that were employed for the purpose of more sustainable cultivation of the under-study crops, are the following.

1) Agrometeorological stations (ETo and precipitation), soil moisture sensors (soil moisture thresholds monitoring), soil type and texture, infrastructure (water resources, irrigation system), crop growth stage and forecasted ETo and precipitation for irrigation management and formulas to ensure the optimal use of water during irrigation (dose and schedule).
2) Plant protection formulas based on microclimatic parameters from agrometeorological stations and field data (phenological stage, cultivation cares etc.) it is estimated the risk of post disease impacts to ensure the optimal use of plant protection products in terms of their quality and quantity.
3) The initial phase of fertilization advice is examined the soil features according to the results of the soil analyses (pH, Electrical Conductivity, N, P, K, $CaCO_3$, Organic Matter, Fe, Zn, Mn, Cu and B). Then, through the soil decision support system and by considering all the parameters (soil analyses, crop nutritional needs, water holding capacity, slope and biodiversity) the appropriate soil fertilization plan is determined.

All the above have the potential to provide a complete and detailed picture of the farm, which contributes significantly to the decision-making process for the provision of the consultancy. After collecting and processing all necessary data, the system can provide specialized advice for each category of work separately (pest management, irrigation, fertilization etc.), aiming at saving resources and reaching a more sustainable crop management at all levels (environmental, financial, social). In current effort, the goal concerned the reduction of GHG, thus ensuring the same or even greater yield by using fewer resources (Adamides et al., 2020; gaiasense, 2018).

3. Results

By applying the methodology as analyzed in the previous chapter and by taking into account all interventions conducted by each producer, the carbon footprint for each crop and each cultivation season was obtained separately. As it has already been mentioned, the methodology was based on the estimations of the GHG emissions that come through the consumption of energy and the application of fertilizers and plant protection products, but also from the energy incorporated in all of the above, plus any mechanical equipment that have been used. Moreover, an assessment of carbon dioxide sequestration from the atmosphere has also been carried out for two out of three crops that were studied. Table 2 shows the results of the calculations per crop and growing season.

Table 2 shows the number of all activities that took place in all the different plots. A brief comparison shows that in terms of olive crops, in the conventional type of cultivation there were from 11% to 16% increased activities on the part of the producer, compared to those following Smart Farming methods. As far as orange cultivation is concerned, the corresponding increase in interventions by producers reaches 20%–22% in the cultivation of conventional methods. Correspondingly, there seems to be less intervention in the Smart Farming of the vine, but this time only for the last two growing seasons (2021, 2022). The first one shows an increase in the level of 14%, but it seems that this is due to the emergency need to fight a fungus that attacked the crop during that period.

Table 3 shows the final carbon footprint results for each individual Smart Farming crop and field and for each growing season. The first column shows the studied growing season, the second shows the carbon footprint of the emissions that arise during the growing process, while the third one presents the balance of emissions, after the changes in the system's carbon stocks (living biomass and soil). Table 4 shows the corresponding results concerning the three conventional crops.

With regards to the olive crop cultivation, the changes that might occur due to possible sequestration were considered to be negligible. According to the relevant methodology mentioned earlier, since the trees of this specific plot have exceeded their developmental limit – which is defined as the middle of their biological cycle - were in a state of balance, in terms of the amount of the living biomass that they carried in the different parts of their bodies. Conversely, in the orange and grape crops there seems to be an absorption of carbon dioxide from the atmosphere, which significantly lowers the emissions balance in both cases. It is also worth mentioning the fact that it was only for the orange crop that data were collected for four growing seasons. For the other two, it was only possible to collect data of only three growing seasons.

Analyzing the results in each crop separately, it is noticed that if the plots of olive cultivation are compared, initially for the 2022 cultivation season, it appears that that of conventional practices shows a 14.85% higher footprint. In corresponding comparisons in the orange crop the conventional crop shows a footprint 16.17% higher for 2022, while a

Table 2
Agricultural tasks/activities and applications for olive, orange, and grape cultivation per season.

Tasks/activities	Season 2019	Season 2020	Season 2021	Season 2022	Season 2022
	Smart Farming Approach				Conventional
Olive					
Soil management operations	n/d	3	1	2	2
Cultivation care operations	n/d	3	3	3	3
Irrigation Events	n/d	15	15	15	15
Fungicide applications	n/d	4	4	4	7
Insecticide applications	n/d	4	4	4	6
NPK fertilizer applications	n/d	5	5	5	5
Orange					
Soil management operations	4	4	4	4	4
Cultivation care operations	1	1	1	1	2
Irrigation Events	10	10	10	10	12
Fungicide applications	3	3	3	3	5
Insecticide applications	8	8	8	8	10
NPK fertilizer applications	6	6	5	5	7
Grape					
Soil management operations	n/d	–	4	1	3
Cultivation care operations	n/d	5	10	6	10
Irrigation Events	n/d	24	21	18	25
Fungicide applications	n/d	46	–	31	42
Fertigation application. (C, Chelate Fe)	n/d	3	–	8	10
Foliar fertigation (biostimulators, copper)	n/d	30	4	–	–
Insecticide applications	n/d	13	38	8	10
Herbicide applications	n/d	–	–	2	4
Organo-chemical fertigation	n/d	–	3	–	–
Phyto-regulator application	n/d	1	1	1	–
Organic fertilizer applications	n/d	–	–	2	–
NPK fertilizer applications	n/d	8	3	7	7

Table 3
Carbon Footprint Results for investigated crops through Smart-Farming.

