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RESEARCH

Benefits of organic agriculture for environment and animal welfare in temperate climates

Jürn Sanders · Jan Brinkmann · Lucie Chmelikova · Florian Ebertseder · Annette Freibauer · Frank Gottwald · Almut Haub · Michael Hauschild · Johanna Hoppe · Kurt-Jürgen Hülsbergen · Rüdiger Jung · Daniel Kusche · Karin Levin · Solveig March · Knut Schmidtke · Karin Stein-Bachinger · Hanna Treu · Philipp Weckenbrock · Klaus Wiesinger · Andreas Gattinger · Jürgen Heß

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Abstract Although scientists have been researching the impacts of organic agriculture on the environment and animal welfare for decades, the conclusions drawn by the scientific community remain controversial. Against this background, this paper provides a comprehensive assessment of the benefits of organic farming in both areas by analysing results of all relevant scientific comparative studies between organic and conventional farming that have dealt with this topic over the last thirty years. So far, this study is the largest one of its kind and the first one that adds the aspect of animal welfare to a comprehensive array of impact categories. The systematic review of the scientific literature from pairwise comparisons found that organic management showed clear advantages over conventional management in the fields of environmental protection and resource conservation, which can be mainly explained by the system approach pursued in organic farming. No clear conclusion was drawn regarding animal welfare

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J. Sanders (✉)
Research Institute of Organic Agriculture (FiBL),
Ackerstrasse 112, CH-5070 Frick, Switzerland
e-mail: juern.sanders@fibl.org

J. Brinkmann · S. March
Thünen-Institute of Organic Farming, Federal Research
Institute for Rural Areas, Forestry and Fisheries,
Trenthorst 32, DE-23847 Westerau, Germany
e-mail: jan.brinkmann@thuenen.de

S. March
e-mail: solveig.march@thuenen.de

L. Chmelikova · K.-J. Hülsbergen
Professorship of Organic Agriculture and Agronomy,
Technical University of Munich, Technical University
of Munich (TUM), Liesel Beckmann Str. 2,
DE-85354 Freising, Germany
e-mail: lucie.chmelikova@mytum.de

K.-J. Hülsbergen
e-mail: kurt.juergen.huelsbergen@mytum.de

F. Ebertseder · A. Freibauer · K. Wiesinger
Bavarian State Research Center for Agriculture, Bavarian
State Research Center for Agriculture (LfL), Lange Point
12, DE-85354 Freising, Germany
e-mail: Florian.Ebertseder@lfl.bayern.de

A. Freibauer
e-mail: annette.freibauer@lfl.bayern.de

K. Wiesinger
e-mail: klaus.wiesinger@lfl.bayern.de

F. Gottwald · K. Stein-Bachinger
Leibnitz Centre for Agricultural Landscape Research
(ZALF), Brodowin Nature Conservation Farm,
Eberswalder Straße 84, DE-15374 Müncheberg, Germany
e-mail: gottwald@naturschutzhof.de

K. Stein-Bachinger
e-mail: kstein@zalf.de

indicating that farm-specific management factors are of greater importance than the production system (organic vs conventional). Consequently, organic farming may contribute to solving current environmental and resource challenges and is rightly considered a key approach for sustainable land use. The positive effects should be further strengthened by decreasing the yield gaps between organic and conventional farming, i.e. by improving yields based on organic principles as well as by altering their relevance through changes in consumption as feed for livestock and food for humans.

