Journal of Cleaner Production 380 (2022) 134937

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Review

Determining organic versus conventional food emissions to foster the transition to sustainable food systems and diets: Insights from a systematic review

Maria Vincenza Chiriacò[a,*], Simona Castaldi[b], Riccardo Valentini[a,c]

[a] CMCC – Fondazione Centro Euro-Mediterraneo Sui Cambiamenti Climatici, IAFES Division, Viterbo, Italy
[b] Department of Environmental, Biological and Pharmaceutical Sciences and Technologies (DiSTABiF), University of Campania "Luigi Vanvitelli", Caserta, Italy
[c] Department for Innovation in Biological, Agro-food and Forest Systems (DIBAF), University of Tuscia, Viterbo, Italy

ARTICLE INFO

Handling Editor: Jing-Li Fan

Keywords:
Sustainable diets
Climate change mitigation
Food GHG emissions
Impact on climate of food system
Organic farming
Organic versus conventional food

ABSTRACT

The global food system is a major contributor to climate change with 23–42% of total greenhouse gas (GHG) emissions. Thus, the transition to sustainable food systems and dietary patterns represents a big challenge and a key solution to feed a fast-growing world population while maintaining safe planet boundaries of sustainability. Organic farming is often proposed as a sustainable option, however a debate is open on its effectiveness in reducing the impact on climate when compared to conventional agriculture. Therefore, there is a need for clear indicators of climate and environmental sustainability to duly inform the food system actors and foster an effective transition towards sustainable food production and consumption. The carbon footprint (CF) is one of the most used indicators to assess the sustainability of food as it measures the contribution to climate change in terms of GHG emissions with different metrics (e.g. GHG per unit of product or per unit of land).

Through a systematic analysis of the existing peer-reviewed studies allowing an unbiased comparison of product-based vs land-based CF, this study shows that organic food has on average lower impact on climate than conventional, both when the CF is assessed per 'land unit' (−43% GHG emissions, average) and per 'product unit' (−12% GHG emissions, average). However, the two CF metrics provide diverse results, even opposite in some cases, when individual conventional vs organic food types are compared: organic food results to be more sustainable than conventional in almost all cases when the 'land unit' CF metric is compared; conversely, conventional food results to be less impacting than organic in the 29% of cases when the 'product unit' CF is considered. According to these results, although the CF per unit of product is far more used and provides useful indications on the food emissions intensity, in some cases it can bring a misleading message towards unsustainability, with the paradox of making more preferable food that apparently shows lower impact per unit of product while having higher emissions per land unit. Contrariwise, the CF per unit of land better reflects the actual agricultural contribution to climate change which is driven by the land-atmosphere GHG fluxes.

According to this study's results and in view of the global climate policies' targets which foster organic food production and the transition to sustainable diets, an extensive conversion of the existing global croplands into organic lands would significantly contribute to reducing total GHG emissions from the land sector.

1. Introduction

How to manage the global agrifood system is one of the most debated issues both at scientific and policy level in the attempt to design the best strategies to limit climate change, ensure food security and promote the shift towards sustainable healthy diets (Bahar et al., 2020; Rosenzweig et al., 2020). Currently, the global food system is the main responsible of climate change contributing to about 23–42% of global greenhouse gas (GHG) emissions with 17 Gt CO_2eq yr^{-1}, the main sources of which comes from agricultural production activities with 6.3 Gt CO_2eq yr^{-1} and the remaining part comes from supply chain activities such as transport, energy and industry part of food systems, including, pre-production and post-production, processing, packaging, storage, retail, consumption and management of residues (IPCC et al., 2022).

* Corresponding author.
E-mail address: mariavincenza.chiriaco@cmcc.it (M.V. Chiriacò).

https://doi.org/10.1016/j.jclepro.2022.134937
Received 28 January 2022; Received in revised form 16 September 2022; Accepted 28 October 2022
Available online 6 November 2022

Intensive agricultural production practices and unsustainable consumption patterns have unprecedently increased since the 1970s (IPCC et al., 2019) resulting in air, water and soil pollution and strongly contributing to climate change and to the loss of biodiversity. The current excessive use of nutrients and pesticides in agriculture as well as of antimicrobials in livestock and aquaculture threaten the environment and human health, with important socio-economic consequences (Sharma and Singhvi, 2017; Ahmed et al., 2017). Thus, reducing land-based emissions for food production became an urgent action required for a substantial contribution to climate change mitigation (Carlson et al., 2017).

At the present, the global food system delivers approximately 4 billion tonnes of food every year (FAOSTAT, 2022), an amount that would be enough to feed the current global population and even the roughly 10 billion expected in 2050 (FAO, UNICEF, WFP and WHO, 2020). Under this perspective, these figures, indeed, reveal a condition of over-production in the global food system compared to the actual food necessities of the current population. Nevertheless, today food security is not ensured for 815 million people in the world that do not have fair access to healthy food and suffer from chronic undernourishment (FAO, UNICEF, WFP and WHO, 2020). Cheaper and low-quality calories have become particularly abundant in the last decades compared to more nutritious food that turned out to be more expensive and relatively less available (Benton et al., 2021). This results in low costs of producing and consuming high amounts of low-quality food. As a consequence, it has become increasingly economically rational to waste food (Benton and Bailey, 2019): about one third of the food globally produced for human consumption is lost or wasted (FAO, 2021), corresponding to 1.3 billion tonnes of food per year which cause needless and avoidable 8–10% of global GHG emissions (UNEP, 2021). At the same time, low quality food and unbalanced diets contribute to obesity and other nutrition-related non-communicable diseases, with more than 2 billion adults overweight or obese, revealing a trend towards unhealthy diets and unequal food distribution at global level (Duro et al., 2020; FAO, UNICEF, WFP and WHO, 2020).

Against this backdrop, many traditional local food systems and dietary patterns have been widely recognized for their health, environmental, cultural and socio-economic values (Kim et al., 2020; Müller et al., 2020; Fridman et al., 2021). However, only recently advancements in understanding the complexity of the planetary system have quantified the positive outcomes which might be reached adopting healthy and sustainable diets (Willett et al., 2019; IPCC et al., 2019) and by switching towards more sustainable food production systems (Willett et al., 2019; Poore and Nemecek, 2018). In addition, the COVID-19 pandemic highlighted the importance of building a robust and resilient food systems centered on sustainable and healthy food productions and consumption patterns that are key in responding to global shocks and disruptions in supply chains (Bajželj et al., 2020; Devereux et al., 2020; Hobbs, 2020; Laborde et al., 2020).

The transition to more sustainable food systems and dietary consumers' habits represents a big challenge and a key solution to feed a fast-growing world population (Bahar et al., 2020) while reducing GHG emissions from the food system (Chand, 2020; Clark et al., 2020). In this context, organic farming is often proposed as a valuable option being one of the most widely recognized form of sustainable agriculture (Muller et al., 2017; Muneret et al., 2018; Eyhorn et al., 2019). Organic food systems are also supported by many EU and global policies, i.e. the Common Agricultural Policy and the Green Deal in its Farm to Fork Strategy (Moschitz et al., 2021), being a model able at the same time to provide healthy food with lower environmental impacts and a plethora of co-benefits such as biodiversity protection, reduced GHG emissions (Skinner et al., 2019), increase of soil organic carbon stock, greater resilience and higher adaptive capacity to shocks, stressors and adverse climate events (Reganold and Wachter, 2016; Knapp and van der Heijden, 2018). However, despite the well-recognized environmental and health benefits, one of the main criticisms moved to the organic agriculture is that yields are on average lower than conventional farming (Seufert et al., 2012; Reganold and Wachter, 2016), with the concern that more cultivated land is needed to produce the same amount of food as conventional methods (Treu et al., 2017). As a consequence, an historical debate is still open in the scientific community and among the food system's actors about the effective sustainability of organic agriculture in terms of GHG emissions, with contrasting positions indicating organic farming, from one side, as inadequate to feed 10 billion people in 2050 (Smith et al., 2019) and, on the other side, as a possible pathway to sustainably feed the global population (Reganold and Wachter, 2016; Muller et al., 2017; Eyhorn et al., 2019; Rosenzweig et al., 2020).

