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Organic food has lower environmental impacts per area unit and similar climate impacts per mass unit compared to conventional

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In recent years, interest in studying the climate and environmental impact of organic food has grown. Here, we compared the environmental impacts of organic and conventional food using data from 100 life cycle assessment studies. Most studies focused on climate impacts, with fewer addressing biodiversity loss and ecotoxicity. Findings revealed no significant differences in global warming, eutrophication potential, and energy use per mass unit. However, organic food showed lower global warming, eutrophication potential, and energy use per area unit, with higher land use. Additionally, organic farming showed lower potential for biodiversity loss and ecotoxicity. Challenges in life cycle assessment include evaluating biodiversity, toxicity, soil quality, and carbon changes. The choice of functional units influences results, highlighting the importance of considering multiple units in assessing organic food's environmental footprint. This study emphasizes the necessity for comprehensive assessments at both product and diet levels to support informed decisions.

The increase in organic food production and consumption is a distinct environmental-economic trend worldwide[1,2]. Organic food production systems depend on ecological processes, biodiversity, and nutrient cycles and aim to sustain the health of soils, ecosystems, and people[3]. The dynamics of organic food demand vary among countries and regions of the world, depending on economic[4], environmental[5–7] and social circumstances[8]. In 2021, 3.7 million organic producers were reported in 191 countries, organic agricultural land had expanded to 76 million hectares, and global sales of organic food and drink reached almost 125 billion euros[9]. With 48.6 billion euros, the United States continued to be the world's leading market, followed by Germany (15.9 billion euros) and France (12.7 billion euros)[9]. Swiss consumers spent the most on organic food (425 euros per capita on average), and Denmark continued to have the highest organic market share, with 13 percent of its total food market[9].

Organic food production has been regulated at European Union (EU) level since 1991. The EU requirements for organic food are set by regulation (EC) No 834/2007, specifying the principles of organic food production. The latest organic regulation (EU) 2018/848 including more organic foods than the previous regulations was published in June 2018 to ensure more control on environmental and economic impacts of organic food and applied from 1 January 2022.

To assess to what extent food and agricultural production systems affect the environment, a proper assessment method evaluating resource depletion issues and pollutant emissions is needed. The method most widely used to assess agricultural systems' environmental impact is life cycle assessment (LCA)[10,11]. LCA is an approach that assesses the environmental impacts and resource use through a product's life cycle[12]. This assessment considers flows of materials and energy and results in aggregated impact indicators for resource consumption and pollutant emissions[11]. Results from LCAs quantify negative impacts of food production systems, which can be used in stakeholder communication and policymaking for identifying sustainable food and agricultural production systems[13,14].

However, current LCA studies on organic food face several challenges to estimate environmental impacts and tend to favor intensive agriculture and often disregard multifunctionality of agriculture[11]. This may be due to a

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lack of comprehensive operational indicators for some environmental aspects (e.g. biodiversity loss and pesticide effects) or often ignoring certain flows (e.g. soil organic carbon changes) or inconsistent modeling of indirect effects (e.g. indirect land use change)[11]. Besides, few databases include environmental data of organic food products. Therefore, disposing of data on the environmental impacts of organic food is important for almost all parts of society: policy makers, farmers, agribusinesses, public procurers, the media, and consumers. A review of studies on environmental impacts of organic food may provide estimations of their environmental profiles to guide environmentally friendly food choices.

Several reviews have compared organic and conventional agricultural systems that either considered a few environmental indicators or lacked statistical strength due to the consideration of a small number of papers[15–17]. Many studies showed that food products differ largely in their environmental impacts[18–22]. Some studies considered only a single environmental impact[19,21] or a specific food type, such as animal-based food[18,20]. A study compared different organic and conventional food items for five environmental indicators, but by reporting the impacts per nutritional value and not per mass or area unit[7]. A review study on about 20 LCA studies considering both area and output functional units, assessed costs and benefits of organic agriculture across multiple production, environmental, producer, and consumer dimensions[23]. Another review on 34 comparative LCA studies[14], focused on efficiency of LCA to compare environmental impacts of organic and conventional agricultural products.

However, so far, there is no systematic review on a large number of LCA studies conducted on organic food solely or both conventional and organic food, that simultaneously addresses results of LCA on organic food considering key environmental indicators in the field of agriculture per mass and area functional units.

The main aim of this review focusing on environmental LCA of organic food was 1) to identify to which extent the LCA studies cover food categories, environmental impacts, and functional units in different geographical regions, 2) to assess and compare environmental impacts among organic foods and to compare their impacts with conventional foods and 3) to evaluate impacts of LCA methodological choices on differences between environmental impact of organic and conventional products.

We conducted a quantitative review of 100 LCA studies on organic food, assessing eight key impact categories from cradle-to-farm gate. Our findings reveal that organic food has lower environmental impacts per area unit and higher land use and similar climate impact per mass unit compared to conventional. Additionally, organic farming exhibited lower potential for biodiversity loss and ecotoxicity impact. The choice of functional units influences results, underscoring the importance of considering multiple units in evaluating organic food's environmental impact.

Materials and methods

Selection of LCA studies

To review relevant LCA studies, a selection of studies published before July 2020 was made via ISI Web of Science for 1991–2020, with the key words 'Organic' and 'Life cycle assessment'. The setup of search criteria yielded a total of 2177 publications based on published scientific studies with detailed information about published items and sum of the citations in each year as presented in Fig.1.

Following PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)[24], selection of relevant studies was performed by including only those studies that conducted LCA of organic food or comparative LCA study, reported environmental impact values (midpoint characterization) for organic food, used real-world experimental sites, and did not scenario-model environmental impacts of organic foods. This yielded a master bibliography of 100 studies including 25 studies on organic food and 75 comparative studies including 94 peer reviewed scientific articles, three scientific reports, two conference papers and one master's thesis. The reviewed studies are listed in Table 1, which shows the food products, type of the study, focus of the study, country of the authors and the country on which the study focused.

Focus areas for review

To review the LCA studies the scheme presented in Fig. 2 was followed. As described in the first section of the Results of this study, the review was guided by an overview of geographical origin and temporal scope of the LCA studies. Moreover methodological choices including system boundary, functional unit and environmental impact were considered under the overview of the studies. Next, the environmental impacts of organic food and the comparison between and within different organic and conventional food categories were presented. The final step is the discussion of the challenges, opportunities and perspectives of the food LCA studies. Methodological choices considered in this review included "system boundary", "functional unit" and "environmental impact category". A "system boundary" specifies which processes and activities related to a product life cycle are considered, and which are excluded[25,26]. A food LCA study should include inputs to the farm and activities at the farm and may include activities that take place after the product has left the farm[26,27]. The data analysis of this review includes studies on cradle-to-farm gate, i.e. not including activities after the product has left the farm. The so-called "functional unit" in LCA studies is a quantitative measure of the function that is delivered by the system[11,26]. Functional units for food products can be based on the quantity (mass-based) or/and the land occupied (area-based). They can also reflect the quality or nutritional values of food from their calories, protein content and/or micronutrients. Environmental impacts of food products via LCA are quantified using a set of indicators called "impact categories"[12]. Eight impact categories were considered in this review including global warming potential (GWP_{100}), acidification potential (AP), eutrophication potential (EP), eco-toxicity potential (ETP), biodiversity impacts (BI), energy use (ENU), water use (WU) and land use (LU). GWP is reported in carbon dioxide equivalents and includes greenhouse gas emissions (GHG) mainly in the form of N_2O, CH_4 and CO_2[28]. AP is an estimation of the potential increase in acidity of an ecosystem, expressed in SO_2 equivalents and includes acidification potential from SO_2, N_2O, NO_x NH_3 and NO, among others. Eutrophication occurs due to the enrichment of terrestrial and aquatic ecosystems with nutrients often characterized in PO_4^{3-} or and NO_3^- equivalents resulted from PO_4^{3-}, NO, NO_2, NH_3 and NH_4^+ among others. ETP in an LCA context includes fate, exposure, and

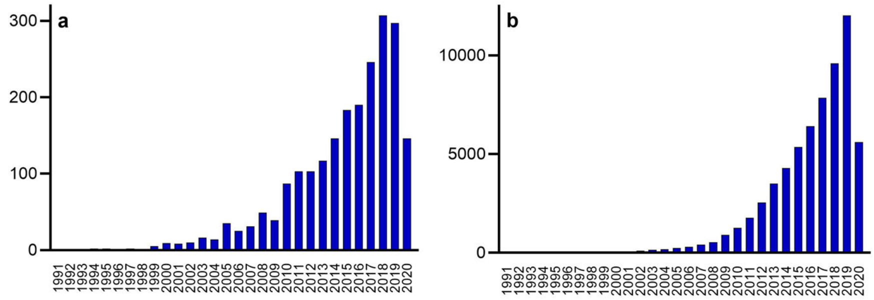

Fig. 1 | Publication trends and citations over time. Number of publications (**a**) and sum of times cited (**b**) per year for publications resulting from the review set up in Web of Science on 22/06/2020.Each bar represents a specific year, showcasing the publication output and citation count over time.