Keywords Organic farming · Comparative studies · Field trials · Public goods

Introduction

Organic agriculture is considered to be a holistic concept of land and livestock management that pays particular attention to nature's boundaries and processes (Regulation (EU) 2018/848). Instead of using synthetic pesticides or mineral nitrogen fertilizers, organic farmers apply a systemic approach targeted at maximizing nutrient recycling and resource efficiency, minimizing losses and prioritizing the use of on-farm and regional inputs and means of production (Freyer 2016; Bellon and Penvern 2014; Lockeretz 2007; Lampkin 1990). The impact of this systemic approach has been the subject of agricultural research since the early 1980s. Numerous studies have compared the effects of organic and conventional farming systems on the environment and on resource use. In most cases, these system comparisons focused on specific aspects such as the conservation of biodiversity (Azeez 2000; Stolze et al. 2000; Hole et al. 2005; Bengtsson et al. 2005; Mondelaers et al. 2009; Rahmann 2011; Tuck et al. 2014) or impacts on climate (Mondelaers et al. 2009; Gattinger et al. 2012; Aguilera et al. 2013; Skinner et al. 2014) or soil microbiota (Lori et al. 2017). To date, only few studies have compared organic and conventional farming systems comprehensively across multiple environmental impacts (Stolze et al. 2000; Pimentel et al. 2005; Tuomisto et al. 2012; Jespersen et al. 2017; Seufert and Ramankutty 2017, Meemken and Qaim 2018; Haller et al. 2020). Furthermore, very little effort has been made to compare animal welfare status between organic and conventional farming systems across all livestock species (Sundrum 2001; Hovi et al. 2003;

A. Haub
Leibnitz Centre for Agricultural Landscape Research,
Leibnitz Centre for Agricultural Landscape Research
(ZALF), Eberswalder Straße 84, DE-15374 Müncheberg,
Germany
e-mail: Almut.Haub@zalf.de

M. Hauschild · P. Weckenbrock · A. Gattinger
Professorship of Organic Farming, Justus-Liebig
University of Gießen, Justus-Liebig University of Gießen
(JLU), Karl-Glöckner-Str. 21C, DE-35394 Gießen,
Germany
e-mail: michael.hauschild@agrar.uni-giessen.de

P. Weckenbrock
e-mail: philipp.weckenbrock@agrar.uni-giessen.de

A. Gattinger
e-mail: Andreas.Gattinger@agrar.uni-giessen.de

J. Hoppe · D. Kusche · J. Heß
Section Organic Farming and Cropping Systems,
University of Kassel, Nordbahnhofstraße 1a,
DE-37213 Witzenhausen, Germany
e-mail: uk068612@uni-kassel.de

D. Kusche
e-mail: daniel.kusche@uni-kassel.de

J. Heß
e-mail: jh@uni-kassel.de

R. Jung
Department of Cropc Science, Georg August University
of Göttingen, Von-Siebold-Str. 8, DE-37075 Göttingen,
Germany
e-mail: rjung@uni-goettingen.de

K. Levin
Technical University of Munich (TUM), Liesel Beckmann
Str. 2, DE-85354 Freising, Germany
e-mail: karin.levin@tum.de

K. Schmidtke
Professorship of Organic Farming, Dresden University
of Applied Sciences (HTWD), Friedrich-List-Platz 1,
DE-01069 Dresden, Germany
e-mail: knut.schmidtke@htw-dresden.de

H. Treu
Thünen Institute of Farm Economics, Bundesallee 63,
DE-38116 Brunswick, Germany
e-mail: hanna.treu@thuenen.de

Lund and Algers 2003; van Wagenberg et al. 2017; Åkerfeldt et al. 2021).

Although scientists have been researching the societal benefits of organic agriculture for decades, it is remarkable that the conclusions drawn by the scientific community remain controversial (Debuschewitz and Sanders 2022). Three main positions can be distinguished: 1) As, for example, Stolze et al. (2000) concluded, a wide range of studies show that impacts of organic farming on the environment are less harmful than those from conventional farming. Furthermore, organic farming practices require fewer fossil resources and use them in a more sustainable way. 2) In contrast, some researchers argue that any environmental benefits of organic farming are offset by lower yields resulting in leakage effects and potentially even greater environmental problems elsewhere (e.g. Mondelaers et al. 2009; Tuomisto et al. 2012; Meemken and Qaim 2018). 3) Another group of researchers plead for a more differentiated assessment and pointed out to existing knowledge gaps, as well as trade-offs between organic principles and practises (e.g. Haller et al. 2020; Seufert and Ramankutty 2017; Jespersen et al. 2017).

In view of the existing environmental problems in agriculture, such as climate change and loss of biodiversity, the question of environmental impacts caused and public services provided by organic farming is of great importance to politics and society. Policymakers need to have well-founded and reliable information on whether supporting organic farming is an effective way to reduce the environmental impact of agriculture and to enhance animal welfare. Further, a substantial proportion of consumers buys organic products, because they like to support a sustainable form of agriculture through their purchases (Nagy et al. 2022). They are therefore interested in a high credibility of organic production. Against this background, this paper aims to assess the benefits of organic farming for environment and animal welfare by analysing quantitative results from all relevant scientific comparative studies between organic and conventional farming that have dealt with this topic over the last thirty years. This makes this work, to the best of our knowledge, the most comprehensive stocktaking of the public benefits of organic farming that has been carried out to date on the basis of pairwise comparisons.