Shedding light on the effective environmental sustainability of organic farming through clear indicators of GHG emissions, thus solving the existing debate on organic versus conventional food production and consumption, is a crucial enabling condition to foster the transition towards sustainable food systems and dietary patterns. In fact, a such needed shift requires a deep societal transformation in which all the actors of the socio-economic segments of the food value chains need to be involved. Farmers, consumers, and policymakers notably play a key role as main drivers of production and consumption patterns. Although among consumers there is growing awareness and willingness to eat healthier and more sustainably (Eyinade et al., 2021), an actual behavioral change is however still difficult to achieve (Van Dam and Van Trijp, 2013) since changing production practices and eating habits requires addressing technical preparation, individual motivations, cognitions and skills, as well as the socio-cultural, organizational and physical environment in which food production and consumption practices are embedded (Cullen et al., 2015; van Woerkum and Bouwman, 2014). Despite consumers are mostly encouraged towards sustainable diets through awareness-raising and education, research has shown that many of them are nearly unable to act on it (Reisch et al., 2016) being incapable to select sustainable food due to the lack of clear information. At the same time, many food producers lack of right knowledge and skills to turn to sustainable production practices (Šūmane et al., 2018). This suggests that for achieving an effective transition towards sustainable diets more attention should be paid in enabling farmers and food producers to make more sustainable their practices and consumers to make informed food choices through clear indicators of food environmental sustainability easily supporting the actors of the food system.

The environmental sustainability of the agrifood systems, intended mostly in terms of impact on climate, is usually quantified by means of appropriate tools such as the life cycle assessment (LCA) and its indicator of carbon footprint (CF). The CF measures the amount of GHG emissions (calculated in CO_2eq) generated to produce a good or a service along its entire life cycle, assessed per functional unit. In particular for the agrifood sector, the CF is usually assessed per product unit as a measure of sustainability used both at scientific level and for commercial purposes, but recently also the CF per unit of utilized land starts to be considered (Meier et al., 2015). In the view of supporting sustainable diets and comparing food products from different agricultural systems (e.g. conventional vs organic), the implication of using one CF metric rather than the other (i.e. GHG per unit of product or per unit of land) is becoming critical.

Indeed, the contribution to climate change of different agricultural systems can be very diverse. Organic food production is usually considered to produce lower GHG emissions in absolute terms (Reganold and Wachter, 2016; Wittwer et al., 2017) compared to conventional farming, resulting in an expected lower CF per unit of land. In fact, the European regulation for the organic farming (Regulation (EU) 2018/848) allows the use of limited inputs per hectare (e.g. no or very limited amount of chemicals for pest and weed control, no mineral fertilizers, etc.), with consequent reduced GHG emissions for their production and use, and requires the implementation of sustainable agronomic practices, such as the maintenance of permanent natural herbaceous layer, crop rotations, greening with hedges, etc., with consequent increase in the soil organic carbon content. However, since yields in organic agriculture are on average lower than conventional farming (Seufert et al., 2012; Reganold and Wachter, 2016), total GHG emissions, although lower in absolute terms, result in a predictable higher CF per unit of product (van der Werf et al., 2020). Therefore, the two CF metrics (i.e. per land unit or product unit) when applied to evaluate the sustainability of food can lead to very diverse results, even opposite, especially when conventional vs organic food products are compared (Meier et al., 2015).

In order to provide evidence on the applicability of the two CF metrics as appropriate indicators of sustainability of food and to contribute to a more informed debate on the actual sustainability of the organic vs conventional food systems, we explored the impact on climate of organic and conventional food by analysing the existing peer-reviewed studies that allow to compare the CF of the two production systems expressed both per unit of product and per unit of utilized land.

2. Method for comparing product-based and land-based carbon footprints of organic vs conventional food

The analysis builds upon the exploration of existing peer-reviewed studies where the CF of the same organic versus conventional food types produced in comparable contexts is assessed with the same approach and within the same system boundaries. To this aim we performed a literature search on Web of Science, Scopus, and Google Scholar, using the following search terms (in various combinations): GHG emissions, food carbon footprint, life cycle assessment, organic farming, conventional farming.

However, results of CF from diverse studies should be carefully compared as they can be strongly influenced by local conditions, boundaries of the analysed systems and methodology applied (Meier et al., 2015). Therefore, out of more than 200 published studies that were analysed, only 27 papers fulfilled the eligibility criteria, directly reporting both the CF per area (Mg CO_2eq ha^{-1} per year) and per product (kg CO_2eq kg^{-1}) or providing the information needed (e.g. yields or land used) to derive both the CF metrics when only one of them was reported. Specifically, 215 papers resulted from Web of Science, 27 of which were useful for this analysis; 213 papers resulted from Scopus – all already included in the results from Web of Science, including the same 27 papers from Web of Science which were considered useful for this analysis; 200 papers resulted from Google Scholar, 22 of which were useful for this analysis – all already included in the results from Web of Science and Scopus.

The 27 selected papers allowed to compare 30 types of organic and conventional food products (with 41 food items, Table 1) which were grouped into 5 main food categories (i.e. fruits, legumes, cereals, vegetables, livestock products). Although the limited number of available papers eligible for this review (27 papers), the information they provide for the 41 food items can be considered representative of the globally utilized agricultural area that accounts to about 5 billion hectares, or 38% of the global land surface, of which 1,4 billion hectares, about one-third, are used as cropland, with the remaining two-thirds consisting of meadows and pastures for grazing livestock (FAOSTAT, 2022). In fact, among the 41 food items, 10 items refer to permanent fruit crops which cover globally more than 150 million hectares, including olive groves (1 study), vineyards (1 study), citrus (1 study), sub-tropical fruits (1 study), and tree nuts (1 study). Cereals, which are cultivated globally on more than 737 million hectares, are represented by 4 items (3 studies), including wheat which covers about 219 million hectares and rice with 164 million hectares. Legumes, which are globally cultivated on about 225 million hectares, is another important food category represented in this study by 4 items (3 studies), including soybean that is cultivated over 127 million hectares in the world. Further, 8 food items (7 studies) refer to vegetables which globally are cultivated on 60 million hectares. Also cotton, which globally covers 32 million hectares, is represented (1 study) as an industrial crop among the 41 food items. Finally, 13 food items (11 studies) can be referred to the area of meadows and pastures for grazing livestock, including milk of which almost 900 million tonnes are produced annually, poultry which supplies about 120 million tonnes of meat each year, pig from which 110 million tonnes of meat are produced per year, beef whit about 68 million tonnes of meat per year, and eggs which amount to about 1,7 million per year corresponding to about 87 million tonnes. Therefore, the 41 food items considered in this study are representative of the most existing food categories covering about 85% of the global croplands.

In the selected papers, different global warming potential (GWP) factors are used to convert non-CO_2 GHGs to CO_2-equivalent emissions, ranging from 21 to 28 for CH_4, from 265 to 310 for N_2O and 1 for CO2, according to the latest IPCC Assessment Report (IPCC et al., 1995; IPCC et al., 2001; IPCC et al., 2007; IPCC et al., 2013) available at the moment in which each study was published. However, the GWP used in all the papers are on a 100-year time scale – the most used also under the United Nation Framework Convention on Climate Change GHG inventories. According to Brennan and Zaitchik (2013) and van Den Berg et al. (2015), using different GWP factors has a negligible impact in the final assessment of GHG emissions especially if the same 100-year time horizon is applied (Cain et al., 2019). Therefore, to the aim of this review, we considered as comparable all the CF reported by the different studies.

Since the comparison of CF assessed in diverse LCA studies can turn out to have a bias (Meier et al., 2015) by differences in the boundaries of the systems, inputs considered, type of allocation and other factors, rather than comparing values in absolute terms we considered the relative percentage difference (R) of the impact of the organic (IO_{GHG}) with respect to the impact of the same conventional (IC_{GHG}) food, assessed as:

$$R = \frac{IO_{GHG}}{IC_{GHG}} - 1$$

3. Results and discussions

A great variability of impacts is observed among food categories and between the two CF metrics for the same food category (Fig. 1). For example, the 3 studies (4 food items) available for legumes show a wide range of relative percentage difference per land unit (light grey bar) going from −59% to +91%, meaning that the CF per land unit of organic legumes production can be either lower (when percentage values are negative) or higher (when percentage values are positive) than conventional production, with a median value of −4% indicating on average a slightly lower impact per unit of land utilized for the production of organic legumes compared to conventional. A similar but more limited variability is observed also for the relative percentage difference per product unit (dark grey bar) which ranges from −41% to +45%, with a median value of +3% indicating on average a slightly higher impact per product unit of organic legumes compared to conventional.