Growing Season	CO_{2eq-}	Net CO_{2eq-}
Olive		
2020	0.516 (kg CO_2/kg prd)	-
2021	0.476 (kg CO_2/kg prd)	-
2022	0.407 (kg CO_2/kg prd)	-
Mean	**0.466 (kg CO_2/kg prd)**	-
Orange		
2019	0.219 (kg CO_2/kg prd)	0.052 (kg CO_2/kg prd)
2020	0.183 (kg CO_2/kg prd)	0.043 (kg CO_2/kg prd)
2021	0.290 (kg CO_2/kg prd)	0.069 (kg CO_2/kg prd)
2022	0.197 (kg CO_2/kg prd)	0.047 (kg CO_2/kg prd)
Mean	**0.222 (kg CO_2/kg prd)**	**0.053 (kg CO_2/kg prd)**
Grape		
2020	0.284 (kg CO_2/kg prd)	0.191 (kg CO_2/kg prd)
2021	0.199 (kg CO_2/kg prd)	0.123 (kg CO_2/kg prd)
2022	0.204 (kg CO_2/kg prd)	0.135 (kg CO_2/kg prd)
Mean	**0.229 (kg CO_2/kg prd)**	**0.150 (kg CO_2/kg prd)**

Table 4
Carbon Footprint Results for investigated crops through conventional approach.

Growing Season	CO_{2eq-}	Net CO_{2eq-}
Olive		
2022	0.478 (kg CO_2/kg prd)	-
Orange		
2022	0.235 (kg CO_2/kg prd)	0.047 (kg CO_2/kg prd)
Grape		
2022	0.238 (kg CO_2/kg prd)	0.120 (kg CO_2/kg prd)

corresponding reduction is also presented in the total footprint, i.e. which also concerns the calculation of emissions and absorptions. Finally, in terms of vine cultivation, the plot with the application of conventional practices is also shown to be higher by 14.28% for 2022.

4. Discussion

The main results to be discussed concern the comparison between the crop footprint between the ones in which conventional practices have been applied and those which follow smart farming advice. In general, it should be mentioned that what is observed here is that in all 3 different crops it appears that the carbon footprint is even slightly reduced when the producers follow the Smart Farming approach. The carbon footprint of conventional crops seems to have been increased both in terms of the results presented by Smart Farming crops in the same growing season that was applied (2022) but also in terms of the overall average they present.

The methodology used in this work was based on a literature study of similar carbon footprint estimates for the three different crops, with a similar system boundary and a cradle-to-farmgate approach. By starting from orange conventional cultivation and examining studies that have both conducted in Europe as well as in the USA, it is observed that similar analyses result in estimations ranging from 0.17 to 0.35 CO_{2eq-} (Bell and Horvath, 2020; Ribal et al., 2019). The results of this study are in accordance with this range, by even approaching their lower values. By also evaluating the result of the carbon balance after considering the sequestration estimation part, it is worth mentioning that since the total carbon balance seems to approach zero, the cultivation of orange seems to be one of the more sustainable ones and, therefore, there seems to be room for further research, which through the application of intelligent agriculture and good practices, will lead the crop to even higher levels of sustainability.

As far as the results of table grape cultivation are concerned, they are close to those of the international literature when it comes to a Mediterranean climate crop at a productive age (Hefler and Kissinger, 2023; Xiao et al., 2018) Relative values obtained from the literature in this case range between 0.158 and 0.347. Although the grapevines in this current study were considered to be at a productive age, they were in an early ripe state, thus it is expected that in the next growing seasons the average carbon footprint will increase, as the inputs will also increase. The grapevine does not present the same ability as the orange tree in the development of biomass through sequestration; however, the difference in the balance is noticeable.

The carbon footprint results with regards to olive cultivation varies within the range of values as recorded by literature references (Proietti et al., 2017). During the literature review, large discrepancies are observed regarding the carbon footprint of olive oil fruit, as the result is affected by several parameters. Indicatively, it seems to range from 0.300 kg to 1.5 kg of emissions per kilogram of product, always noting that this is exclusively for the calculation of emissions and not absorptions (Proietti et al., 2017). Similar methodology was applied in OliveUp project in Fthiotis, prefecture of Central Greece and it depicts comparable results on carbon footprints. Specifically, this project examined five different fields for two growing seasons each and the range of these values were from 0.371 to 1.025, excluding however, cases of unfruitfulness. Research of the OliveUp has been co-financed by the European Regional Development Fund of the European Union and Greek national funds through the Operational Program Research & Innovation Strategy for Smart Specialization RIS3 (project code: STER1-0021068) (Galanis et al., 2023).