Table 1 | Reviewed LCA studies on organic products (O) and LCA studies comparing organic and conventional products (C)

Study	Country		Type of the study[a]	Focus of the study[b]	Analyzed products
	Origin of the study	Origin of food production in the study			
17	UK	UK	JA	O and C	Winter wheat
28	Norway	Norway	JA	C	Milk, beef, wheat
32	Greece	Greece	JA	C	Grape
33	Italy	Italy	JA	C	Grape
34	Spain	Spain/Italy	JA	C	Clementine
35	Brazil	Brazil	JA	O	White and brown rice
36	Brazil	Brazil	JA	O	White and brown rice
37	Denmark	Denmark	JA	O	Pig
38	Spain	Spain	JA	O	Goat milk, pig, beef, lamb
39	USA	USA	JA	C	Wheat bread
40	Denmark	Denmark	JA		Soybean
41	Denmark	Brazil	JA	C	Orange, orange juice
42	USA	USA	JA	C	Lettuce, broccoli, apple, strawberry, blueberry, grape, almond, walnut
43	Denmark	Denmark	JA	C	Potato, winter wheat, spring barley, fava bean
44	Denmark	UK/Denmark/ Austria	JA	C	Milk
45	Austria	Austria	JA	C	Milk
46	Sweden	Sweden	JA	C	Milk
47	Italy	Italy/Denmark/	JA	O	Milk
48	Germany	Germany	JA	C	Milk
49	Spain	Spain	JA	C	Grape
50	Sweden	Vietnam	JA	C	Shrimps
51	Brazil	Brazil	JA	C	Melon
52	Thailand	Thailand	JA	O	Rice
54	Canada	Canada	JA	C	Apple
55	Switzerland	Portugal	JA	C	Wheat bread
56	Italy	Italy	JA	O	Rice
57	Italy	Italy	JA	C	Apple
58	Germany	Germany	JA	C	Carp fish
59	France	France	JA	C	Pig
60	France	France	JA	C	Milk
61	Sweden	Sweden	JA	C	Milk
62	Sweden	Sweden	JA	O	Milk, beef
63	Sweden	Sweden	SR	C	Milk
64	UK	UK	SR	C	Milk, pig, beef, lamb, chicken, eggs, tomato, potato, wheat, oilseed rape
65	UK	UK	JA	C	Potato, wheat, oilseed rape
66	UK	UK	JA	C	Chicken
68	Japan	Japan	JA	C	Brown rice

Table 1 (continued) | Reviewed LCA studies on organic products (O) and LCA studies comparing organic and conventional products (C)

Study	Country		Type of the study[a]	Focus of the study[b]	Analyzed products
	Origin of the study	Origin of food production in the study			
69	Greece	Greece	JA	C	Beans
70	France	France	JA	C	Apple
71	Italy	Italy	JA	C	Olive
72	UK	UK	JA	C	Eggs
73	Italy	Italy	JA	C	Chicken
74	Belgium	Belgium	JA	C	Wheat
77	Spain	Spain	JA	C	Olive
78	China	China	JA	C	Tomato
79	China	China	JA	C	Rice
81	Germany	Germany	JA	C	Milk
82	Italy	Italy	JA	O	Rice
112	USA	USA	JA	O	Potato, onion, cauliflower, winter and summer squash, chard, pepper, beans
113	Belgium	Belgium	JA	C	Leek
114	The Netherlands	The Netherlands	CP	C	Potato, sugar beet, leek, lettuce, bean, peas
115	Sweden	Sweden	JA	O	Tomato
116	USA	USA	JA	C	Diced tomato, tomato paste
117	Italy	Italy	JA	C	Beef
118	Peru	Peru	JA	O	Quinoa
119	Ireland	Ireland	JA	C	Beef
120	Italy	Italy	JA	C	Potato, carrot, apple, pear, peach
121	USA	Chile /USA	JA	O	Blueberries
122	France	France	JA	C	Milk
123	Italy	Italy	JA	C	Wheat bread
124	Italy	Italy	JA	O	Wheat pasta
125	The Netherlands	The Netherlands	JA	C	Eggs
126	France	Denmark/Germany/ France/Spain	JA	C	Pig
127	Greece	Greece	JA	C	Lettuce
128	Finland	Finland	JA	C	Milk, rye bread
129	USA	USA	JA	O	Milk
130	The Netherlands	The Netherlands	MT	C	Milk
131	The Netherlands	Brazil	JA	C	Soybeans
132	Denmark	China	JA	C	Milk, beef
133	China	China	JA	C	Pear
134	Spain	Spain	JA	O	Almond
135	Denmark	Denmark	SR	C	Wheat, rye, spring and winter barley, oat, oilseed rape
136	Chile	Chile	JA	C	Blueberries

Table 1 (continued) | Reviewed LCA studies on organic products (O) and LCA studies comparing organic and conventional products (C)

Study	Country		Type of the study[a]	Focus of the study[b]	Analyzed products
	Origin of the study	Origin of food production in the study			
137	Thailand	Thailand	JA	O	Rice
138	New Zealand	New Zealand	JA	C	Kiwi
139	The Netherlands	The Netherlands	JA	C	Milk
140	Canada	Canada	JA	C	wheat, corn, oil-seed rape, soy
141	Canada	Canada	JA	C	Eggs
142	Italy	Italy	JA	C	Orange, lemon
143	Canada	Canada	JA	O	Grape wine
144	Portugal	Portugal	JA	C	Beef
145	Spain	Spain	JA	C	Citrus
146	Spain	Spain	JA	C	Banana
147	Spain	Spain	JA	C	Strawberry
148	Italy	Italy	JA	C	Tomato
149	Italy	Italy	JA	C	Milk
150	Switzerland	Switzerland	JA	O	Milk
151	Germany	Germany	JA	O	Milk
152	Japan	Japan	JA	C	Mustard spinach
153	Italy	Italy	JA	O	Tomato, chicory, wheat, apple, pear
154	The Netherlands	The Netherlands	JA	O	Milk
155	The Netherlands	The Netherlands	JA	C	Milk
156	Italy	Italy	JA	C	Barley
157	Japan	Japan	JA	C	Beef
158	Italy	Italy	JA	O	Grape wine
159	The Netherlands	The Netherlands	CP	C	Tomato
160	Italy	Italy	JA	O	Beef
161	UK	UK	JA	C	Strawberry
162	China	China	JA	O	Tea
163	China	China	JA	C	Apple

[a] Type of the study: JA: Journal article, SR: Scientific report, MT: Master thesis, CP: Conference paper.

[b] Focus of the study: O: LCA studies on organic food products, C: Comparative LCA studies.

effects of eco-toxic substances on different species in soil and water[29] that were aggregated in a single parameter (toxic equivalence factor) and often characterized in either Comparative Toxic Unit for eco-toxicity (CTUe) or kg 1.4 Dichlorobenzene equivalent (DB- eq.). BI is included as a mid-point impact category in agricultural LCA studies, it essentially considers the effect of farm scale activities on species diversity of plants and animals and their vulnerability[30]. ENU refers to the depletion of energetic resources and represents a source of GHG emissions from human activities and generally includes, but is not limited to fertilizer production, infrastructure construction and machinery use. WU refers to the quantity of blue water consumption or withdrawals. LU refers to use of land as a resource being temporarily used for cultivation of crops and feeding and housing of animals.

Analysis of selected studies

Data extraction. The selected papers were grouped according to the products that were assessed and each study was analyzed according to the stages of the review approach (see Supplementary Data 1, a tabular overview). Data on the impact categories for each food product were collected considering the following criteria:

- The study had to include either environmental impacts of organic food or a comparison of organic and conventional food. If studies were conducted on conventional agricultural systems and their results were compared with the results of other studies on organic systems, they were not considered for review.
- The study had to report midpoint characterization results on impact categories.
- The study that considered ENU as an impact category had to report midpoint characterization results on energy consumed for agricultural production.

Further, for a study reporting impact categories per mass unit and providing product yield of organic and conventional systems per hectare at farm gate (plant products), the impact values were calculated per unit area for data analysis.