A similar trend is observed also for cereals, where the 3 studies available (4 food items) show a relative percentage difference per land unit (light grey bar) going from −65% to +9%, with a median value of −48% indicating on average a marked lower impact per land unit for organic cereals compared to conventional. The variability of the relative percentage difference per product unit (dark grey bar) ranges from −42% to +59%, with a median value of +8% indicating on average higher impact per product unit of organic cereals compared to conventional.

A wide range is observed also for the relative percentage difference per product unit (dark grey bar) of livestock products that, according to the 10 studies available (14 food items), fluctuates from −48% to +73%, meaning that the GHG emissions per unit of organic livestock products can be either lower (negative values) or higher (positive values) than conventional ones, with median value of −9% indicating on average

Table 1
Data from the analysed studies providing a comparison of CF per 'land unit' and 'product unit' for the same organic and conventional food types. Negative values of relative percentage difference represent an advantage of organic versus conventional food production in term of sustainability, positive values (in bold) represent an advantage of conventional food.

Category	Type of food product	Country	Reference	Method	GHG emissions Per area (Mg CO_2eq ha^{-1} $year^{-1}$) Conv.	Per area Org	Per product (kg CO_2eq kg^{-1}) Conv.	Per product Org	Relative percentage difference of organic/conventional LAND	PRODUCT
Fruits	Apple	Canada	Keyes et al. (2015)	LCA, data collected in 10 conventional and 3 organic orchards.	1,52	0,87	0,06	0,07	−43%	***14%***
Fruits	Apple (area 1)	China	Zhu et al. (2018)	LCA, data collected in 97 conventional and 22 organic producers (2 areas).	47,06	25,82	0,91	0,86	−45%	−5%
Fruits	Apple (area 2)	China	Zhu et al. (2018)	LCA, data collected in 97 conventional and 22 organic producers (2 areas).	32,77	17,81	0,96	0,87	−46%	−9%
Fruits	Peach	Greece	Michos et al. (2012)	LCA, data collected in 3 organic and 4 conventional farms. Results are reported per unit of product (tons of fruit produced), emissions per ha are calculated considering reported yields.	5,3	1,9	0,16	0,17	−64%	***3%***
Fruits	Subtropical	Spain	Aguilera et al. (2015b)	LCA, data collected in 42 pairs of organic and conventional farms. Carbon sequestration is also included.	5,29	2,31	0,30	0,11	−56%	−62%
Fruits	Treenuts	Spain	Aguilera et al. (2015b)	LCA, data collected in 42 pairs of organic and conventional farms. Carbon sequestration is also included.	1,53	1,27	0,97	0,96	−17%	−2%
Fruits	Citrus	Spain	Aguilera et al. (2015b)	LCA, data collected in 42 pairs of organic and conventional farms. Carbon sequestration is also included.	6,32	1,90	0,15	0,08	−70%	−44%
Fruits	Fruits	Spain	Aguilera et al. (2015b)	LCA, data collected in 42 pairs of organic and conventional farms. Carbon sequestration is also included.	2,60	1,48	0,12	0,09	−43%	−20%
Fruits	Olive	Spain	Aguilera et al. (2015b)	LCA, data collected in 42 pairs of organic and conventional farms. Carbon sequestration is also included.	1,11	−0,17	0,32	−0,01	−115%	−103%
Fruits	Vineyard	Spain	Aguilera et al. (2015b)	LCA, data collected in 42 pairs of organic and conventional farms. Carbon sequestration is also included.	0,96	0,64	0,16	0,11	−34%	−33%
Legumes	Rainfed legumes	Spain	Aguilera et al. (2015a)	LCA, data collected in 38 pairs of organic and conventional farms. Carbon sequestration is also included.	0,57	0,23	0,23	0,20	−59%	−16%
Legumes	Bean (var. gigantes)	Greece	Abeliotis et al. (2013)	LCA, data collected by interviewing several producers (2 varieties).	0,69	0,95	0,25	0,30	***39%***	***23%***
Legumes	Bean (var. plake)	Greece	Abeliotis et al. (2013)	LCA, data collected by interviewing several producers (2 varieties).	0,35	0,67	0,30	0,44	***91%***	***45%***
Legumes	Soybean	China	Knudsen et al. (2010)	LCA, data collected in 20 organic and 15 conventional farms.	0,81	0,43	0,26	0,16	−46%	−41%
Cereals	Rainfed cereals	Spain	Aguilera et al. (2015a)	LCA, data collected in 38 pairs of organic and conventional farms. Carbon sequestration is also included.	1,02	0,36	0,32	0,18	−65%	−42%
Cereals	Rice	Spain	Aguilera et al. (2015a)	LCA, data collected in 38 pairs of organic and conventional farms. Carbon sequestration is also included.	12,40	13,48	1,66	2,64	***9%***	***59%***
Cereals	Wheat	USA	Meisterling et al. (2009)	LCA data collection in a case study and literature. Results are reported per unit of product, emissions per ha are calculated considering reported yields.	1,19	0,75	0,28	0,24	−37%	−16%
Cereals	Wheat/ wholemeal bread	Italy	Chiriacò et al. (2017)	LCA, data collected in a case study with 1 organic and 1 conventional farm, in the same geographical area.	2,87	1,15	1,18	1,55	−60%	***31%***
Vegetables	Greenhouse vegetables	Spain	Aguilera et al. (2015a)	LCA, data collected in 38 pairs of organic and conventional farms. Carbon sequestration is also included.	11,84	7,59	0,22	0,18	−36%	−17%
Vegetables	Open-air vegetables	Spain	Aguilera et al. (2015a)	LCA, data collected in 38 pairs of organic and conventional farms. Carbon sequestration is also included.	3,45	1,42	0,24	0,16	−59%	−32%
Vegetables	Asparagus	Greece	Zafiriou et al. (2012)	LCA with primary data collected in 3 organic and 3 conventional farms. Results are reported per unit of product (ton of spear produced), emissions per ha are calculated considering reported yields.	7,9	5,2	0,85	0,74	−34%	−13%

(*continued on next page*)

Table 1 (*continued*)