In parallel with any research process concerning agriculture involving Smart Farming methods, questions are always raised regarding the difficulty of adopting digital media by farmers. Although several novel studies highlight the environmental benefits that are obtained from their use (Doshi et al., 2019; Moysiadis et al., 2021). It is always a challenge to achieve widespread utilization by the majority of farmers in a given area at a political level. Various behavioral determinants are presented as causes of this issue. A few indicative ones are lack of appropriate introduction and education/training and the cost of acquiring these media (Giua et al., 2022; Kiropoulos and Bibi, 2024; Osrof et al., 2023; Ouédraogo et al., 2019). The difficulty of adopting modern digital data collection methods in agriculture is not an issue that concerns specific countries. Various research programs at international and regional levels have been mobilized to investigate the difficulties and implement proposals to resolve the issue (Marianos and Chadid, 2023; Moniz and Langefeld, 2023). Moreover, the resistance that appears to adoption does not exclusively concern producers but also other actors, and this is what makes the problem complex (Autio et al., 2021; Bacco et al., 2019; Klerkx et al., 2019).

Similarly to the above, this specific issue is also presented in Greece. The digital transformation of agriculture is a challenge for every involved body and for this reason, in recent years, academic and research organizations, with the contribution of companies active in the field, have participated in research programs or have conducted independent research, with the aim of investigating the causes and submitting proposals with the aim of disseminating and making easier access for all interested parties to information regarding these digital media (Marianos and Chadid, 2023; Moniz and Langefeld, 2023; Moysiadis et al., 2021). Moreover, in a research context, the Hellenic Ministry of Rural Development and Food with Information Society have installed 3050 stations in many different crops throughout the country with the aim of obtaining precise digital data and introducing and familiarizing the country's agricultural potential with a part of the digital technology that can be applied in agriculture (Ministry of Digital Policy, Telecommunications and Media, 2024).

5. Conclusions

Agriculture contributes, to a large extent, to the release of GHG emissions and in connection with the ever-increasing world population, it is realized that food needs are going to increase significantly. The prevailing demand for high-quality and sufficient food highlights the need for joint mitigation efforts for the future reduction of emissions while, at the same time, within this context, the necessity to identify, or identify and quantify, agricultural emissions. Therefore, to achieve reduction in the impact of agriculture on climate change, there must be a gradual improvement in the efficiency of food production and in the long term to limit negative climate impacts and ultimately make the agri-food sector more sustainable and resilient. In addition, certification systems, Eco-Labeling, Internet of Things and various tools from Farm to Fork for cultivations, could provide a lower impact on natural resources and products with an improved quality.

The carbon footprint is a valuable tool by which it is possible to assess the environmental performance of an agricultural holding. In the future, carbon footprint will be an integral part of agricultural activity, and the producers will have to demonstrate in practice that they are fully aligned with policies that promote its reduction at a crop level. At the same time, carbon footprint will be recognized through certification systems that promote environmental sustainability. Crops can also adapt to the new data of observed climate variation by applying innovative management systems, aiming at the continuous improvement of soil fertility through increasing organic matter and following carbon sequestration practices. Smart Farming is essential for the application of precision farming and will significantly contribute to a more effective use of energy. In this context, the agricultural sector can mitigate its environmental impacts, save energy and natural resources and, eventually, reduce the carbon footprint for each farm. As mentioned before the results of Smart Farming driven crops present lower carbon footprint values. Therefore, for olive fruits is 0.400–0.520 per kg, for oranges is 0.180–0.290 and for grapes 0.190–0.290. On the contrary, the crops following traditional methods presented an increased trend.

Smart farming practices appear to be a catalyst for the environmental sustainability of crops and a very important factor in reducing greenhouse gas emissions. The findings of the present study indicate a consistent trend of decreasing carbon footprint at the agricultural product level in three different crops which cannot go unnoticed. Although each different technology that is introduced in the field of agriculture brings in its turn a quantity of integrated emissions which should of course not be ignored, it is considered that these can be amortized within certain cultivation periods.

CRediT authorship contribution statement

Dimitrios E. Tsesmelis: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ippokratis Gkotsis:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Christos Saltogiannis:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Spyridon Reppas:** Writing – review & editing, Methodology, Formal analysis. **Stavros Panagakis:** Writing – review & editing, Formal analysis, Data curation. **Efthimios Zervas:** Writing – review & editing, Supervision, Conceptualization.

Consent to participate

All authors consent to participate in the current research.