Materials and methods

A detailed and comprehensive description of the data sources and the selection process of studies can be found in the supplement (S2).

Data sources

In accordance with the theory of public goods (Samuelson 1954; Musgrave 1969), in this paper a positive or less negative impact of agriculture is considered a public benefit, if it contributes to achieving public policy objectives that cannot be achieved to a sufficient extent through market incentives. Following this definition, six different areas with public services were selected and analysed: water protection, soil conservation, biodiversity enhancement, climate protection, resource-use efficiency as well as animal welfare. The selection reflects the predominant scope of previous research and current empirical knowledge.

To find studies comparing organic and conventional farming, a systematic literature search was conducted in the databases Web of Science, Scopus and Organic Eprints.[1] The database search was supplemented by a web-based search using the snowball (chain-referral) sampling method. The latter search focused in particular on reports from relevant scientific projects, conference papers and dissertations. The basic selection criteria for including studies in this review are:

- The study was carried out in a temperate climate zone according to the Köppen-Geiger classification: BSk, all C climate zones, Dfa, Dfb, Dwa, Dwb according to the updated Köppen map (Peel et al. 2007).
- The study contained at least one pairwise comparison of an organic (including biodynamic) and a conventional (including integrated) farming system.
- Organic production systems had been managed organically for at least two years prior to the start of data collection.
- The date of publication was between 1990 and 2018.

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[1] Other databases were also used for individual areas (see Supplement material S1).

- The publication was in English or German.

More details on the selection criteria are described in the supplements (S2, Table 1). In most cases, the studies involved field trials or on-farm research. In order to avoid pseudo-replication, if there were multiple publications from one research site, only the most recent or most complete dataset for each research location was included in the analysis. Based on the selected studies, several indicators were defined for each public good. An overview of the number of studies and the resulting number of pairwise comparisons for each public good and indicator is given in Table 1.

Data analysis

Relevant data were extracted from publications and, if necessary and possible, converted to the same unit of measurement. In some cases, the authors were contacted for missing information. The online tool WebPlotDigitizer (Rohatgi 2017) was used for standardized data extraction when data were provided graphically. In view of the highly heterogeneous dataset, descriptive statistical analyses were used to summarize the main findings of the pairwise comparisons. Boxplots were created for all indicators/sub-indicators for which at least nine pairwise comparisons were available. The indicator value of each

Table 1 Number of studies and pairwise comparisons of selected public goods and indicators

Public goods	Indicators	Number of studies	Number of pairwise comparisons
Water protection	Nitrate leaching	61	386
	Pesticides load	15	62
Soil conservation	Earthworm abundance[a]	20	64
	Nutrient availability[b]	44	106
	Water regulation[c]	38	135
	Soil erosion[d]	25	54
Biodiversity enhancement	Flora richness[e]	39	105
	Flora abundance[e]	8	15
	Fauna richness[f]	26	53
	Fauna abundance[f]	25	92
Climate protection	SOC content	104	270
	SOC sequestration	17	41
	N_2O emissions	13	35
	CH_4 emissions	3	6
Resource-use efficiency	Nitrogen input	27	63
	Nitrogen efficiency	25	64
	Energy input	28	57
	Energy efficiency	19	41
Animal welfare	Animal health	66	420
	Animal behaviour	7	16
	Emotional state	5	9

a)Earthworm biomass was also analysed. Data were not included due to overlap with studies on earthworm abundance

b)Sub-indicators used: plant-available phosphorus, soil pH

c)Sub-indicators used: penetration resistance, bulk density, aggregate stability, infiltration rate

d)Sub-indicators used: surface runoff, soil loss caused by rainfall. In addition, the C factor of the Universal Soil Loss Equation (USLE) was analysed. Data were however not considered here due to overlap with studies on surface runoff and soil loss caused by rainfall

e)Focusing on arable flora, seedbank, field margin flora (mean)

f)Focusing on birds, flower-visiting insects (e.g. bees, hoverflies, butterflies) (mean) comparison pair was calculated as the percentage deviation of the organic variant (vo) from the conventional variant (vc):

$$I[\%] = [(vo - vc)/vc]^{*}100$$

The boxplots for each performance indicator show the descriptive statistics.[2] In a second step, we attributed the result of each pairwise comparison to one of the following three categories:

+ Clearly more public services provided by the organic farming system
= No clear difference between the public services provided by the conventional and the organic farming system
– Clearly fewer public services provided by the organic farming system

In cases where the significance level of the difference was indicated in the original publication, the categorisation was made mainly based on significance level. If no information on significance level was provided, a threshold value of ± 20% was used for most indicators, above which a difference was defined as "clear". Lower threshold values were used for the following indicators, reflecting their smaller variation in pairwise comparisons: (a) soil pH (± 1%) and (b) bulk density, C_{org} content, C_{org} sequestration, N_2O emissions, CH_4 emissions, nitrogen input, nitrogen efficiency, energy input as well as energy efficiency (each ± 10%). In view of the high diversity of indicators used in studies on animal welfare, their classification was based on the qualitative assessment of the results made by the study authors, if no information on significance level was provided.

Results

The data analysis revealed that organic farming achieves a better performance in the majority of the pairwise comparisons; i.e. that organic farming generally provides more environmental and animal welfare benefits compared to conventional agriculture. However, a more detailed look at the results shows that the differences between both farming systems vary considerably in the extent as well as clarity of the empirical findings (see Figs. 1 and 2). In the following, the results are therefore described in more detail for different public goods and indicators, respectively. In each section, first, the number of pairwise comparisons showing that organic farming provides clearly more, similar or fewer benefits than conventional agriculture are described. Second, the relative differences between both farming systems are stated (median value).

Water protection

In 175 of 386 comparisons (45%) organic management led to clear lower nitrate leaching, while in 73 cases the opposite was observed. Comparatively high N-losses of organic farming were usually a result of a very high plough-in rate of legumes or a high share of intercrops under conventional systems – both not being representative for organic and conventional systems. Taking all pair comparisons into account, organic farming could reduce nitrate leaching by 26% (median) on average.

Only 15 scientific studies were found that compared the impact of pesticide use on water quality in organic and conventional agriculture. The reason is obvious, as the avoidance of chemically- synthesized pesticides in organic agriculture restricts the input of active substances with potentially high environmental toxicity. Therefore, it is not surprising that in 57 of 62 comparison pairs (92%), the potential or proven risk to groundwater and surface water from the use of plant protection products is lower in the organic compared to the conventional variant. Only in three comparison pairs from a single study, advantages were shown for the conventional variant which was explained by drift from conventional farms in the neighbourhood.

Due to the typically more diverse crop rotations and more frequent use of intercrops, it can be expected that organic farming may lead to lower soil erosion and thus also contribute to a reduction of phosphorus contamination. However, there were insufficient comparison studies available for a well-founded statement on phosphorus losses. The same is also true for veterinary drugs from animal production for which an advantage can be assumed due to

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[2] The length of the whiskers corresponds to 1.5 times the interquartile range (IQR).


Water protection
Nitrogen leaching
Pesticide load
Soil conservation
Earthworm abundance
Nutrient availability
Water regulation
Soil erosion
Biodiversity enhancement
Flora richness
Flora abundance
Fauna richness
Fauna abundance
Climate protection
SOC content
SOC sequestration
N2O emissions
CH4 emissions
Resource use and efficiency
Nitrogen input
Nitrogen efficiency
Energy input
Energy efficiency
Animal welfare
Animal health
Animal behaviour
Emotional state
-250
-200
-150
-100
-50
0
50
100
150
200
250
🟩 more public goods
⬜ similar public goods
🟧 fewer public goods

◂**Fig. 1** Number of pairwise comparisons showing that organic farming provides clearly more, similar and fewer benefits than conventional agriculture for different impact areas

restrictive production rules but has not been empirically proven.

Soil conservation

The positive effects of organic farming on soil conservation were clearly demonstrated by various biological, chemical and physical soil indicators. In 236 of 359 comparisons (53%), organic farming led to better soil conservation, while the opposite was found for 62 pairs.