Category	Type of food product	Country	Reference	Method	GHG emissions Per area (Mg CO_2eq ha^{-1} $year^{-1}$) Conv.	Org	Per product (kg CO_2eq kg^{-1}) Conv.	Org	Relative percentage difference of organic/conventional LAND	PRODUCT
Vegetables	Carrot	Poland	Kowalczyk and Cupiał (2020)	LCA, data collected in 10 organic and 10 conventional farms.	1,87	1,28	0,03	0,03	−32%	−5%
Vegetables	Chinese Kale	Thailand	Yuttitham (2019)	LCA, data collected with questionnaires to farmers.	8,79	1,95	0,402	0195	−78%	−51%
Vegetables	Leek	Belgium	De Backer et al. (2009)	Conventional and organic production scenarios with data collected through questionnaires, surveys, logbooks, data from agricultural extension services.	3,57	1,20	0,09	0,04	−66%	−54%
Vegetables	Tomato	Italy	Ronga et al. (2019)	LCA, data collected for three years (2010–2012) in open field.	5,29	3,15	0,06	0,07	−40%	***22%***
Vegetables	Vegetables	Philippines	Oliquino-Abasolo and Zamora (2016)	LCA, data collected in 23 organic and 87 conventional farms.	0,03	0,01	0,21	0,12	−61%	−43%
Livestock products	Milk	Denmark	Guerci et al. (2013)	LCA with primary data collected in 2 organic and 5 conventional farms. Results are reported per unit of product (kg energy corrected milk - ECM), emissions per ha are calculated considering the land used to produce 1 kg ECM.	5,33	1,61	0,22	0,11	−70%	−48%
Livestock products	Milk	Austria (Alpine)	Hörtenhuber et al. (2010)	GHG scenarios from LCA applied to a modelled system from national farm statistical data.	5,2	4,2	1173	1017	−20%	−13%
Livestock products	Milk	Austria (Uplands)	Hörtenhuber et al. (2010)	GHG scenarios from LCA applied to a modelled system from national farm statistical data.	6,8	5,9	1032	0,946	−12%	−8%
Livestock products	Milk	Austria (Uplands, pastoral)	Hörtenhuber et al. (2010)	GHG scenarios from LCA applied to a modelled system from national farm statistical data.	6,5	5,4	1027	0,908	−17%	−12%
Livestock products	Milk	Austria (Lowlands)	Hörtenhuber et al. (2010)	GHG scenarios from LCA applied to a modelled system from national farm statistical data.	7,64	6,20	0,898	0814	−19%	−9%
Livestock products	Milk	Denmark	Kristensen et al. (2011)	LCA, data collected in 32 organic and 35 conventional farms. Results are reported per unit of product (kg energy corrected milk - ECM), emissions per ha are calculated considering the land used to produce 1 kg ECM.	6,74	5,36	1,2	1,27	−21%	***6%***
Livestock products	Milk	Netherlands	Thomassen et al. (2008)	LCA, data collected in 11 organic and 10 conventional farms. Results are reported per unit of product (fat and protein corrected milk - FPCM), emissions per ha are calculated considering the land used to produce 1 kg FPCM.	21,88	13,64	1,4	1,5	−38%	***7%***
Livestock products	Milk	France	van der Werf et al. (2009)	LCA, data collected in 6 organic and 41 conventional farms.	6,05	4,63	0,98	0,89	−23%	−10%
Livestock products	Milk	Germany	Haas et al. (2001)	LCA, data collected in 6 conventical and 6 organic farms.	9,40	6,30	1,30	1,30	−33%	0%
Livestock products	Milk	Italy	Pirlo and Lolli (2019)	LCA, data collected in 8 conventional and 6 organic dairy farms (unit of product is per kg of fat protein corrected milk - FPCM).	25,80	11,50	1,24	1,37	−55%	***10%***
Livestock products	Beef	Ireland	Casey and Holden (2006)	LCA, data collected in 5 conventional and 5 organic farms (unit of product is per kg of animal live weight).	5,35	2,30	13,00	11,10	−57%	−15%
Livestock products	Pig	France	Basset-Mens and Van der Werf (2005)	GHG scenarios from data based on French official farm statistics, expert judgment and from a local feed producer.	4,24	4,02	2,30	3,97	−5%	***73%***
Livestock products	Poultry	UK	Leinonen et al. (2012a)	GHG scenarios from LCA applied to a modelled system from national inventories and industry database data. Results are reported per unit of product (kg of expected edible carcass weight), emissions per ha are calculated considering the land used to produce 1 kg of expected edible carcass weight.	1,98	0,36	1,11	0,91	−82%	−18%

(continued on next page)

Table 1 (*continued*)

Category	Type of food product	Country	Reference	Method	GHG emissions Per area (Mg CO_2eq ha^{-1} $year^{-1}$) Conv.	GHG emissions Per area Org	GHG emissions Per product (kg CO_2eq kg^{-1}) Conv.	GHG emissions Per product Org	Relative percentage difference of organic/conventional LAND	Relative percentage difference of organic/conventional PRODUCT
Livestock products	Eggs	UK	Leinonen et al. (2012b)	GHG scenarios from LCA applied to a modelled system from national inventories and industry database data. Results are reported per unit of product (kg of eggs), emissions per ha are calculated considering the land used to produce 1 kg of eggs (conventional is considered as hen-egg production system in cage).	7,30	2,02	2,92	3,42	−72%	*17%*
Industrial crops	Cotton	Benin	Bonou-zin et al. (2019)	LCA, data collected in 180 organic and 175 conventional cotton producers.	0,88	0,46	0,72	0,50	−48%	−30%

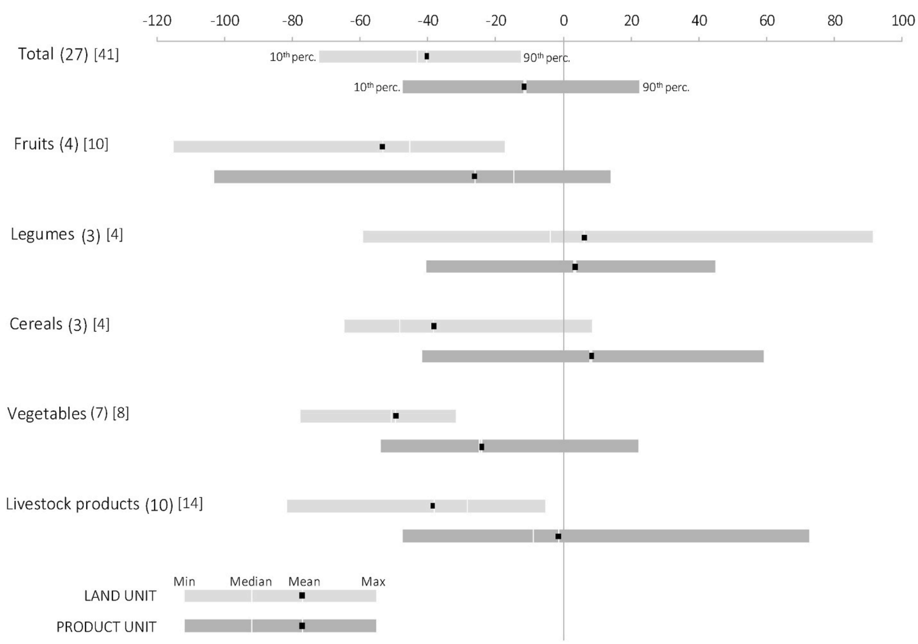

Fig. 1. Relative percentage difference of GHG emissions of the organic with respect to conventional food products, per land unit (light grey bars) and product unit (dark grey bars). In round brackets the number of studies, in square bracket the number of food items. As indicated in the legend, the bars go from the minimum to the maximum (except for the bars of the total which go from the 10th to 90th percentile) and include the median and mean value. Negative numbers represent an advantage of organic versus conventional food production in term of sustainability, zero line represent equal impact, positive values represent an advantage of conventional food production.

lower impact per product unit compared to conventional. The relative percentage difference per land unit (light grey bar) is always below zero, going from −82% to −5%, meaning that the GHG emissions per land unit used for livestock production are always lower than conventional production, with a median value of −28%. Also the 4 studies available for fruits (10 food items) show a relevant variability of the relative percentage difference per product unit (dark grey bar), which ranges from −103% to +14%, and per land unit (light grey bar), which ranges from −115% to −17%, with median values of −15% and −45% respectively, indicating on average lower impact both per product unit and land unit of organic fruits compared to conventional. Similar patterns are showed also for vegetable for which the 7 studies available (8 food items) show a variability of the relative percentage difference between −54% and +22% per product unit (dark grey bar) and between −78% and −32% per land unit (light grey bar), with median values of −25% and −50% respectively, indicating on average lower impact both per product unit and land unit of organic vegetables compared to conventional. Analogous results are also reported by the only study addressing industrial crops (cotton) which shows a relative percentage difference of −30% per land unit and −48% per product unit (Table 1).

In summary, if looking at the median values of relative percentage difference of both the CF metrics for each food category they are always below zero – with a note for the land unit of legumes and the product unit of livestock products whose median values are just slightly below zero – suggesting a general advantage of organic farming systems, except in the case of product unit of legumes and cereals whose median values are positive thus showing in these cases an advantage of conventional farming (Fig. 1).