Ethics approval/declarations

All authors harmonized with journal ethics.

Consent for publication

All authors consent for publication of the current research.

Code availability (software application or custom code)

Not applicable.

Funding

This research received no external funding.

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.

Acknowledgements

The authors would like to acknowledge the partners of the QuantiFarm project for their work and contributions, which are included in this paper. QuantiFarm has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101059700.

Data availability

The data presented in this study are available on request from the corresponding author.

References

Adamides, G., Kalatzis, N., Stylianou, A., Marianos, N., Chatzipapadopoulos, F., Giannakopoulou, M., Papadavid, G., Vassiliou, V., Neocleous, D., 2020. Smart farming techniques for climate change adaptation in Cyprus. Atmosphere 11, 557. https://doi.org/10.3390/atmos11060557.

Autio, A., Johansson, T., Motaroki, L., Minoia, P., Pellikka, P., 2021. Constraints for adopting climate-smart agricultural practices among smallholder farmers in Southeast Kenya. Agric. Syst. 194, 103284. https://doi.org/10.1016/j.agsy.2021.103284.

Azapagic, A., Clift, R., 1999. The application of life cycle assessment to process optimisation. Comput. Chem. Eng. 23, 1509–1526. https://doi.org/10.1016/S0098-1354(99)00308-7.

Bacco, M., Barsocchi, P., Ferro, E., Gotta, A., Ruggeri, M., 2019. The digitisation of agriculture: a survey of research activities on smart farming. Array 3–4, 100009. https://doi.org/10.1016/j.array.2019.100009.

Barral, S., Detang-Dessendre, C., 2023. Reforming the Common agricultural policy (2023–2027): multidisciplinary views. Rev Agric Food Environ Stud 104, 47–50. https://doi.org/10.1007/s41130-023-00191-9.

Bell, E.M., Horvath, A., 2020. Modeling the carbon footprint of fresh produce: effects of transportation, localness, and seasonality on US orange markets. Environ. Res. Lett. 15, 034040. https://doi.org/10.1088/1748-9326/ab6c2f.

Bevan, E.A.R., 2022. Hydrothermal carbonisation of waste biomass: current limitations, strategic success and market position analysis. In: Jacob-Lopes, E., Queiroz Zepka, L., Costa Deprá, M. (Eds.), Handbook of Waste Biorefinery: Circular Economy of Renewable Energy. Springer International Publishing, Cham, pp. 723–768. https://doi.org/10.1007/978-3-031-06562-0_27.

Bhander, G.S., Hauschild, M., McAloone, T., 2003. Implementing life cycle assessment in product development. Environ. Prog. 22, 255–267. https://doi.org/10.1002/ep.670220414.

Bronson, K., 2018. Smart farming: including rights holders for responsible agricultural innovation. Technology Innovation Management Review 8, 7–14. https://doi.org/10.22215/timreview/1135.

Chauhan, M.K., Varun, Chaudhary, S., Kumar, S., Samar, 2011. Life cycle assessment of sugar industry: a review. Renew. Sustain. Energy Rev. 15, 3445–3453. https://doi.org/10.1016/j.rser.2011.04.033.

Crettaz, O.J., Saade-Sbeih, Myriam, Shaked, Shanna, Jolliet, Alexandre, Pierre, 2015. Environmental Life Cycle Assessment. CRC Press, Boca Raton. https://doi.org/10.1201/b19138.

Directorate-General for Research and Innovation (European Commission), 2021. European Green Deal: Research & Innovation Call. Publications Office of the European Union, LU.

Dong, L., 2021. Toward resilient agriculture value chains: challenges and opportunities. Prod. Oper. Manag. 30, 666–675. https://doi.org/10.1111/poms.13308.

Doshi, J., Patel, T., Bharti, S. kumar, 2019. Smart Farming using IoT, a solution for optimally monitoring farming conditions. Procedia Computer Science, The 10th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN-2019)/The 9th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH-2019) / Affiliated Workshops 160, 746–751. https://doi.org/10.1016/j.procs.2019.11.016.

European Environment Agency, 2023. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023. European Environment Agency (Publication).

Fan, J., Liu, C., Xie, J., Han, L., Zhang, C., Guo, D., Niu, J., Jin, H., McConkey, B.G., 2022. Life cycle assessment on agricultural production: a mini review on methodology,