Data analysis. To assess the environmental impacts of organic food, the statistical distributions (mean, standard deviation, and ranges) of the impacts of organic products were calculated using both studies on organic food and comparative studies (see Supplementary Information). To assess how organic and conventional products differed in their environmental impacts, products were aggregated into groups of similar types defined as food categories. Further, impacts of agricultural systems of each category were compared using an analytical approach adapted from a study[17]. First, the response ratio of environmental impacts for each item within each publication, denoted as *RR*, was calculated using the following formula:

$$RR = \left(\frac{impact\ \ of\ \ organic\ system}{impact\ \ of\ \ conventional\ system} - 1\right)$$

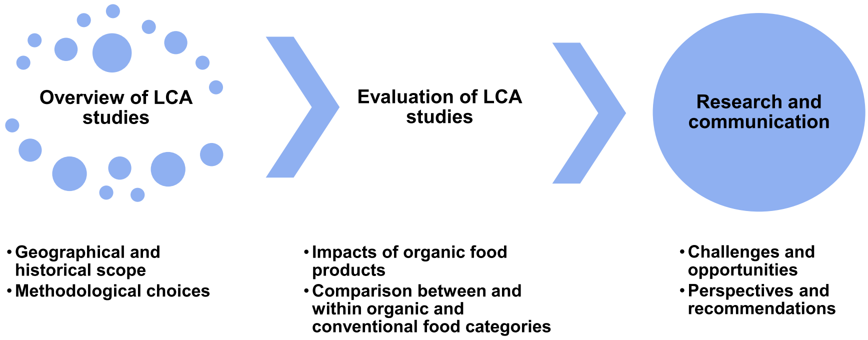

Fig. 2 | Components of the review approach. The review approach includes an analysis of geographical and temporal scopes, methodological choices, environmental impacts of organic food, and discussions on challenges and opportunities in food LCA studies.

Thus, negative values show lower impacts and positive values indicate higher impacts of organic compared to conventional. Next, median values of the response ratios for each impact were calculated. Results of each impact were not weighted due to the small sample size per food category, therefore all cases contributed equally to the results. A Shapiro–Wilk test was used to test the normality of data related to each impact. Because not all impact ratios were normally distributed, a Wilcoxon Signed Rank test was used to determine whether the median impact ratios differed significantly from zero. Statistical analyses were performed using the R package stats from version 3.6.1 of the R statistical computing environment[31].

Results

Overview of the reviewed studies

Table 2 provides an overview of the number of LCA studies and considered product categories for this review divided into studies focusing on either only organic or organic versus conventional production in different periods for publication date (2000-2006, 2007–2013, and 2014–2020) and geographic regions of the world (Asia, America, Europe, and Oceania), shows only the data extracted from the reviewed articles and not the calculated data. There was no study reported from Africa and it was therefore not included in the study regions. The studies vary in considering different impacts, system boundaries and functional units. Studies on both animal and plant products are considered. Animal products include milk, pig, cattle, lamb, seafood, chicken and eggs and plant products include vegetables, grain and cereals, fruits, nuts, and aromatic beverages (e.g. tea). Studies on “alcoholic beverages”, “breads and pasta”, “tomato paste, diced and dried tomatoes” that report their results considering both farm gate and post farm gate were considered under the fruits, grain and cereals and vegetables, respectively.

Spatial and temporal scope. Table 2 shows that most studies were from Europe and North America. In detail, most of the studies on organic food were from Southern Europe (35%) and for comparative studies from Northern Europe (44%). These results therefore are representative of industrialized agricultural systems and comparisons among the present studies will show differences between environmental impacts of products. It also shows that most of the organic and comparative studies included more plant products than animal products. There was in general greater focus on grain and cereals, fruits and vegetables for plant products and milk and cattle for animal products than on other products. Table 2 also shows that most of the studies (72% of organic and 49% of comparative) were recent (2014-2020). The years between 2007 and 2013 covered 20% of organic and 37% of comparative studies. The 2000-2006 period had few organic and comparative studies.

Methodological choices

System boundary. System boundary in Table 2 was reported for all publications including either cradle-to-farm gate or cradle-to-post-farm gate, but for evaluation of LCA studies, only estimations available on cradle-to-farm gate were considered. Based on Table 2, 64% and 80% of studies on organic food and comparative studies, respectively used cradle-to-farm gate system boundary.

Functional unit. Based on Table 2 more studies used mass-based than area-based functional unit (Table 2). This included 68% of studies on organic products and 65% of comparative studies. 24% and 30% of the studies used both mass- and area-based functional units for organic and comparative LCA studies, respectively (Table 2). Three comparative studies on fruits[32–34] considered only area-based functional unit and two organic food studies on grain and cereals used protein-based functional units[35,36].

Environmental impact. All LCA studies on organic food and 96% of comparative studies evaluated impacts of products and their agricultural systems on GWP for a 100-year time horizon. However, they considered slightly different characterization factors for CH_4 and N_2O from 2000 until now, which could not be modified to obtain GWP of all reported products with same characterization factors (Table 2). Few of these studies considered soil carbon sequestration (SOC) (Table 2). Of the organic LCA studies only two papers[37,38] and of comparative studies only six papers[39–44] included SOC in their assessment. Some other studies considered emissions from dLUC[45–52].

Of 50 studies that considered AP, 11 and 39 were related to organic and comparative studies, respectively and most of these studies were on plant products (69% of organic studies and 55% of comparative studies) (Table 2).

The publications reviewed here covered different ways of reporting EP, because current LCA characterization models either use a single or combined impact category for terrestrial, marine, and freshwater environments[53]. Most recent studies report their results in separate EP categories[33,51,54–58]. EP in Table 2 was reported for all publications, without considering the methods that were used but for evaluation of LCA studies and their relevant data analysis only estimations on NO_3- equivalents were considered. 48% of the LCA studies on organic food and 54% of the comparative LCA studies considered EP (Table 2).

Of the 100 studies, only 26 analyzed the water toxicity related impacts and 86% of them concerned plant products (Tables 2 and 3). Four studies focused on eco-toxicity potential of animal products[44,58–60] and use of pesticide or active substances were reported in six studies[61–66].

The complexity of biodiversity in the broadest sense of the Rio Convention cannot be totally measured and, even for agroecosystems, a single impact category that reflects impacts on a wide range of organisms due to farming operations is not likely to be devised[30,67]. For this reason, few studies on biodiversity impacts of agricultural production systems were available (Table 4). Of the four LCA studies that included BI of food products, two studies[47,52] focused on organic milk and rice production systems, respectively, and the two others reported on both organic and conventional milk production systems (Tables 2, 4).

Of the 13 LCA studies that reported WU (Table 5), 85 % were related to comparative studies mainly on plant products (73%) and 15% were just on plant-based organic food (Table 2).

Of the 35 comparative LCA studies that reported ENU, the highest number of analyses for energy use was for grain and cereals (33%) (Table 2). LU in reviewed studies was not giving information on soil quality aspects and similar to ENU, was more frequent in comparative studies (33%) than in studies on organic products (20%) (Table 2).

Evaluation of LCA studies

Supplementary Table 1 and 2 of Supplementary Information show an overview of the reported environmental impacts of organic food from cradle-to-farm gate per mass and area-unit, respectively, extracted from both LCA studies on organic food and comparative LCA studies (See Supplementary Information for detailed results on the comparison of environmental impacts among organic food per mass and area units). Figures 3 and 4 show an overview of the observed variation of food environmental profiles per mass and area units from cradle-to-farm gate and their associated response ratio, respectively, in different agricultural systems extracted from only comparative LCA studies as well as the data per unit area calculated based on the values per mass unit and yield per hectare. As most LCA studies have been conducted with a strong focus on GWP considering mass-based functional unit, a more detailed comparison of the carbon footprints of organic and conventional food in kg of product is presented in Fig. 5.