By analyzing the single food types, for almost all the 41 food items – except 1 study for cereals (rice) and 1 study (2 food items) for legumes, see Table 1 – the average relative difference between the two cropping systems per land basis is always negative (light grey bars, Fig. 1), i.e. organic food has almost always a lower impact with respect to conventional food when assessed per unit of utilized land, with an average −43% (median value). While these results are expected, what is indeed surprising is that when the relative difference between organic and conventional is measured using the CF per unit of product (dark grey bars, Fig. 1), the majority of the studies (28 food items out of 41, see Table 1) still provides a percentage ratio below zero. This means that organic food showed on average a lower global warming impact than conventional food also when the CF is assessed per product units, with an average −12% (median value). However, among the food items which show a higher CF per unit of organic versus conventional product there are some important staple crops such as rice (which covers about 164 million hectares, the 22% of the global area for cereals or the 0,01% of the global croplands) with a relative organic/conventional percentage difference of +59%. Another staple food which shows higher CF per unit of organic product is pig (which provides 110 million tonnes of meat each year, the 32% of the total meat globally produced) with a relative organic/conventional percentage difference of +73%. The same is observed for organic eggs which show a relative percentage difference of +17% per product unit, compared to conventional ones. Also tomatoes, which occupy about 5 million hectares, the 8% of the total area used for vegetables production, show a higher CF per unit of organic product with a relative organic/conventional percentage difference of +22% (Fig. 1). It is interesting to note that in almost all these cases, the higher impact of organic food per unit of product is associated with a lower impact of organic food per unit of land, except for rice which performs worse when it is organically produced in both the CF metrics (per unit of land and unit of product). These findings reveal the need for some crops to further improve the performance of organic production, particularly in terms of increasing yields in the direction of sustainable agricultural intensification (Mockshell and Kamanda, 2018).

3.1. The misleading effect of the product-based carbon footprint

The observed results raise some main issues which deserve to be further discussed. First, the two CF metrics provide diverse results in terms of sustainability of food production systems. Organic food results to be more impacting than conventional in the 29% of cases, if using the CF per unit of product (12 food items out of 41 have negative values and 1 has a zero value; see Table 1); while organic food results to be more sustainable in almost all cases (with few exceptions, 3 food items, Table 1) when considering the emissions per unit of land. Therefore, in the 29% of analysed cases, the same organic food product shows higher CF per product and lower CF per area respect to the same conventional food (see also Table 1, figures in bold).

Of the two CF metrics, the one that most correctly assesses the food sustainability is the CF per land unit that allows to directly quantify and properly understand the effective contribution to climate change of agriculture and food production (van der Werf et al., 2020). Climate change is driven by the GHG fluxes between the land and the atmosphere, which in the agricultural sector mainly depend on the land management practices (Frank et al., 2019; Chiriacò and Valentini, 2021), independently from the amount of food that is produced per unit of land. This is particularly factual considering also that sustainable agronomic practices can increase the carbon sequestration of the system (Eyhorn et al., 2019) even reaching in some cases a carbon neutral food production (Chiriacò et al., 2019; Chiriacò and Valentini, 2021) in line with the global climate goals set by the Paris Agreement, being the 'agriculture, forestry, and other land use' (AFOLU) the only sector able to sequester and store atmospheric carbon. Indeed, also the official national GHG inventories performed under the United Convention Framework on Climate Change report and account emissions and removals for the "land use, land use change and forestry' (LULUCF) sector on a land basis.

Accordingly, although the CF per product unit provides useful indications on the food emissions intensity and is far more used as a metric to assess the food sustainability for commercial purposes since it allows consumers to compare products on the shelfs (allowing comparability of LCA results as required by the ISO 14040), the information it provides (Balmford et al., 2018) may not reveal the actual food contribution to climate change (van der Werf et al., 2020). In fact, the CF of food product units is much related to the yields and higher GHG emissions for a more intense management per hectare can overshadow the higher productivity.

Therefore, to have a more comprehensive assessment of the real contribution to climate change of agricultural systems and increase the relevance of the LCA sustainability, there is a need to consider the CF metric per land unit, besides the CF per product unit, as highlighted in literature by many studies (e.g. Charles et al., 2006; Harada et al., 2007; Kavargiris et al., 2009; Ferng, 2011; Litskas et al., 2011; Nalley et al., 2011; Michos et al., 2012; Notarnicola et al., 2012; Roer et al., 2012; Zafiriou et al., 2012; Eshun et al., 2013; Hayashi, 2013; Murphy and Kendall, 2013; Meier et al., 2015; Renzulli et al., 2015; Balmford et al., 2018).

Considering our results, in many cases (29% of the analysed cases), higher GHG emissions per unit of organic products overshadow actual minor emissions per hectare of organic croplands (−43% average, compared to intensive croplands; Fig. 1) which indeed drive climate change. Conversely, conventional food with lower CF per product unit can correspond to higher CF per unit of land. Therefore, using the carbon footprint of food product units as a measure of sustainability may lead to the risk to classify unsustainable food as sustainable and vice versa, while a land-based CF accounting would avoid any misleading message.

3.2. Global implications of the expected shift towards organic food production

Another relevant issue evidenced by this analysis is that, when considering the impact per food categories, in 3 (fruits, vegetables and livestock products) out of the 5 main categories identified, organic food was more sustainable than conventional even when the CF is per unit of product (negative median values in dark grey bars, Fig. 1). This becomes even more evident when considering the impact of single food items, since the 68% of the analysed cases (28 food items out of 41) shows values of relative percentage ratio per unit of product below zero (Table 1). This is very impressive considering the historical debate that exists in the scientific community about the effectiveness of the sustainability of organic agriculture in terms of GHG emissions, with some studies in favor (Reganold and Wachter, 2016; Muller et al., 2017; Eyhorn et al., 2019; Rosenzweig et al., 2020) and others not supporting (Smith et al., 2019) organic farming as a solution to feed the global population. Our results show that a great part of the analysed organic food has a lower impact compared to conventional, both in terms of CF per unit of land and per unit of product, with a general value of −43% and −12% respectively (Fig. 1), definitively solving the existing scientific debate in favor of the organic food production, being more sustainable both in terms of total climate altering gases emitted in atmosphere and in terms of GHG emissions per product.

Organic food production is expected to further increase globally with respect to the current 1.5% global share (https://statistics.fibl.org/world.html) since it is recognized as an important milestone in the achievement of all the 17 UN Sustainable Development Goals (IFOAM, 2019) and is encouraged by many political instruments as for example the EU Green Deal and its "Farm to Fork Strategy" which has the objective to reach at least 25% of the EU's agricultural land under organic farming by 2030. Also consumers are increasing their willingness to choose organic food as the awareness of the environmental and health issues is growing (Eyinade et al., 2021), thus organic products seem to become the food of the future. Under this perspective, an hypothetical full conversion of today global croplands into organic lands would change the average emission intensity of the ~4.8 billion hectares of global agricultural lands (FAOSTAT, 2022) from the current 2.3 Mg CO_2eq ha^{-1} y^{-1} (IPCC et al., 2019) to 1.3 Mg CO_2eq ha^{-1} y^{-1} (if the average cut of −43% of GHG emissions per ha - obtained by this study considering the CF per land unit of organic vs conventional food, Fig. 1 - is applied as general median value for all food categories), ideally almost halving the emissions from the land sector from the current 11 GtCO2eq yr–1 to 6 GtCO2eq yr–1 (Table 2). This result is however only hypothetical since the 100% of conversion of cropland into organic lands is not realistic at global level, at least in the short to medium term, and future scenarios of global climate change as well as of increase in global population and related expected changes in the dietary composition of

Table 2
GHG emissions overview of the global food system.

Attributes of the global food system	Values
Global food system emissions form the land sector[a] (Gt CO_2eq y^{-1})	11.1 ± 2.8
Global agricultural lands[b] (M ha)	4800
Global organic croplands[c] (M ha)	71.5
Emission intensity of the current croplands[d] (Mg CO_2eq ha^{-1} yr^{-1})	2.3
Emission intensity of organic croplands[e] (Mg CO_2eq ha^{-1} yr^{-1})	1.3

[a] GHG Emissions of global food system (land use change + agriculture) as reported in Table SPM1 of the IPCC et al., 2019 Special report on Climate Change and Land - Summary for Policy Makers.
[b] FAOSTAT (2022).
[c] FiBL Statistics - Area https://statistics.fibl.org/world.html; corresponding to 1.5% of global croplands.
[d] Considering 4.8 billion hectares of global agricultural lands of which 1.5% are organic croplands (Source: FAOSTAT and FiBL Statistics - Area).
[e] Considering an average cut of −43% of GHG emissions per ha, as derived by this study.

different proportions of the various food categories - each with its own value of GHG emissions per land unit – should be also considered. However, it provides an idea of the theoretical maximum potential of organic food systems in reducing the GHG emissions at the global level (if using median values), thus highlighting the importance to foster as much as possible the transition towards organic food production and consumption.