application, and challenges. Int. J. Environ. Res. Publ. Health 19, 9817. https://doi.org/10.3390/ijerph19169817.
FAO, 2017. Global Database of GHG Emissions Related to Feed Crops: Methodology. Version 1. Livestock Environmental Assessment and Performance Partnership. Food and Agriculture Organization of the United Nations, Rome, Italy.
Fassouli, V.P., Karavitis, C.A., Tsesmelis, D.E., Alexandris, S.G., 2021. Factual Drought Index (FDI): a composite index based on precipitation and evapotranspiration. Hydrol. Sci. J. 0, null. https://doi.org/10.1080/02626667.2021.1957477.
Finkbeiner, M., Inaba, A., Tan, R., Christiansen, K., Klüppel, H.-J., 2006. The new international standards for life cycle assessment: ISO 14040 and ISO 14044. Int. J. Life Cycle Assess. 11, 80–85. https://doi.org/10.1065/lca2006.02.002.
gaiasense, 2018. LIFE GAIASense project-presentation of LIFE GAIA sense at IV agriculture forum | the industry's digital transition. LIFE GAIA Sense project-Presentation of LIFE GAIA Sense at IV Agriculture Forum | The Industry's Digital Transition. URL. https://lifegaiasense.eu/presentation-of-life-gaia-sense-at-iv-agriculture-forum-the-industrys-digital-transition/. (Accessed 10 January 2023).
Galanis, G., Giortsou, M., Papadopoulou, D., Papastergiou, A., 2023. Integrated system of carbon footprint (STER1-0021068 No. II2.6). Research of the OliveUp Has Been Co-financed by the European Regional Development Fund of the European Union and Greek National Funds through the Operational Program Research & Innovation Strategy for Smart Specialization RIS3.
Gardezi, M., Abuayyash, H., Adler, P.R., Alvez, J.P., Anjum, R., Badireddy, A.R., Brugler, S., Carcamo, P., Clay, D., Dadkhah, A., Emery, M., Faulkner, J.W., Joshi, B., Joshi, D.R., Khan, A.H., Koliba, C., Kumari, S., McMaine, J., Merrill, S., Mitra, S., Musayev, S., Oikonomou, P.D., Pinder, G., Prutzer, E., Rathore, J., Ricketts, T., Rizzo, D.M., Ryan, B.E.K., Sahraei, M., Schroth, A.W., Turnbull, S., Zia, A., 2024. The role of living labs in cultivating inclusive and responsible innovation in precision agriculture. Agric. Syst. 216, 103908. https://doi.org/10.1016/j.agsy.2024.103908.
Giua, C., Materia, V.C., Camanzi, L., 2022. Smart farming technologies adoption: which factors play a role in the digital transition? Technol. Soc. 68, 101869. https://doi.org/10.1016/j.techsoc.2022.101869.
Gordillo, V., Rankovic, N., Abdul-Manan, A.F.N., 2018. Customizing CO2 allocation using a new non-iterative method to reflect operational constraints in complex EU refineries. Int. J. Life Cycle Assess. 23, 1527–1541. https://doi.org/10.1007/s11367-017-1380-1.
Güven, B., Baz, İ., Kocaoğlu, B., Toprak, E., Erol Barkana, D., Soğutmaz Özdemir, B., 2023. Smart farming technologies for sustainable agriculture: from food to energy. In: Oncel, S.S. (Ed.), A Sustainable Green Future: Perspectives on Energy, Economy, Industry, Cities and Environment. Springer International Publishing, Cham, pp. 481–506. https://doi.org/10.1007/978-3-031-24942-6_22.
Hefler, Y.T., Kissinger, M., 2023. Grape wine cultivation carbon footprint: embracing a life cycle approach across climatic zones. Agriculture 13, 303. https://doi.org/10.3390/agriculture13020303.
Holka, M., Kowalska, J., Jakubowska, M., 2022. Reducing carbon footprint of agriculture—can organic farming help to mitigate climate change? Agriculture 12, 1383. https://doi.org/10.3390/agriculture12091383.
Hospido, A., Davis, J., Berlin, J., Sonesson, U., 2010. A review of methodological issues affecting LCA of novel food products. Int. J. Life Cycle Assess. 15, 44–52. https://doi.org/10.1007/s11367-009-0130-4.
Huijbregts, M.A.J., 1999. Life-cycle impact assessment of acidifying and eutrophying air pollutants, Calculation of characterisation factors with RAINS-LCA. Interfaculty Department of Environmental Science, Faculty of Environmental Science. University of Amsterdam, Amsterdam, The Netherlands.