Environmental impacts of organic and conventional production systems

Global warming potential (GWP) per mass unit. Cattle and lamb showed the highest average GWP for both production systems, followed by pig, eggs, nuts, seafood, chicken, milk, grain and cereals, fruits, and vegetables (Figs. 3, 5a, b). When assessing per produced mass unit, organic and conventional did not significantly differ in their GWP$(p = 0.0924\,, n = 125)$. The median response ratio for GWP was −0.057 (Fig. 4a) indicating that organic products on average had 6% lower GWP per mass unit than conventional. The median response ratio was also close to 0 for the different food categories (Fig. 4b), except for nuts that had higher impacts for organic and

Table 2 | Number of LCA studies, study regions, publication years, considered products, system boundaries, functional units and impact categories

Selected papers																		
Selection criteria		**Considered aspects for review**			**Number of studies**		**Number of studies for the considered product categories[a]**											
							Animal product							**Plant product**				
					Performed for the country	**Performed for other countries**	**Milk**	**Pig**	**Cattle**	**Lamb**	**Sea food**	**Chicken**	**Eggs**	**Vegetables**	**Grains and cereals**	**Fruits**	**Nuts**	**Aromatic beverages**
Studied agri-cultural system	Organic	Study region	Asia		3	3	–	–	–	–	–	–	–	–	2	–	–	1
			America	North	4	5	1	–	–	–	–	–	–	1	–	2	–	–
				South	3	3	–	–	–	–	–	–	–	–	3	–	–	–
			Europe	North	6	7	4	1	–	–	–	–	–	1	–	1	–	–
				South[b]	9	8	2	1	2	1	–	–	–	1	4	2	1	–
			Oceania		–	–	–	–	–	–	–	–	–	–	–	–	–	–
		Publication year	2000–2006		2		2	–	–	–	–	–	–	–	–	–	–	–
			2007–2013		5		2	1	–	–	–	–	–	–	–	4	–	–
			2014–2020		18		3	1	2	1	–	–	–	3	9	1	1	1
		System boundary	Cradle-to-farm gate		16		6	2	1	1	–	–	–	2	5	2	1	–
			Cradle-to-post-farm gate[c]		9		1	–	1	–	–	–	–	1	4	2	–	1
		Functional unit	Mass-based		17		4	1	1	–	–	–	–	2	6	4	–	1
			Area-based		-		–	–	–	–	–	–	–	––	–	–	–	–
			Both mass- and area based		6		3	1	1	1	–	–	–	1	1	–	1	–
			Nutritional values (Protein)		2		–	–	–	–	–	–	–	–	2	–		–
		Impact category	Acidification		11		3	1	1	–	–	–	–	2	5	4	–	–
			Biodiversity		2		1	–	–	–	–	–	–	–	1	–	–	–
			Global warming potential	SCS[d]	2		1	2	1	1	–	–	–	–	–	–	–	–
				No SCS	23		6	–	1	–	–	–	–	3	9	4	1	1
			Eco-toxicity	TE[e]	6		–	–	–	–	–	–	–	2	4	4	–	–
				UOP[f]	1		1	–	–	–	–	–	–	–	–	–	––	–
			Energy use		8		4	–	–	–	–	–	–	2	1	1	–	1
			Eutrophication[g]		12		3	1	1	–	–	–	–	1	4	4	–	–
			Land use		5		3	1	–	–	–	–	–	–	1	–	–	–
			Water use		2		–	–	–	–	–	–	–	2	2	2	–	–
	Organic & conventional	Study region	Asia		7	8	–	–	1	–	–	–	–	2	2	2	–	–
			America	North	6	6	–	–	–	–	–	–	1	2	2	2	1	–
				South	2	2	–	–	–	–	–	–	–	–	–	2	––	–
			Europe	North	33	34	16	1	5	1	2	3	4	6	13	2	–	–
				South	26	27	3	2	2	–	–	1	–	3	3	13	–	–
			Oceania		1	1	–	–	–	–	–	–	–	–	–	1	–	–
		Publication year	2000–2006		10		7	2	2	1	–	1	1	1	3	–	–	–
			2007–2013		28		6	–	2	–	–	2	2	6	9	7	1	–
			2014–2020		37		5	1	3	–	2	–	1	6	6	15	–	–
		System boundary	Cradle-to-farm gate		60		17	3	6	1	2	3	3	9	15	17	1	–
			Cradle-to-post-farm gate		15		–	–	–	–	–	–	1	4	4	6	–	–
		Functional unit	Mass-based		49		10	1	6	1	2	3	4	9	13	15	1	–
			Area-based		3		–	–	–	–	–	–	–	–	–	3	–	–
			Both mass- and area based		23		7	2	1	–	–	–	–	4	6	3	–	–
		Impact category	Acidification		39		8	3	3	1	2	3	4	6	12	11	–	–
			Biodiversity		2		2	–	–	–	–	–	–	–	–	–	–	–
			Global warming potential	SCS	6		1–		–	–	–	–	–	3	5	5	2	–
				No SCS	67		15	3	7	1	2	3	4	10	13	14	–	–

Table 2 (continued) | Number of LCA studies, study regions, publication years, considered products, system boundaries, functional units and impact categories

Selected papers																
Selection criteria	Considered aspects for review		Number of studies		Number of studies for the considered product categories[a]											
					Animal product							Plant product				
			Performed for the country	Performed for other countries	Milk	Pig	Cattle	Lamb	Sea food	Chicken	Eggs	Vegetables	Grains and cereals	Fruits	Nuts	Aromatic beverages
	Eco-toxicity	TE	20		2	1	–	–	1	–	–	2	4	10	–	–
		UOP	5		3	1	1	1	–	2	1	3	3	–	––	–
	Energy use		35		8	3	1	1	–	2	5	6	13	–	–	–
	Eutrophication		41		10	3	3	1	1	3	3	4	9	12	–	–
	Land use		25		7	3	1	1	–	2	3	3	9	4	––	–
	Water use		11		–	–	–	–	–	1	2	2	3	3	–	–

[a] Number of studies does not necessarily match sum of the numbers related to the food categories, for some of the studies considered more than one food category.

[b] Southern Europe includes Spain, Italy, France, Greece and Portugal.

[c] Cradle-to-post-farm gate for system boundary in the review includes cradle-to-grave, cradle-to-market, cradle-to-retail gate and cradle-to-factory gate.

[d] Soil carbon sequestration was considered for assessment of GWP.

[e] Toxic effects of pesticide use were reported.

[f] Use of pesticide (active substances) was reported.

[g] One type or different types of eutrophication including freshwater, marine, terrestrial and not specified (single value) were reported.

seafood and lamb that had lower impacts. This was however based on very few studies ($n = 2$ for nuts, $n = 2$ for seafood, $n = 1$ for lamb) (Fig. 3).

Global warming potential (GWP) per area unit. Dairy production systems had the highest GWP per area unit for both production systems (Fig. 3). A significant difference between organic and conventional systems was observed for GWP per area unit $\left(p = 0.0002\,, n = 59\right)$ and the median response ratio for GWP was −0.22 (Fig. 4g), i.e. 22% lower impact of organic products per area unit. However, some studies on grain and cereals[68,69], fruits[70,71] and nuts[42] showed lower GWP per ha for conventional systems than organic (24% of the studies) (Figs. 3 and 4h).

Acidification potential (AP) per mass unit. Based on Fig. 3, animal products (except milk) had higher AP for both production systems compared to plant products. The median response ratio for AP was zero and the difference between organic and conventional was not significant $\left(p = 0.7344\,, n = 52\right)$ (Fig. 4a). There were differences in the median response ratios between food categories (Fig. 4c). Most studies on organic milk (86%), pig (67%), chicken (60%), grain and cereals (67%) showed lower AP whilst more studies on organic eggs (100%) and vegetables (60%) had higher AP than conventional (Fig. 4c). Manure had the greatest impact on the AP of both chicken[66] and eggs production[72] because of NH_3 emissions[73]. A study on seafood reported a larger impact of conventional shrimp than organic[50], while a study on lamb showed larger AP of organic[64].

Acidification potential (AP) per area unit. The difference between organic and conventional systems for AP per area unit was not significant $\left(p = 0.1243\,, n = 23\right)$ (Fig. 4g). Nevertheless, the median response ratio was −0.38 (Fig. 4g). The exceptions were some studies on grain and cereals[68,69,74] and on fruits[34,54] that showed lower AP per ha for conventional than organic (26% of the studies) (Fig. 4i). The higher AP for organic systems could be explained by model emission factors for NH_3 volatilization, which are higher for organic N fertilizers than for mineral N fertilizers[75].

Eutrophication potential (EP) per mass unit. Similar to AP, cattle and lamb had the highest EP per mass unit followed by eggs, chicken, pig, grain and cereals, vegetables, milk and fruits (Fig. 3). No significant difference between organic and conventional systems was observed for EP $\left(p = 0.2151\,, n = 51\right)$, the median response ratio for EP was 0.038 (Fig. 4a). However, 49% of the studies showed lower EP for organic food compared to conventional (Fig. 4a). Larger EP for organic products as compared to conventional system was mainly due to lower yields of both animal and plant products. Most organic milk (82%), pig (67%) and fruits (80%) had lower EP than conventional, whereas organic chicken (80%), eggs (100%), grain and cereals (56%) and vegetables (100%) had higher EP than conventional (Fig. 4d).

Eutrophication potential (EP) per area unit. The highest EP per unit area for both production systems was found in fruit, milk, and pig (Fig. 3). The difference between organic and conventional was significant $\left(p = 0.0091\,, n = 24\right)$ and the median response ratio for EP was −0.47 (Fig. 4g) showing 47% lower EP in organic systems. However, 21% of the studies, including studies on grain and cereals[68,69,74] had higher EP for organic than conventional (Fig. 4j). Similar to AP, higher EP for organic systems can be due to higher emission factors for NH_3 volatilization of organic N fertilizers compared to mineral N fertilizers. These factors affect NH_3 and NO_x emissions and indirect N_2O emissions, contributing to AP, EP and GWP.