Moreover, food security is a crucial element to consider (Reganold and Wachter, 2016; Muller et al., 2017; Rosenzweig et al., 2020) when discussing the importance to promote organic farming as a key asset of the future agriculture vision and a target in the roadmap toward sustainable and healthy diets. It is generally believed that the organic food production (more generally agro-ecology or sustainable agriculture) is not able to support the global food demand (Smith et al., 2019) due to average lower yields (Seufert et al., 2012; Reganold and Wachter, 2016). However, a sustainable increase of organic yields can be achieved with experiences and research advancements (Seufert and Ramankutty, 2017; Cassman and Grassini, 2020). In some cases, depending on the region of the world, organic systems already nearly match conventional yields (Seufert et al., 2012) – this is the reason of the unexpected higher sustainability of organic food observed on this analysis even when the CF is assessed per unit of product – and can even become higher in the long term thanks to the improved soil fertility as an effect of the enhanced soil biodiversity (Wittwer et al., 2017; Röös et al., 2018). Yet, results for some food items in this study (e.g. apples, wheat and milk produced in Italy, eggs – Table 1) show higher impact of organic vs conventional food per product unit and lower impact per land unit, revealing that organic yields are still too low in that cases to consider those organic products more sustainable than the same conventional ones under both the CF metrics. As previously reported, this highlights the need for some crops to further improve the performance of organic production, increasing yields through sustainable agricultural intensification (Mockshell and Kamanda, 2018).

The expected increase of the global share of organic croplands if coupled with a sustainable increase of organic yields, up to match the conventional ones, would enable the transition towards more sustainable diets, allowing to fully replace conventional with organic croplands to produce the same amount of food of today, but more sustainable and healthier, and without increasing the total cultivated land.

4. Conclusions

This analysis encompasses all the relevant exiting studies that allow to compare land-based vs product-based carbon footprints of organic vs conventional food products. The findings arising from this analysis demonstrates that organic food has in general a lower impact compared to conventional, both in terms of CF per unit of land and per unit of product, definitively recognizing organic farming as the sustainable option for the future. Another finding of the study is that the CF sustainability metric designed on a product unit basis can lead to misleading messages. We may arrive to the paradox to build actions for the adoption of sustainable diets on unsustainable considerations based on the apparent benefit disclosed in some cases by the lower CF per product unit, thus incentivizing intensive farming systems and fostering the unsustainable intensification of agricultural production (while we already have an over-production of food). Conversely, the use of a CF metric based on per land unit should be promoted for achieving an effective shift towards sustainable and healthy diets and a consequent GHG emissions reduction in the land and food sector for a substantial contribution to the global climate change mitigation goals set by the Paris Agreement.

Author contributions

Conceptualization: MVC, RV.
Methodology: MVC.
Investigation: MVC.
Writing: MVC, RV, SC.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

References

Abeliotis, K., Detsis, V., Pappia, C., 2013. Life cycle assessment of bean production in the Prespa National Park, Greece. J. Clean. Prod. 41, 89–96.
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 (2), 713–724.
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 (2), 725–737.
Ahmed, M., Rauf, M., Mukhtar, Z., Saeed, N.A., 2017. Excessive use of nitrogenous fertilizers: an unawareness causing serious threats to environment and human health. Environ. Sci. Pollut. Control Ser. 24 (35), 26983–26987.
Bahar, N.H.A., Lo, M., Sanjaya, M., Van Vianen, J., Alexander, P., Ickowitz, A., Sunderland, T., 2020. Meeting the food security challenge for nine billion people in 2050: what impact on forests? Global Environ. Change 62, 102056. https://doi.org/10.1016/j.gloenvcha.2020.102056.
Bajželj, B., Quested, T.E., Röös, E., Swannell, R.P., 2020. The role of reducing food waste for resilient food systems. Ecosyst. Serv. 45, 101140.
Balmford, A.T., Bartlett, H., Chadwick, D., Collins, A., Edwards, D., et al., 2018. The environmental costs and benefits of high-yield farming. Nat. Sustain. 1 (9), 477–485.
Basset-Mens, C., Van der Werf, H.M., 2005. Scenario-based environmental assessment of farming systems: the case of pig production in France. Agric. Ecosyst. Environ. 105 (1–2), 127–144.
Benton, T.G., Bailey, R., 2019. The paradox of productivity: agricultural productivity promotes food system inefficiency. Glob. Sustain. 2.
Benton, T., Bieg, C., Harwatt, H., Pudasaini, R., Wellesley, L., 2021. Food System Impacts on Biodiversity Loss: Three Levers for Food System Transformation in Support of Nature. Royal Institute of International Affairs, London.
Bonou-zin, R.D., Allali, K., Fadlaoui, A., 2019. Environmental efficiency of organic and conventional cotton in Benin. Sustainability 11 (11), 3044.
Brennan, M.E., Zaitchik, B.F., 2013. On the potential for alternative greenhouse gas equivalence metrics to influence sectoral mitigation patterns. Environ. Res. Lett. 8 (1), 014033.
Cain, M., Lynch, J., Allen, M.R., Fuglestvedt, J.S., Frame, D.J., Macey, A.H., 2019. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. NPJ Clim. Atmos. Sci. 2 (1), 1–7.
Carlson, K.M., Gerber, J.S., Mueller, N.D., Herrero, M., MacDonald, G.K., Brauman, K.A., et al., 2017. Greenhouse gas emissions intensity of global croplands. Nat. Clim. Change 7 (1), 63–68.
Casey, J.W., Holden, N.M., 2006. Greenhouse gas emissions from conventional, agri-environmental scheme, and organic Irish suckler-beef units. J. Environ. Qual. 35 (1), 231–239.