Intergovernmental Panel on Climate Change (IPCC), 2022. Land–climate interactions. In: Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. Cambridge University Press, Cambridge, pp. 131–248. https://doi.org/10.1017/9781009157988.004.
IPCC, 2006. Guidelines for National Greenhouse Gas Inventories Volume 4 Agriculture, Forestry and Other Land Use.
ISO (International Organization for Standardization), 2018. Greenhouse Gases — Carbon Footprint of Products — Requirements and Guidelines for Quantification.
ISO (International Organization for Standardization), 2006a. Environmental Management — Life Cycle Assessment — Principles and Framework.
ISO (International Organization for Standardization), 2006b. Environmental Management — Life Cycle Assessment — Requirements and Guidelines.
Jaiswal, B., Agrawal, M., 2020. Carbon footprints of agriculture sector. In: Muthu, S.S. (Ed.), Carbon Footprints: Case Studies from the Building, Household, and Agricultural Sectors, Environmental Footprints and Eco-Design of Products and Processes. Springer, Singapore, pp. 81–99. https://doi.org/10.1007/978-981-13-7916-1_4.
Jeswani, H.K., Azapagic, A., Schepelmann, P., Ritthoff, M., 2010. Options for broadening and deepening the LCA approaches. J. Clean. Prod. 18, 120–127. https://doi.org/10.1016/j.jclepro.2009.09.023.
Joshi, S., 1999. Product environmental life-cycle assessment using input-output techniques. J. Ind. Ecol. 3, 95–120. https://doi.org/10.1162/108819899569449.
Karavitis, C.A., Alexandris, S., Tsesmelis, D.E., Athanasopoulos, G., 2011. Application of the standardized precipitation index (SPI) in Greece. Water 3, 787–805. https://doi.org/10.3390/w3030787.
Karavitis, C.A., Chortaria, C., Alexandris, S., Vasilakou, C.G., Tsesmelis, D.E., 2012. Development of the standardised precipitation index for Greece. Urban Water J. 9, 401–417. https://doi.org/10.1080/1573062X.2012.690431.
Karavitis, C.A., Tsesmelis, D.E., Oikonomou, P.D., Kairis, O., Kosmas, C., Fassouli, V., Ritsema, C., Hessel, R., Jetten, V., Moustakas, N., Todorovic, B., Skondras, N.A., Vasilakou, C.G., Alexandris, S., Kolokytha, E., Stamatakos, D.V., Stricevic, R., Chatzigeorgiadis, E., Brandt, J., Geeson, N., Quaranta, G., 2020. A desertification risk assessment decision support tool (DRAST). Catena 187, 104413. https://doi.org/10.1016/j.catena.2019.104413.
Karavitis, C.A., Tsesmelis, D.E., Skondras, N.A., Stamatakos, D., Alexandris, S., Fassouli, V., Vasilakou, C.G., Oikonomou, P.D., Gregorič, G., Grigg, N.S., Vlachos, E. C., 2014. Linking drought characteristics to impacts on a spatial and temporal scale. Water Pol. 16, 1172–1197. https://doi.org/10.2166/wp.2014.205.
Karwacka, M., Ciurzyńska, A., Lenart, A., Janowicz, M., 2020. Sustainable development in the agri-food sector in terms of the carbon footprint: a review. Sustainability 12, 6463. https://doi.org/10.3390/su12166463.
Kiropoulos, K., Bibi, S., 2024. Smart farming adoption in Europe. IEEE Technol. Soc. Mag. 43, 51–64. https://doi.org/10.1109/MTS.2024.3443542.
Klerkx, L., Jakku, E., Labarthe, P., 2019. A review of social science on digital agriculture, smart farming and agriculture 4.0: new contributions and a future research agenda. NJAS - Wageningen J. Life Sci. 90–91, 100315. https://doi.org/10.1016/j.njas.2019.100315.
Koufos, G., Mavromatis, T., Koundouras, S., Fyllas, N.M., Jones, G.V., 2014. Viticulture–climate relationships in Greece: the impacts of recent climate trends on harvest date variation. Int. J. Climatol. 34, 1445–1459. https://doi.org/10.1002/joc.3775.
Lal, R., 2004. Carbon emission from farm operations. Environ. Int. 30, 981–990. https://doi.org/10.1016/j.envint.2004.03.005.
Lamboll, R., Stathers, T., Morton, J., 2017. Chapter 13 - climate change and agricultural systems. In: Snapp, S., Pound, B. (Eds.), Agricultural Systems, second ed. Academic Press, San Diego, pp. 441–490. https://doi.org/10.1016/B978-0-12-802070-8.00013-X.