Energy use (ENU) per mass unit. Figure 3 shows ENU per mass unit with the highest average for cattle, lamb and egg followed by pig, chicken, fruits, milk, grain and cereals, and vegetables. Significant differences between organic and conventional products were not found for ENU $\left(p = 0.1008\,, n = 63\right)$. Although the variation of ENU was important (from 62% lower to 38% higher ENU in organic products), the median ENU showed 13% lower ENU per mass unit in organic than conventional products (Fig. 4a). Larger ENU in conventional products can be caused by the large amount of energy required for production (and transport) of mineral fertilizers[17]. Most organic milk (89%), cattle and lamb (100%), and grain and cereals (94%) had lower ENU than conventional, whereas organic pig (67%), chicken (100%), eggs (50%), vegetables (67%) and fruits (63%) had higher ENU than conventional (Fig. 4e).

Energy use (ENU) per area unit. Figure 3 shows a higher average ENU per unit area for fruits and vegetables followed by pig, grain and cereals, and milk. Organic and conventional products differed significantly for ENU per area $\left(p < 0.0001\,, n = 17\right)$. The median response ratio for ENU was −0.32 (Fig. 4g), showing 32% lower ENU per area unit in organic than conventional products.

Land use (LU) per mass unit. Animal products (except milk) had higher LU per kg for both production systems than plant products (Fig. 3). Production

Table 3 | LCA studies that included eco-toxicity potential an impact category in their analysis

Study	Food product	System boundary	Eco-toxicity						
			Unit	Freshwater		Marine water		Terrestrial	
				Org.[a]	Con.[b]	Org.	Con.	Org.	Con.
33	Grape	Cradle -to-farm gate including orchard disposal	**kg 1.4-DB eq./ha**	494.44	264.5	543.9	274.8	6.83	6.50
		Cradle -to-farm gate including orchard disposal	**kg 1.4-DB eq./ha**	482.8	295.6	532.1	308	6.58	7.20
34		Cradle -to-farm gate	**CTUe/ha**	91800	941000	–	–	–	–
	Clementine	Cradle -to-farm gate	**CTUe/ha**	2540	339000	–	–	–	–
36	White rice	Cradle -to-factory gate	kg 1.4-DB eq. /kg protein	0.226	–	0.894	–	0.00039	–
	Brown rice	Cradle -to-factory gate	kg 1.4-DB eq./kg protein	0.236	–	0.917	–	0.00062	–
44	Milk	Cradle -to-farm gate	CTUe/kg	0.01	0.84	–	–	–	–
		Cradle -to-farm gate	CTUe/kg	0.03	1.1	–	–	–	–
		Cradle -to-farm gate	CTUe/kg	0.02	0.88	–	–	–	–
49	Grape	Cradle -to-farm gate	CTUe/kg	0.319	32.9	–	–	–	–
		Cradle -to-farm gate	CTUe/kg	0.309	15.7	–	–	–	–
51	Melon	Cradle -to-farm gate	CTUe/kg	2	5	–	–	–	–
52	Rice	Cradle -to-farm gate	kg 1.4-DB eq./kg	0.0006	–	–	–	0.0796	–
		Cradle -to-farm gate	kg 1.4-DB eq./kg	0.0003	–	–	–	0.0658	–
55	Wheat bread	Cradle -to-consumer gate	kg 1.4-DB eq./kg	0.157	0.143	–	–	–	–
56	Rice	Cradle -to-farm gate	CTUe/kg	0.899	–	–	–	–	–
57	Apple	Cradle -to-retail gate	CTUe/kg	2.89	3.07	–	–	–	–
58	Carp fish	Cradle -to-farm gate	CTUe/kg	23	19	–	–	–	–
59	Pig	Cradle -to-farm gate	kg 1.4-DB eq./kg	–	–	–	–	0.0304	0.0184
			kg 1.4-DB eq./ha	–	–	–	–	30.8	30.4
60	Milk	Cradle -to-farm gate	kg 1.4-DB eq./kg	–	–	–	–	0.75	1.83
			kg 1.4-DB eq./ha	–	–	–	–	3.50	11.18
69	Beans	Cradle -to-farm gate	kg 1.4-DB eq./kg	0.00026	−0.00001	47.4	48.4	0.00014	0.00015
			kg 1.4-DB eq./kg	−0.0007	−0.0001	44	40	0.00014	0.00013
			kg 1.4-DB eq./ha	−0.0002	−0.349	138000	108000	0.431	0.346
			kg 1.4-DB eq./ha	−0.265	−0.142	72000	557000	0.223	0.178
70	Apple	Cradle -to-farm gate	kg 1.4-DB eq./kg	0.018	0.01	–	–	0.001	0.002
		Cradle -to-farm gate	kg 1.4-DB eq./kg	0.006	0.005	–	–	0.000	0.002
		Cradle -to-farm gate	kg 1.4-DB eq./kg	0.010	0.009	–	–	0.000	0.002
71	Olive	Cradle -to-farm gate	**kg 1.4-DB eq./ha**	–	–	9360000	9340000	–	–
74	Wheat	Cradle -to-farm gate	CTUe/kg	4	7	–	–	–	–
			CTUe/ha	18600	59400	–	–	–	–
77	Olive	Cradle -to-farm gate	CTUe/kg	1.1	0.8	–	–	–	–
		Cradle -to-farm gate	CTUe/kg	1.5	1.86	–	–	–	–
		Cradle -to-oil mill gate	CTUe/kg	1.75	2.14	–	–	–	–
78	Tomato	Cradle -to-farm gate including distribution	kg 1.4-DB eq./kg	–	–	–	–	0.0103	0.0073
79	Rice	Cradle -to-farm gate	kg 1.4-DB eq./kg	0.0067	0.3434	–	–	0.0066	0.0073
		Cradle -to-farm gate	kg 1.4-DB eq./kg	0.006	0.3434	–	–	0.0076	0.0073
		Cradle -to-farm gate	kg 1.4-DB eq./kg	0.0055	0.3434	–	–	0.0081	0.0073
113	Leek	Cradle -to-farm gate	kg 1.4-DB eq./kg	–	–	–	–	0.00004	0.007
121	Blueberries	Cradle -to-consumer gate	kg 1.4-DB eq./kg	0.066	–	1.52	–	0.42	–
		Cradle -to-consumer gate	kg 1.4-DB eq./kg	13.65	–	2.38	–	0.49	–
		Cradle -to-consumer gate	kg 1.4-DB eq./kg	13.59	–	1.94	–	0.49	–
143	Grape	Cradle -to-farm gate	kg 1.4-DB eq./kg	0.0499	–	–	–	0.0042	–
		Cradle -to-grave	kg 1.4-DB eq./kg	0.1228	–	–	–	0.0073	–
145	Citrus	Cradle -to-farm gate	CTUe/kg	0.015	12.8	–	–	–	–
		Cradle -to-farm gate	**CTUe/ha**	163	394000	–	–	-	–
147	Strawberry	Cradle -to-farm gate	CTUe/kg	5.02	5.66	–	–	–	–
			CTUe/ha	157000	313000	–	–	–	–
153	Tomato	Cradle -to-farm gate	kg 1.4-DB eq./kg	0.0425	–	33.56	–	0.00086	–
	Chicory	Cradle -to-farm gate	kg 1.4-DB eq./kg	0.0710	–	123.29	–	0.00116	–

Table 3 (continued) | LCA studies that included eco-toxicity potential an impact category in their analysis

Study	Food product	System boundary	Eco-toxicity						
			Unit	Freshwater		Marine water		Terrestrial	
				Org.[a]	Con.[b]	Org.	Con.	Org.	Con.
	Wheat	Cradle -to-farm gate	kg 1.4-DB eq./kg	0.0290	–	68.46	–	0.00098	–
	Apple	Cradle -to-farm gate	kg 1.4-DB eq./kg	0.166	–	86.53	–	0.00337	–
	Pear	Cradle -to-farm gate	kg 1.4-DB eq./kg	0.0860	–	58.05	–	0.001	–

The bold values represent eco-toxicity potential measured based on area unit (ha).
[a]Org.: organic.
[b]Con.: conventional.