Cassman, K.G., Grassini, P., 2020. A global perspective on sustainable intensification research. Nat. Sustain. 3 (4), 262–268.
Chand, A., 2020. Paris Agreement needs food system change. Nat. Food 1 (12), 772, 772.
Charles, R., Jolliet, O., Gaillard, G., Pellet, D., 2006. Environmental analysis of intensity level in wheat crop production using life cycle assessment. Agric. Ecosyst. Environ. 113, 216e225.
Chiriacò, M.V., Valentini, R., 2021. A land-based approach for climate change mitigation in the livestock sector. J. Clean. Prod. 283, 124622.
Chiriacò, M.V., Belli, C., Chiti, T., Trotta, C., Sabbatini, S., 2019. The potential carbon neutrality of sustainable viticulture showed through a comprehensive assessment of the greenhouse gas (GHG) budget of wine production. J. Clean. Prod. 225, 435–450.
Chiriacò, M.V., Grossi, G., Castaldi, S., Valentini, R., 2017. The contribution to climate change of the organic versus conventional wheat farming: a case study on the carbon footprint of wholemeal bread production in Italy. J. Clean. Prod. 153, 309–319.
Clark, M.A., Domingo, N.G., Colgan, K., Thakrar, S.K., Tilman, D., Lynch, J., et al., 2020. Global food system emissions could preclude achieving the 1.5° and 2° C climate change targets. Science 370 (6517), 705–708.
Cullen, T., Hatch, J., Martin, W., Higgins, J.W., Sheppard, R., 2015. Food literacy: definition and framework for action. Can. J. Diet Pract. Res. 76 (3), 140–145.
De Backer, E., Aertsens, J., Vergucht, S., Steurbaut, W., 2009. Assessing the ecological soundness of organic and conventional agriculture by means of life cycle assessment (LCA): a case study of leek production. Br. Food J. 111 (10), 1028–1061.
Devereux, S., Béné, C., Hoddinott, J., 2020. Conceptualising COVID-19's impacts on household food security. Food Secur. 12 (4), 769–772.
Duro, J.A., Lauk, C., Kastner, T., Erb, K.H., Haberl, H., 2020. Global inequalities in food consumption, cropland demand and land-use efficiency: a decomposition analysis. Global Environ. Change 64, 102124.
Eshun, J.F., Apori, S.O., Wereko, E., 2013. Greenhouse gaseous emission and energy analysis in rice production systems in Ghana. Afr. Crop Sci. J. 21 (2), 119e125.
Eyhorn, F., Muller, A., Reganold, J.P., et al., 2019. Sustainability in global agriculture driven by organic farming. Nat. Sustain. 2, 253–255. https://doi.org/10.1038/s41893-019-0266-6.
Eyinade, G.A., Mushunje, A., Yusuf, S.F.G., 2021. The willingness to consume organic food: a review. Food Agric. Immunol. 32 (1), 78–104.
FAO, UNICEF, WFP and WHO, 2020. The State of Food Security and Nutrition in the World 2020. Transforming Food Systems for Affordable Healthy Diets. FAO, Rome. https://doi.org/10.4060/ca9692en.
FAOSTAT, 2022. https://www.fao.org/faostat/en/#home. (Accessed 19 August 2022).
Ferng, J.J., 2011. Measuring and locating footprints: a case study of Taiwan's rice and wheat consumption footprint. Ecol. Econ. 71, 191e201.
Frank, S., Havlík, P., Stehfest, E., van Meijl, H., Witzke, P., Pérez-Domínguez, I., Valin, H., 2019. Agricultural non-CO_2 emission reduction potential in the context of the 1.5 C target. Nat. Clim. Change 9 (1), 66–72.
Fridman, D., Koellner, T., Kissinger, M., 2021. Exploring global interregional food system's sustainability using the functional regions typology. Global Environ. Change 68, 102276.
Guerci, M., et al., 2013. Parameters affecting the environmental impact of a range of dairy farming systems in Denmark, Germany and Italy. J. Clean. Prod. 54, 133–141.
Haas, G., Wetterich, F., Köpke, U., 2001. Comparing intensive, extensified and organic grassland farming in southern Germany by process life cycle assessment. Agric. Ecosyst. Environ. 83 (1–2), 43–53.
Harada, H., Kobayashi, H., Shindo, H., 2007. Reduction in greenhouse gas emissions by no-tilling rice cultivation in Hachirogata polder, northern Japan: life-cycle Inventory analysis. Soil Sci. Plant Nutr. 53, 668e677.
Hayashi, K., 2013. Practical recommendations for supporting agricultural decisions through life cycle assessment based on two alternative views of crop production: the example of organic conversion. Int. J. Life Cycle Assess. 18, 331e339.
Hobbs, J.E., 2020. Food supply chains during the COVID-19 pandemic. Can. J. Agric. Econ. Revue Can. d'agroecon. 68 (2), 171–176.
Hörtenhuber, S., Lindenthal, T., Amon, B., Markut, T., Kirner, L., Zollitsch, W., 2010. Greenhouse gas emissions from selected Austrian dairy production systems-model calculations considering the effects of land use change. Renew. Agric. Food Syst. 316–330.
IFOAM, 2019. Organic agriculture and the sustainable development goals. Part of the solution. Available at: https://archive.ifoam.bio/sites/default/files/nm19_329_report_sdg_lr.pdf.
IPCC, 1995. In: Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.), Climate Change 1995: the Science of Climate Change, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 0-521-56433-6.
IPCC, 2001. In: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., van der Linden, P.J., Dai, X., Maskell, K., Johnson, C.A. (Eds.), Climate Change 2001: the Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 0-521-80767-0 (pb: 0-521-01495-6.
IPCC, 2007. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: the Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 978-0-521-88009-1 (pb: 978-0-521-70596-7.
IPCC, 2013. In: Stocker, T.F., et al. (Eds.), Climate Change 2013: the Physical Science Basis. Working Group 1 (WG1) Contribution to the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (AR5). Cambridge University Press.
IPCC, 2019. In: Shukla, P.R., Skea, J., Calvo Buendia, E., Masson-Delmotte, V., Pörtner, H.-O., Roberts, D.C., Zhai, P., Slade, R., Connors, S., van Diemen, R., Ferrat, M., Haughey, E., Luz, S., Neogi, S., Pathak, M., Petzold, J., Portugal Pereira, J., Vyas, P., Huntley, E., Kissick, K., Belkacemi, M., Malley, J. (Eds.), Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems.
IPCC, 2022. In: Shukla, P.R., Skea, J., Slade, R., Al Khourdajie, A., van Diemen, R., McCollum, D., Pathak, M., Some, S., Vyas, P., Fradera, R., Belkacemi, M., Hasija, A., Lisboa, G., Luz, S., Malley, J. (Eds.), Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA. https://doi.org/10.1017/9781009157926.
Kavargiris, S.E., Mamolos, A.P., Tsatsarelis, C.A., Nikolaidou, A.E., Kalburtji, K.L., 2009. Energy resources' utilization in organic and conventional vineyards: energy flow, greenhouse gas emissions and biofuel production. Biomass Bioenergy 33, 1239e1250.
Keyes, S., Tyedmers, P., Beazley, K., 2015. Evaluating the environmental impacts of conventional and organic apple production in Nova Scotia, Canada, through life cycle assessment. J. Clean. Prod. 104, 40–51.
Kim, B.F., Santo, R.E., Scatterday, A.P., Fry, J.P., Synk, C.M., Cebron, S.R., et al., 2020. Country-specific dietary shifts to mitigate climate and water crises. Global Environ. Change 62, 101926.
Knapp, S., van der Heijden, M.G.A., 2018. A global meta-analysis of yield stability in organic and conservation agriculture. Nat. Commun. 9, 3632. https://doi.org/10.1038/s41467-018-05956-1.
Knudsen, M.T., Yu-Hui, Q., Yan, L., Halberg, N., 2010. Environmental assessment of organic soybean (Glycine max.) imported from China to Denmark: a case study. J. Clean. Prod. 18 (14), 1431–1439.
Kowalczyk, Z., Cupiał, M., 2020. Environmental analysis of the conventional and organic production of carrot in Poland. J. Clean. Prod., 122169
Kristensen, T., Mogensen, L., Knudsen, M.T., Hermansen, J.E., 2011. Effect of production system and farming strategy on greenhouse gas emissions from commercial dairy farms in a life cycle approach. Livest. Sci. 140 (1–3), 136–148.
Laborde, D., Martin, W., Swinnen, J., Vos, R., 2020. COVID-19 risks to global food security. Science 369 (6503), 500–502.
Leinonen, I., Williams, A.G., Wiseman, J., Guy, J., Kyriazakis, I., 2012a. Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: broiler production systems. Poultry Sci. 91 (1), 8–25.
Leinonen, I., Williams, A.G., Wiseman, J., Guy, J., Kyriazakis, I., 2012b. Predicting the environmental impacts of chicken systems in the United Kingdom through a life cycle assessment: egg production systems. Poultry Sci. 91 (1), 26–40.
Litskas, V.D., Mamolos, A.P., Kalburtji, K.L., Tsatsarelis, C.A., Kiose-Kampasakali, E., 2011. Energy flow and greenhouse gas emissions in organic and conventional sweet cherry orchards located in or close to Natura 2000 sites. Biomass Bioenergy 35, 1302e1310.
Meier, M.S., Stoessel, F., Jungbluth, N., Juraske, R., Schader, C., Stolze, M., 2015. Environmental impacts of organic and conventional agricultural products-Are the differences captured by life cycle assessment? J. Environ. Manag. 149, 193–208.
Meisterling, K., Samaras, C., Schweizer, V., 2009. Decisions to reduce greenhouse gases from agriculture and product transport: LCA case study of organic and conventional wheat. J. Clean. Prod. 17 (2), 222–230.
Michos, M.C., Mamolos, A.P., Menexes, G.C., Tsatsarelis, C.A., Tsirakoglou, V.M., Kalburtji, K.L., 2012. Energy inputs, outputs and greenhouse gas emissions in organic, integrated and conventional peach orchards. Ecol. Indicat. 13 (1), 22–28.
Mockshell, J., Kamanda, J., 2018. Beyond the agroecological and sustainable agricultural intensification debate: is blended sustainability the way forward? Int. J. Agric. Sustain. 16 (2), 127–149.
Moschitz, H., Muller, A., Kretzschmar, U., Haller, L., de Porras, M., Pfeifer, C., et al., 2021. How can the EU Farm to Fork strategy deliver on its organic promises? Some critical reflections. EuroChoices 20 (1), 30–36.
Muller, A., Schader, C., Scialabba, N.E.H., Brüggemann, J., Isensee, A., Erb, K.H., et al., 2017. Strategies for feeding the world more sustainably with organic agriculture. Nat. Commun. 8 (1), 1–13.
Müller, B., Hoffmann, F., Heckelei, T., Müller, C., Hertel, T.W., Polhill, J.G., et al., 2020. Modelling food security: bridging the gap between the micro and the macro scale. Global Environ. Change 63, 102085.
Muneret, L., Mitchell, M., Seufert, V., Aviron, S., Pétillon, J., Plantegenest, M., et al., 2018. Evidence that organic farming promotes pest control. Nat. Sustain. 1 (7), 361–368.
Murphy, C., Kendall, A., 2013. Life cycle inventory development for corn and stover production systems under different allocation methods. Biomass Bioenergy 58, 67–75.
Nalley, L., Popp, M., Fortin, C., 2011. The impact of reducing greenhouse gas emissions in crop agriculture: a spatial and production-level analysis. Agric. Resour. Econ. Rev. 40 (1), 63e80.
Notarnicola, B., Hayashi, K., Curran, M.A., Huisingh, D., 2012. Progress in working towards a more sustainable agri-food industry. J. Clean. Prod. 28, 1e8.
Oliquino-Abasolo, A., Zamora, O., 2016. Agro-environmental sustainability of conventional and organic vegetable production systems in Tayabas, Quezon, Philippines. J. Environ. Sci. Manag. 19 (1).
Pirlo, G., Lolli, S., 2019. Environmental impact of milk production from samples of organic and conventional farms in Lombardy (Italy). J. Clean. Prod. 211, 962–971.
Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360 (6392), 987–992.
Reganold, J., Wachter, J., 2016. Organic agriculture in the twenty-first century. Nat. Plants 2, 15221. https://doi.org/10.1038/nplants.2015.221.