Leip, A., Billen, G., Garnier, J., Grizzetti, B., Lassaletta, L., Reis, S., Simpson, D., Sutton, M.A., Vries, W. de, Weiss, F., Westhoek, H., 2015. Impacts of European livestock production: nitrogen, sulphur, phosphorus and greenhouse gas emissions, land-use, water eutrophication and biodiversity. Environ. Res. Lett. 10, 115004. https://doi.org/10.1088/1748-9326/10/11/115004.
Loukas, M., Krimbas, C.B., 1983. History of olive cultivars based on their genetic distances. J. Hortic. Sci. 58, 121–127. https://doi.org/10.1080/00221589.1983.11515099.
Marianos, N., Chadid, D., 2023. Assessment Framework and Governance Mechanisms (Deliverable No. D 2.2.).
Marinussen, M., Kernebeek, H.V., Broekema, R., Groen, E., Kool, A., Dolman, M., Blonk, H., Consultants, B., 2012. LCI Data for the Calculation Tool Feedprint for Greenhouse Gas Emissions of Feed Production and Utilization.
Masnadi, M.S., El-Houjeiri, H.M., Schunack, D., Li, Y., Englander, J.G., Badahdah, A., Monfort, J.-C., Anderson, J.E., Wallington, T.J., Bergerson, J.A., Gordon, D., Koomey, J., Przesmitzki, S., Azevedo, I.L., Bi, X.T., Duffy, J.E., Heath, G.A., Keoleian, G.A., McGlade, C., Meehan, D.N., Yeh, S., You, F., Wang, M., Brandt, A.R., 2018. Global carbon intensity of crude oil production. Science 361, 851–853. https://doi.org/10.1126/science.aar6859.
Mathioudakis, M.M., Tektonidis, N., Karagianni, A., Mikalef, L., Gómez, P., Hasiów-Jaroszewska, B., 2023. Incidence and epidemiology of citrus viroids in Greece: role of host and cultivar in epidemiological characteristics. Viruses 15, 605. https://doi.org/10.3390/v15030605.
Matthews, H.S., Hendrickson, C.T., Weber, C.L., 2008. The importance of carbon footprint estimation boundaries. Environ. Sci. Technol. 42, 5839–5842. https://doi.org/10.1021/es703112w.
Michalopoulos, G., Kasapi, K.A., Koubouris, G., Psarras, G., Arampatzis, G., Hatzigiannakis, E., Kavvadias, V., Xiloyannis, C., Montanaro, G., Malliaraki, S., Angelaki, A., Manolaraki, C., Giakoumaki, G., Reppas, S., Kourgialas, N., Kokkinos, G., 2020. Adaptation of mediterranean olive groves to climate change through sustainable cultivation practices. Climate 8, 54. https://doi.org/10.3390/cli8040054.
Migliorini, P., Gkisakis, V., Gonzalvez, V., Raigón, M.D., Bàrberi, P., 2018. Agroecology in mediterranean Europe: genesis, state and perspectives. Sustainability 10, 2724. https://doi.org/10.3390/su10082724.
Ministry of Digital Policy, Telecommunications and Media, 2024. Digital Transformation of the Agricultural Sector.
Ministry of Environment and Energy, 2023. National inventory report of Greece for greenhouse and other gases for the years 1990-2021. Clim. Change.
Ministry of Rural Development and Food, 2022. Agricultural data - statistics [WWW document]. URL. https://www.minagric.gr/the-ministry-2/statistikes-tekmhrioshs/8510-statistika-ekt-parag-fytikonproionton, 9.30.23.
Moniz, D., Langefeld, A., 2023. Behavioural Determinants for DAT Adoption (Deliverable No. D 1.1).
Moysiadis, V., Sarigiannidis, P., Vitsas, V., Khelifi, A., 2021. Smart farming in Europe. Computer Science Review 39, 100345. https://doi.org/10.1016/j.cosrev.2020.100345.
Nemecek, T., Kägi, T., 2007. Life Cycle Inventories of Swiss and European Agricultural Production Systems, Final Report Ecoinvent V2.0 No. 15a. Agroscope Reckenholz-Taenikon Research Station ART. Swiss Centre for Life Cycle Inventories, Zurich and Dübendorf, CH.
Olmez, G.M., Dilek, F.B., Karanfil, T., Yetis, U., 2016. The environmental impacts of iron and steel industry: a life cycle assessment study. Journal of Cleaner Production, Special Volume: SDEWES 2014 - sustainable Development of Energy. Water and Environment Systems 130, 195–201. https://doi.org/10.1016/j.jclepro.2015.09.139.
Osrof, H.Y., Tan, C.L., Angappa, G., Yeo, S.F., Tan, K.H., 2023. Adoption of smart farming technologies in field operations: a systematic review and future research agenda. Technol. Soc. 75, 102400. https://doi.org/10.1016/j.techsoc.2023.102400.
Ouédraogo, M., Houessionon, P., Zougmoré, R.B., Partey, S.T., 2019. Uptake of climate-smart agricultural technologies and practices: actual and potential adoption rates in