Table 4 | LCA studies that included biodiversity as an impact category in their analysis

Study	Food product	Method of analysis	Biodiversity impacts		Unit /or estimation index/ or score
			Org. [(a)]	Con. [(b)]	
44	Milk	Applying characterization factors suggested by a study[93], plant species were used as a proxy for biodiversity and impacts on biodiversity were quantified as the potential reduction in biodiversity compared to natural conditions of both organic and conventional farms in threes systems of grass based, mountainous and mixed. The biodiversity damage potential was calculated as the land use per kg milk.	Mixed systems in Denmark: 0.16	0.48	Unit: PDF[(c)] per kg FPCM[(d)]
			Grass based systems in UK: −0.2	0.37	
			Mountainous systems in Austria: −0.12	0.26	
47	Milk	Using biodiversity damage scores as proposed by a study[164] impact on biodiversity provided an estimation of biodiversity losses caused by the different land uses to produce 1 kg of milk.	Danish organic farm with 168 cows and 225.5 ha of crop area: 0.25	–	Unit: DS[(e)] per kg ECM[(f)]
			Danish organic farm with 122 cows and 162.5 ha of crop area: 0.27	–	
81	Milk	Impacts on biodiversity, landscape image and animal husbandry were qualitatively estimated based on self-defined criteria considering indicators number of grassland species, grazing cattle, layout of farmstead and herd management. These were determined on a per area unit and the scientific basis for them were derived from methods by a study for biodiversity[165] and by two studies for animal welfare[166,167].	2.4	3.7	Estimation index per whole farm area: 1: very good 3:average 5: unsatisfactory
137	Rice	To estimate the impacts on biodiversity, both flora and fauna species and their associated environmental impacts were listed and the effects of rice farming and their effects on the species were assessed based on the local assessors. Finally using the LCIA- method “SALCA-BD” (30, 2014), a scoring system estimated the reaction of every indicator species group regarding management options.	Phytoplankton (per litre): 23.63	–	SALCA- biodiversity score (30, 2014)
			Zooplankton (per litre): 14.18	–	
			Benthos (per 256 cm^2): 16.36	–	
			Invertebrates with plants: 12.31	–	
			Fish (per 100 m^2): 13.81	–	

[a]Org.: organic.
[b]Con.: conventional.
[c]PDF: potentially disappeared fraction.
[d]FPCM: fat and protein corrected milk.
[e]DS: damage score.
[f]ECM.: energy corrected milk.

of 1 kg of meat from cattle in both production systems required more land (m^2) than the production of 1 kg of meat from lamb, pig or chicken (two, four- and six times more, respectively). Organic and conventional products differed significantly $\left(p < 0.0001\ , n = 46\right)$, organic products required 64% more land than conventional products (Fig. 4a) mainly due to lower yields[17,76] Organic milk, meat of pig, cattle, lamb, and chicken, eggs, vegetables, grain and cereals and fruits had 51%, 73%, 83%, 126%, 195%, 80%, 86%, 48% and 108% more LU respectively, than conventional (Fig. 4f).

Eco-toxicity potential (ETP). Table 3 generally shows lower ETP for organic products than conventional, mainly due to the application of synthetic pesticides in conventional systems. However exceptions were studies on organic fish[58], pig[59], olive[71,77] apple[70], grape[33], tomato[78], bean[69], rice[79] and wheat bread[55]. Higher toxicity impacts in some studies can stem from lower yields in organic farming and the use of copper sulfate, that have high characterization factors in some impact assessment methods[80].

Biodiversity impacts (BI). The BI comparing organic and conventional products via LCA were considered in only three studies on milk production (Table 4). A study[81] found positive impacts of organic farming in the indicators number of grassland species, grazing cattle, layout of the farm and herd management, but indices in these categories showed a wide range and were partly independent of the farming system. In agreement with that, a biodiversity assessment by a study[44] showed that on average the biodiversity loss from organic milk were 33% of the conventional. Furthermore, a study[47] compared BI of organic and conventional milk for twelve farms in Denmark, Italy and Germany and showed lowest impact on biodiversity loss for the organic milk, due to the higher share of grassland in their system.

Water use (WU). Table 5 generally shows lower WU for organic products than conventional with the exceptions of organic chicken[66] and olive[77]. Further, a study[82] showed equal amount of water use for both systems.

Discussion and conclusions

Geographical coverage of organic LCA studies

The present review showed that LCA studies are not available for all organic food products from all world regions. Most LCA studies (74%) are based on European production, indicating the need for studies in Africa, South

Table 5 | LCA studies that included water use as an impact category in their analysis

Study	Food product	System boundary	Type of system	Unit	Water use	
					Organic	Conventional
33	Grape	Cradle -to-farm gate	Spalier system	**m^3/ha**	9401.29	9711.84
	Grape	Cradle -to-farm gate	Gobelet system	**m^3/ha**	8945.19	10686.68
51	Melon	Cradle- to -distribution	-	l/kg	156.49	268.91
66	Chicken	Cradle -to-farm gate	Conventional standard indoor	l/kg	**7.03**	4.41
			Conventional free range	l/kg	**7.03**	6.86
72	Eggs	Cradle -to-farm gate	Conventional cage	l/kg	5.6	5.11
			Conventional barn	l/kg	5.6	5.23
			Conventional free range	l/kg	5.6	5.35
74	Wheat	Cradle -to-farm gate	–	l/kg	0.149	0.861
				m^3/ha	0.672	7.36
77	Olive	Cradle -to-farm gate	–	l/kg	6.133	5.114
79	Rice	Cradle -to-farm gate	Organic after 5 years	l/kg	1737	5139
		Cradle -to-farm gate	Organic after 10 years	l/kg	1533	5139
		Cradle -to-farm gate	Organic after 15 years	l/kg	1494	5139
82	Paddy rice	Cradle -to-farm gate	–	l/kg	3846	3846
116	Tomato	Cradle -to-farm gate	–	**m^3/ha**	8128	9144
127	Lettuce	Cradle -to-farm gate	–	**m^3/ha**	2000	2500
137	Rice	Cradle -to-farm gate	–	l/kg	1340	–
141	Eggs	Cradle -to-consumer gate	Conventional cage	l/kg	13.2	16.5
			Conventional enriched cage	l/kg	13.2	16.6
			Conventional Free run	l/kg	13.2	18.5
			Conventional Free range	l/kg	13.2	17.8
153	Tomato	Cradle -to-farm gate	–	l/kg	180	–
	Apple	Cradle -to-farm gate	–	l/kg	253	–
	Pear	Cradle -to-farm gate–		l/kg	463	–
	Wheat	Cradle -to-farm gate	–	l/kg	345	–
	Chicory	Cradle -to-farm gate	–	l/kg	1109	–

The bold values represent water use measured based on area unit (ha).

America, Oceania, and Asia where the production conditions are different and organic production is increasing[83]. Furthermore, organic LCA studies have focused primarily on milk, cereals/grains (in Northern Europe) and fruit (in Southern Europe), showing the lack of studies on environmental impacts of other food categories such as e.g. nuts, seafood, chicken, and vegetables that might be a major part of future diets[2]. Therefore, with introduction of new dietary choices, there is a need for more studies on LCA of organic foods both in developed and developing countries that would provide further insight and a clearer overview of the environmental profile of organic foods compared to other food systems globally.

Environmental impacts of food products

The environmental impacts of our food system are considerably affected by our dietary choices[7,14,17,18,22]. In general, meat from ruminants (e.g. cattle and lamb) had the highest impacts per mass unit and other livestock products (e.g. pig, eggs, chicken, seafood, and milk) had intermediate impacts that were higher than those of most plant products (Fig. 3 and Supplementary Table 2). It should be noted that impacts shown in Fig. 3 and Supplementary Table 2 only include GWP, EP, AP, LU and ENU and not e.g. BI and ETP. A study[84] showed that, in conventional systems, chicken and pork have larger freshwater ecotoxicity impacts than beef and milk. The present study further showed that organic products generally had lower impacts per unit area compared to conventional products mainly due to lower emissions associated with the inputs used.

The differences between the organic and conventional production systems are mainly based on differences in regulations, where nutrient inputs to organic agriculture are mainly from nitrogen fixation and manure, and conventional agriculture largely depend on synthetic fertilizers and pesticides. However, in both organic and conventional production systems, there may also be differences due to differences in local conditions, intensity levels, type of fertilizer, weed and pest management practices, use of catch crops etc. The trade-off between inputs and yields resulted in almost similar GWP per mass product unit from organic and conventional systems. Manure application[85,86] and more diversified crop rotation, often including temporary grassland (ley)[87] have the potential to increase soil organic carbon in organic systems showing potential to lower GWP. However, the higher SOC and the lower GWP may be compensated by lower yield in organic systems[76]. It should be noted that the allocation of emissions caused by the application of manure remains as a general allocation challenge in the LCA of agricultural systems, which has been handled using different approaches. In some cases, all emissions and positive effects (e.g. SOC changes) are allocated to livestock, and in other cases only emissions from stables and storage are allocated to livestock and emissions from application to plant production.