Reisch, L.A., Sunstein, C.R., Andor, M.A., Doebbe, F.C., Meier, J., Haddaway, N.R., 2020. Mitigating climate change via food consumption and food waste: a systematic map of behavioral interventions. J. Clean. Prod., 123717

Renzulli, P.A., Bacenetti, J., Benedetto, G., Fusi, A., Ioppolo, G., Niero, M., Proto, M., Salomone, R., Sica, D., Supino, S., 2015. Application of life cycle assessment in the cereal and derived products sector. In: Notarnicola, B., Salomone, R., Petti, L., Renzulli, P.A., Roma, R., Cerutti, A.K. (Eds.), 2015. Life Cycle Assessment in the Agri-Food Sector Case Studies, Methodological Issues and Best Practices. Springer International Publishing, p. 185e249.

Roer, A.G., Korsaeth, A., Henriksen, T.M., Michelsen, O., Strømman, A.H., 2012. The influence of system boundaries on life cycle assessment of grain production in central southeast Norway. Agric. Syst. 111, 75e84.

Ronga, D., Gallingani, T., Zaccardelli, M., Perrone, D., Francia, E., Milc, J., Pecchioni, N., 2019. Carbon footprint and energetic analysis of tomato production in the organic vs the conventional cropping systems in Southern Italy. J. Clean. Prod. 220, 836–845.

Röös, E., Mie, A., Wivstad, M., Salomon, E., Johansson, B., Gunnarsson, S., et al., 2018. Risks and opportunities of increasing yields in organic farming. A review. Agron. Sustain. Dev. 38 (2), 14.

Rosenzweig, C., Mbow, C., Barioni, L.G., Benton, T.G., Herrero, M., Krishnapillai, M., et al., 2020. Climate change responses benefit from a global food system approach. Nat. Food 1 (2), 94–97.

Seufert, V., Ramankutty, N., 2017. Many shades of gray-The context-dependent performance of organic agriculture. Sci. Adv. 3 (3), e1602638.

Seufert, V., Ramankutty, N., Foley, J., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229–232. https://doi.org/10.1038/nature11069.

Sharma, N., Singhvi, R., 2017. Effects of chemical fertilizers and pesticides on human health and environment: a review. Int. J. Agric. Environ. Biotechnol. 10 (6), 675–680.

Skinner, C., Gattinger, A., Krauss, M., Krause, H.M., Mayer, J., Van Der Heijden, M.G., Mäder, P., 2019. The impact of long-term organic farming on soil-derived greenhouse gas emissions. Sci. Rep. 9 (1), 1–10.

Smith, L.G., Kirk, G.J.D., Jones, P.J., et al., 2019. The greenhouse gas impacts of converting food production in England and Wales to organic methods. Nat. Commun. 10, 4641. https://doi.org/10.1038/s41467-019-12622-7.

Šūmane, S., Kunda, I., Knickel, K., Strauss, A., Tisenkopfs, T., des Ios Rios, I., Ashkenazy, A., 2018. Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. J. Rural Stud. 59, 232–241.

Thomassen, M.A., van Calker, K.J., Smits, M.C., Iepema, G.L., de Boer, I.J., 2008. Life cycle assessment of conventional and organic milk production in The Netherlands. Agric. Syst. 96 (1–3), 95–107.

Treu, H., Nordborg, M., Cederberg, C., Heuer, T., Claupein, E., Hoffmann, H., Berndes, G., 2017. Carbon footprints and land use of conventional and organic diets in Germany. J. Clean. Prod. 161, 127–142.

UNEP, 2021. Food Waste Index Report 2021. Nairobi.

van Dam, Y.K., van Trijp, H.C., 2013. Relevant or determinant: importance in certified sustainable food consumption. Food Qual. Prefer. 30 (2), 93–101.

Van Den Berg, M., Hof, A.F., Van Vliet, J., Van Vuuren, D.P., 2015. Impact of the choice of emission metric on greenhouse gas abatement and costs. Environ. Res. Lett. 10 (2), 024001.

van der Werf, H.M., Kanyarushoki, C., Corson, M.S., 2009. An operational method for the evaluation of resource use and environmental impacts of dairy farms by life cycle assessment. J. Environ. Manag. 90 (11), 3643–3652.

van der Werf, H.M.G., Knudsen, M.T., Cederberg, C., 2020. Towards better representation of organic agriculture in life cycle assessment. Nat. Sustain. 3, 419–425. https://doi.org/10.1038/s41893-020-0489-6.

van Woerkum, C., Bouwman, L., 2014. 'Getting things done': an everyday-life perspective towards bridging the gap between intentions and practices in health-related behavior. Health Promot. Int. 29 (2), 278–286. https://doi.org/10.1093/heapro/das059.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., et al., 2019. Food in the Anthropocene: the EAT-Lancet Commission on healthy diets from sustainable food systems. Lancet 393 (10170), 447–492.

Wittwer, R.A., Dorn, B., Jossi, W., Van Der Heijden, M.G., 2017. Cover crops support ecological intensification of arable cropping systems. Sci. Rep. 7 (1), 1–12.

Yuttitham, M., 2019. Comparison of carbon footprint of organic and conventional farming of Chinese Kale. Environ. Nat. Resour. J. 17 (1), 78–92.

Zafiriou, P., Mamolos, A.P., Menexes, G.C., Siomos, A.S., Tsatsarelis, C.A., Kalburtji, K.L., 2012. Analysis of energy flow and greenhouse gas emissions in organic, integrated and conventional cultivation of white asparagus by PCA and HCA: cases in Greece. J. Clean. Prod. 29, 20–27.

Zhu, Z., Jia, Z., Peng, L., Chen, Q., He, L., Jiang, Y., Ge, S., 2018. Life cycle assessment of conventional and organic apple production systems in China. J. Clean. Prod. 201, 156–168.