the climate-smart village site of Mali. Sustainability 11, 4710. https://doi.org/10.3390/su11174710.

Paleari, L., Movedi, E., Foi, M., Pilatti, A., Vesely, F.M., Rusconi, C., Brancadoro, L., Poni, S., Bacenetti, J., Confalonieri, R., 2024. A new digital technology to reduce fungicide use in vineyards. Sci. Total Environ. 917, 170470. https://doi.org/10.1016/j.scitotenv.2024.170470.

Pelletier, N., 2014. Life cycle assessment in agriculture. Alberta Agriculture and Rural Development.

Phelan, A.Anya, Meissner, K., Humphrey, J., Ross, H., 2022. Plastic pollution and packaging: corporate commitments and actions from the food and beverage sector. J. Clean. Prod. 331, 129827. https://doi.org/10.1016/j.jclepro.2021.129827.

Phillips, L., Ilcan, S., 2003. 'A world free from hunger': global imagination and governance in the age of scientific management. Sociol. Rural. 43, 434–453. https://doi.org/10.1046/j.1467-9523.2003.00254.x.

Proietti, S., Sdringola, P., Regni, L., Evangelisti, N., Brunori, A., Ilarioni, L., Nasini, L., Proietti, P., 2017. Extra Virgin Olive oil as carbon negative product: experimental analysis and validation of results. J. Clean. Prod. 166, 550–562. https://doi.org/10.1016/j.jclepro.2017.07.230.

Prutzer, E., Gardezi, M., Rizzo, D.M., Emery, M., Merrill, S., Ryan, B.E.K., Oikonomou, P. D., Alvez, J.P., Adereti, D.T., Anjum, R., Badireddy, A.R., Bhattarai, D., Brugler, S., Cheney, N., Clay, D., Clay, S., Dadkhah, A., Faulkner, J.W., Joshi, D.R., Koliba, C., McMaine, J., Michael, S., Musayev, S., O'Neil-Dunne, J., Pinder, G., Ricketts, T., Schroth, A.W., Turnbull, S., Zia, A., 2023. Rethinking 'responsibility' in precision agriculture innovation: lessons from an interdisciplinary research team. Journal of Responsible Innovation 10, 2202093. https://doi.org/10.1080/23299460.2023.2202093.

Rehman, A., Jingdong, L., Khatoon, R., Hussain, I., Shahid Iqbal, M., 2017. Modern agricultural technology adoption its importance, role and usage for the improvement of agriculture. Life Sci. J. 1414, 70–74. https://doi.org/10.7537/marslsj140217.10.

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.

Rossignol, J.-Y., 2020. Accounting of emissions due to the production of fixed assets. In: Climatic Impact of Activities. John Wiley & Sons, Ltd, pp. 191–201. https://doi.org/10.1002/9781119695097.app3.

Sharif, S.A., Hammad, A., 2019. Simulation-based multi-objective optimization of institutional building renovation considering energy consumption, life-cycle cost and life-cycle assessment. J. Build. Eng. 21, 429–445. https://doi.org/10.1016/j.jobe.2018.11.006.

Stathopoulos, N., Skrimizeas, P., Kalogeropoulos, K., Louka, P., Tragaki, A., 2018. Statistical analysis and Spatial correlation of rainfall in Greece for a 20-year time period. https://doi.org/10.29007/vzcm.

Tomar, P., Kaur, G., 2021. Artificial intelligence and IoT-based technologies for sustainable farming and smart. Agriculture. https://services.igi-global.com/resolvedoi/resolve.aspx?doi=10.4018/978-1-7998-1722-2. IGI Global.

Tsesmelis, D.E., Karavitis, C.A., Kalogeropoulos, K., Tsatsaris, A., Zervas, E., Vasilakou, C. G., Stathopoulos, N., Skondras, N.A., Alexandris, S.G., Chalkias, C., Kosmas, C., 2021. Development and application of water and land resources degradation index (WLDI). Earth 2, 515–531. https://doi.org/10.3390/earth2030030.

Tsesmelis, D.E., Karavitis, C.A., Kalogeropoulos, K., Zervas, E., Vasilakou, C.G., Skondras, N.A., Oikonomou, P.D., Stathopoulos, N., Alexandris, S.G., Tsatsaris, A., Kosmas, C., 2022a. Evaluating the degradation of natural resources in the mediterranean environment using the water and land resources degradation index, the case of crete island. Atmosphere 13, 135. https://doi.org/10.3390/atmos13010135.

Tsesmelis, D.E., Karavitis, C.A., Oikonomou, P.D., Alexandris, S., Kosmas, C., 2019. Assessment of the vulnerability to drought and desertification characteristics using the standardized drought vulnerability index (SDVI) and the environmentally sensitive areas index (ESAI). Resources 8, 6. https://doi.org/10.3390/resources8010006.

Tsesmelis, D.E., Vasilakou, C.G., Kalogeropoulos, K., Stathopoulos, N., Alexandris, S.G., Zervas, E., Oikonomou, P.D., Karavitis, C.A., 2022b. Chapter 46 - drought assessment using the standardized precipitation index (SPI) in GIS environment in Greece. In: Pourghasemi, H.R. (Ed.), Computers in Earth and Environmental Sciences. Elsevier, Amsterdam, The Netherlands, pp. 619–633. https://doi.org/10.1016/B978-0-323-89861-4.00025-7.

Wrzaszcz, W., Prandecki, K., 2020. Agriculture and the European Green Deal.

Xiao, X., Zhu, Z., Fu, Z., Mu, W., Zhang, X., 2018. Carbon footprint constrained profit maximization of table grapes cold chain. Agronomy 8, 125. https://doi.org/10.3390/agronomy8070125.