The ENU per area unit in organic system was lower compared to the conventional system mainly due to lower dependency on energy intensive production of synthetic fertilizer and pesticides. The ETP of organic systems generally showed lower impact compared to conventional

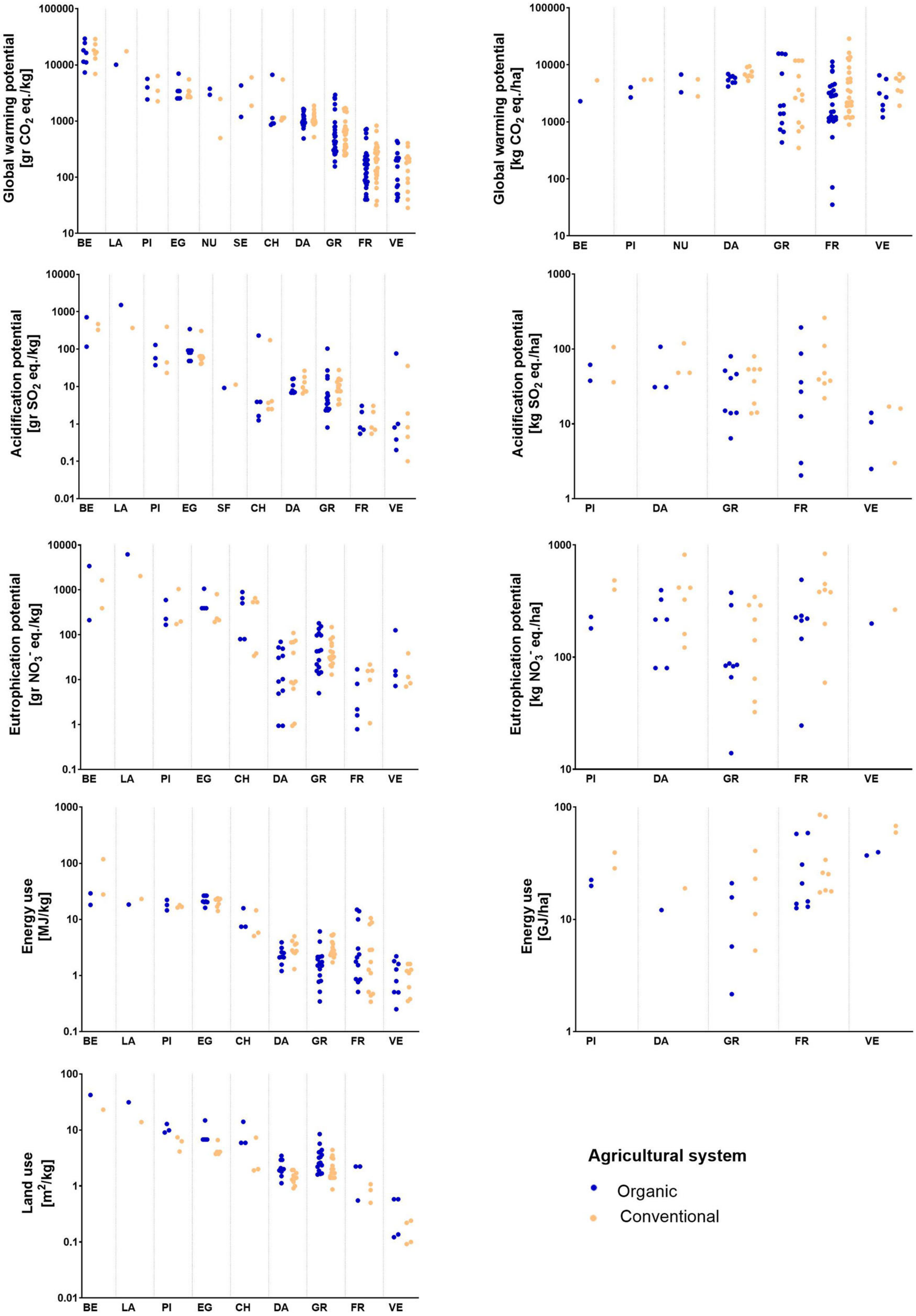

Fig. 3 | Comparison of cradle-to-farm gate impacts of organic and conventional agricultural products. Comparison of cradle-to-farm gate impacts of agricultural products from organic and conventional systems, measured both per mass (kg) and per area (ha) units. The impact categories include GWP: global warming potential, AP: acidification potential, EP: eutrophication potential, ENU: energy use, and LU: land use. Food categories are BE: cattle meat (beef), LA: lamb, PI: pig, EG: eggs, CH: chicken, SE: seafood, DA: milk, GR: grain and cereals, VE: vegetables, FR: fruits, NU: nuts. The results of studies in each plot are sorted by the average of the organic food impacts. The environmental impact of beef, lamb, pig and chicken are not separated for live and carcass weight, for the aim here is a presentation of the differences between environmental impact of organic and conventional systems. A base-10 log scale is used for the *Y*-axis of all the graphs.

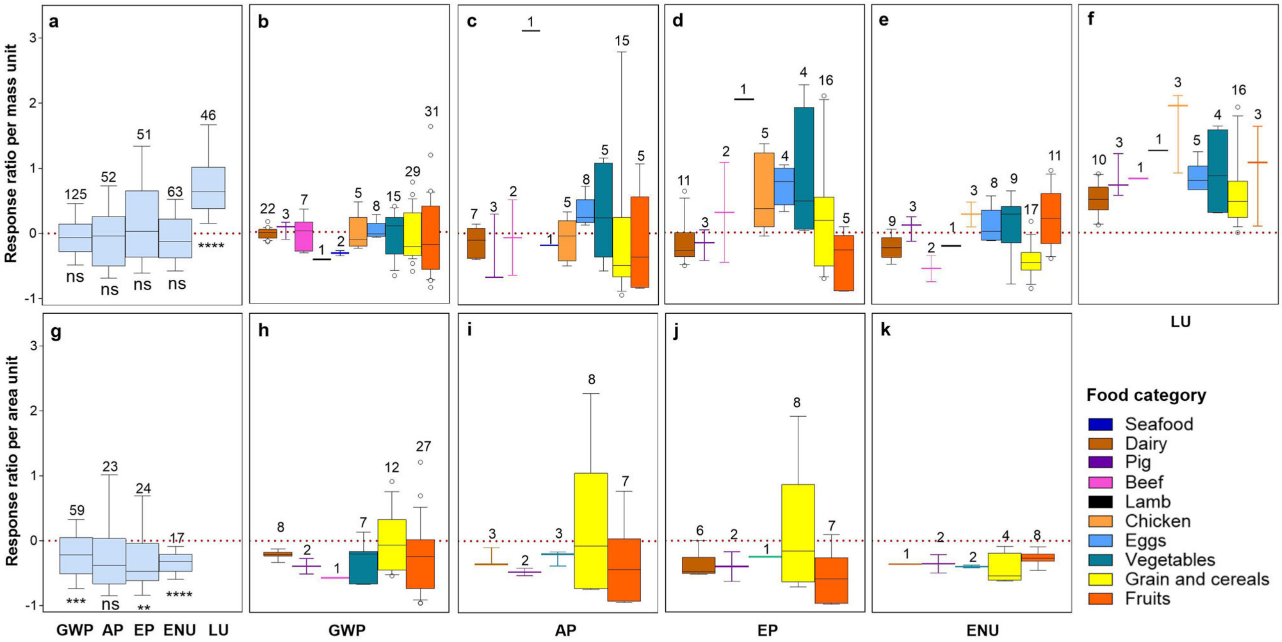

Fig. 4 | Response ratios for impacts of organic and conventional products. Response ratios for impacts of organic and conventional products expressed per mass (**a**: for GWP, AP, EP, ENU and LU, **b**: GWP, **c**: AP, **d**: EP, **e**: ENU, **f**: LU) and area (**g**: for GWP, AP, EP, ENU and LU, **h**: GWP, **i**: AP, **j**: EP, **k**: ENU) units. Impact categories are GWP: global warming potential, AP: acidification potential, EP: eutrophication potential, ENU: energy use, LU: land use. Response ratios for nuts (two values) are not shown in B and H sections of this figure. Box plot boundaries represent 25 and 75 percentiles, thick line within the box represents the median and whiskers represent 10 and 90 percentiles. Dashed line represents the zero-response ratio where the impacts of organic and conventional products are the same. Positive values indicate higher impacts from organic products and negative values indicate lower impacts from organic products. Numbers within each plot show the number of cases for each impact category or product category. ns= not significantly different from zero (Wilcoxon Signed Rank Test $P > 0.05$), $^{**}P < 0.01$, $^{***}P < 0.001$, $^{****}P < 0.0001$.

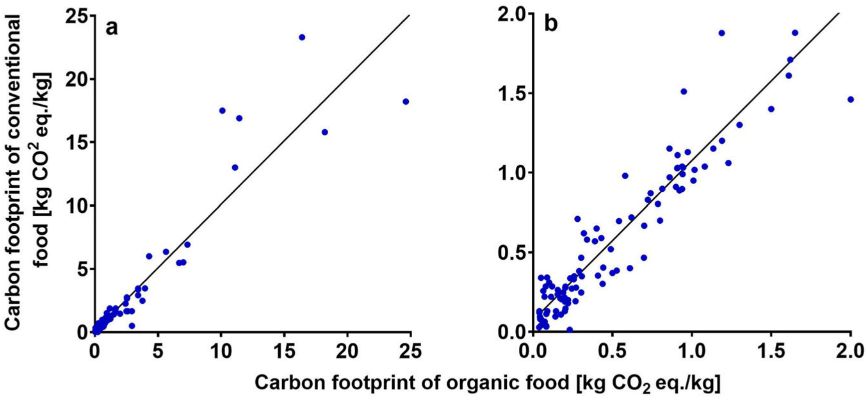

Fig. 5 | Carbon footprint comparison of organic and conventional foods. Carbon footprint for organic and conventional food (kg CO_2 equivalent per kg) based on comparative studies of the same product. (**a**) includes data for all food items, i.e., ranging from plant-based foods like fruits and vegetables at the low end of the scale to animal foods such as pork and beef at the high end. (**b**) zoomed in on the lower end of the scale on plant-based food products and milk. The black line marks where the carbon footprint of organic and conventional foods is the same. Points below the line indicate a larger carbon footprint for organic food compared to conventional, while points above the line indicate a higher carbon footprint for conventional food compared to organic.

systems especially when measured per hectare due to lower pesticide inputs and alternative pest and disease measures, but there were also exceptions dependent on the differences in the management of the organic and conventional system and the functional unit (ha or kg). The BI of the organic systems was lower than that of the conventional systems, which is in accordance with other studies[88–90], but the number of studies was still low. Larger LU for organic systems may result in more natural habitat conversion that increases biodiversity loss and decreases carbon stocks[7], but other indirect and rebound effects in the organic food consumption patterns might go in the other direction as discussed in a study[11].

Environmental impacts captured by LCA and the need for improvement

LCA has become an established and important tool for assessing environmental sustainability in food and farming systems. It can help to improve production systems, provide a basis for political decision making, deliver consumer information and compare agricultural production systems. In LCA of agricultural systems, environmental impacts are assessed by considering a set of indicators and referenced to agricultural product as the functional unit (mass, area, nutrition value, energy). This reference to food products is an expression of the environmental impact resulting from the production of a certain amount of food product and can be seen as a measure of eco-efficiency[91], where the aim is to identify which system can provide the same amount of food product with the lowest environmental impacts. However, LCA faces some challenges when assessing multi-functional agricultural systems such as organic agriculture, where more research is needed. LCA is focused on the supply of products (e.g. crops and animals) by the agricultural system[11]. In addition, more research is still needed to model potential biodiversity loss, pesticide effects and changes in soil organic carbon in LCA. For this reason, although the use of pesticides affects both toxicity and biodiversity impacts, BI and ETP of food systems were rarely considered in LCA of food products. In this review, only 3% and 21% of LCA studies comparing conventional and organic agriculture considered biodiversity and eco-toxicity impacts, respectively. In a meta-analysis study[88] showed 30% higher species richness for organic systems compared to conventional systems. The approach to include biodiversity in LCA suggested by a study[92] as recommended by the EU PEF is not suited for comparing impacts on biodiversity of the different systems, as it can only be used for identifying the hotspots within the product systems[11]. Although a study[93] provides characterization factors to differentiate impacts of organic and conventional agriculture on biodiversity, there is still room for improvement of the LCA method to consider the effect of different land management practices on biodiversity in both agricultural systems[11]. Assessment of eco-toxicity impacts of agricultural systems is also limited by both lack of data[14] and the need for several decades of use of a given pesticide to fully understand its health and toxic effects[94].

LCA studies on food products to target reduction of negative environmental impacts need to adapt to local geographic and climatic conditions considering different scales. What might seem as an effective mitigation option at the global scale when assessed per kg, might not be an efficient mitigation option at the local scale when assessed per ha. Mass-based functional units work best for global impacts such as GWP, while for impacts that can have large local-scale impacts such as eutrophication, land-based functional units are important for the assessment. For this reason, it is important to use functional units based on both mass and area in LCA studies of agricultural systems. Furthermore, the effects at local scale might be affected by impacts at wider regional scale. Limited attention has been paid to spatially oriented assessments in relation to agri-food LCA studies[95–100]. There is therefore, still considerable scope for progressing in the explicit assessment of spatial variation in LCA using suitable and complementary models (e.g. both land scape and field scale models), databases and technologies such as geographic information systems[100,101].

The most widely considered impact on farm scale is GWP including estimations on GHG emissions from different farming activities. Most of the studies analyzing the environmental impact of food products have not included land use change (LUC) for estimation of GHG. Though, some studies on food products have included direct land use change (dLUC) in their analysis but with slightly different approaches. Whether dLUC is included or not as well as the method chosen to quantify LUC can lead to large variations in LUC factors, and thus highly influence the GWP results of different intensities of food production systems[11].

So far, soil carbon sequestration has been included in a few studies using different methodologies and time horizons. Land degradation, including processes such as erosion, compaction, salinization, and soil organic carbon loss is another neglected issue in LCA studies[11]. This is while land degradation is estimated to affect 90% of the soil globally by 2050[102]. A global indicator of the land degradation could be the percentage change in soil organic carbon[103].

Ignoring important impact categories such as biodiversity, eco-toxicological and soil quality impacts and water and resource use in comparative LCA studies is problematic since the overall conclusions will be strongly affected by this choice. There is a need for methodological development regarding biodiversity and toxicity assessment. Further in relation to WU, most of the studies focus on the assessment of off-stream consumptive use (i.e. the part of withdrawn water from a groundwater or surface-water source that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise not available for immediate use) of blue water while other types of water use are underrepresented[104]. In addition, since different watercourses perform different functions, more detailed inventories and impact pathways should be considered in assessing water use[105].

It is also needed to provide more data on organic food systems for LCA inventories, because lack of data might cause under- or overestimation of environmental impacts and challenges in thorough comparisons between organic and conventional systems[14].

Uncertainties in estimates of environmental impacts of agricultural systems and food products may arise from several sources, such as the way current agricultural systems are conceptualized in LCA models, the way environmental impacts are estimated or the setup of the models and input data. Within all these issues there are also multiple interactions that may contribute to uncertainties.

The current review shows that most LCA studies assess the environmental impacts per mass unit and not per area unit. Certainly, LCA results are highly sensitive towards the choice of the functional unit, as observed in this and other review studies comparing organic and conventional systems[14]. Better performance of organic farming per unit area (e.g. for biodiversity and eco-toxicity) is the main reason for policies favoring a transition to organic farming systems. However, organic agriculture is less productive than conventional agriculture, resulting in similar values per unit product for most environmental impacts. Thus, focusing only on impacts per unit of product may result in decisions in favor of conventional food production systems that may increase negative environmental impacts in the farming region[11]. Although nutritional quality of organic food may be better[7], expressing impacts of single organic and conventional food items per mass unit ignores food quality and the dietary patterns that they are part of. Therefore, the need to develop a more refined functional unit that represents the actual functions of foods is obvious. The use of nutrient-based functional units (e.g. unit protein) has been advocated by several authors[106,107]. The use of a protein-based functional unit may produce LCA results that more accurately reflect impacts of the actual function of foods than when mass is used as the functional unit. However, providing protein is not the only function of food, and the search for a perfect nutritional functional unit has been a key challenge for LCA of food[108]. Furthermore, it may significantly increase data requirements[107]. Assessing the environmental impacts at the diet level could link farm management decisions to diet-level environmental impacts considering an enhanced focus on human nutrition across the entire value chain[109]. Furthermore, including the entire diet could bridge the gap between diet-level and product-level and provide implementable action plans for both consumers and producers and at the same time take into account that organic consumers tend to lower their intake of animal-based food[110,111].

Data availability

All data on the impact categories for all food products considered in this study and their statistical distributions that support the findings of this study are included within this paper and its supplementary Information files. Additionally, the data associated with this study have been deposited in a publicly accessible repository with the following https://doi.org/10.5281/zenodo.11032394. This repository ensures that the data can be freely and enduringly accessed by readers.

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Author contributions

F.H. conceived and designed the study, developed the methodology and analytical procedures, performed the data collection and curation, result analysis, visualization, and writing—original draft. L.M., H.M.G.V., C.C. and M.T.K. contributed to the conception and design of the study. All authors contributed to editing and discussion of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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