The clearest benefits of organic farming were found for the indicator earthworm abundance. From 64 comparisons, the abundance was higher in 57 cases under organic management. On average, it was 78% higher. Higher earthworm abundances in organic farming can be explained by, among other factors, the comparatively high amounts of organic fertilizers and the avoidance of synthetic chemical pesticides.

A diverse, species-rich and abundant earthworm population on a site indicates a fertile and biologically active soil with intact soil structure and good water infiltration capacity. This is however only partly demonstrated by the other soil indicators used. In terms of nutrient availability, the amount of plant-available phosphorus was higher in just 15 of 35 pair comparisons, while the soil acidity (pH-value) was lower in 48 of 71 comparisons. On average, the P content and pH value were 5% and 3% higher, respectively, under organic management.

With regard to the ability of soils to store water and regulate the water balance, the analysis shows also a differentiated picture for organic farming. On the one hand, organic farming practices lead to a higher infiltration rate (in 16 of 19 comparison pairs, on average + 137%) and a higher aggregate stability (in 28 of 40 comparison pairs, on average + 15%). On the other hand, the difference between both farming systems is less pronounced regarding bulk density and penetration resistance. The bulk density was lower in 8 and similar in 8 of 18 comparisons (on average, −4%) and the penetration resistance was lower in 28 and similar in 28 of 58 comparisons (on average, −18%).

Clear benefits for organic farming were found in reducing soil erosion. The surface runoff was lower in 12 of 17 comparisons (on average −22%). A similar result was shown for soil loss. From 37 comparison pairs, clearly lower loss values were found in 24 pairs (on average, −26%).

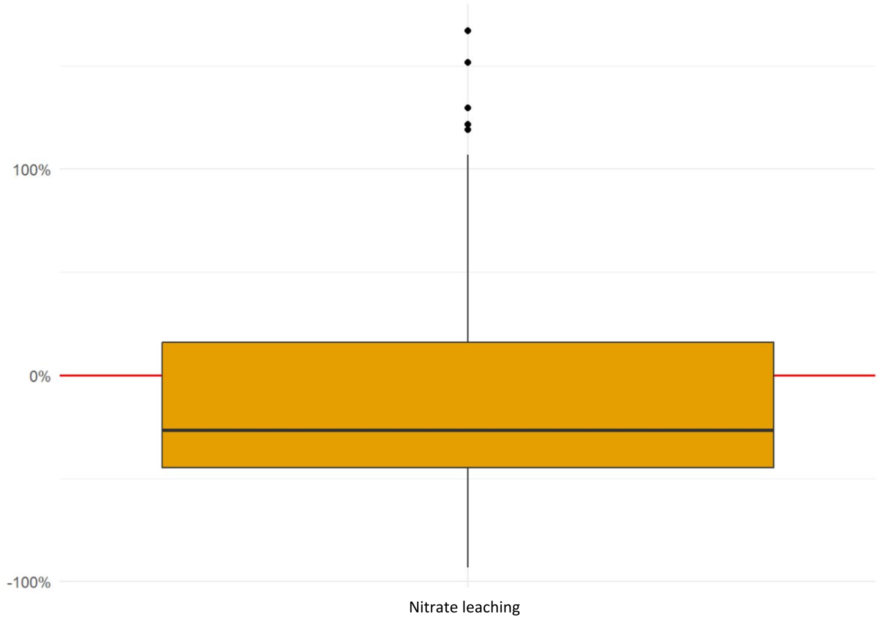
The advantages of organic farming identified in the analysis can be explained by the crop rotation in organic systems with a significant share of grass-clover leys, by higher soil cover and the high relevance of soil protection in the organic farming. On the other hand, soil conservation was often worse when organic variants with conventional tillage (i.e. ploughing) were compared to conventional variants with reduced tillage or no-till systems.

Biodiversity enhancement

The positive effects of organic farming on biodiversity were clearly demonstrated for the species groups studied. As most studies focus on mean values of species richness and abundance we refer here to these results. Comparing the impact of organic and conventional management on flora richness, the evaluation of 105 comparative pairs showed that 89 pairs had a higher number of species in favour of the organic variant (arable flora: 69 comparisons, arable seedbank: 10 comparisons, field margin vegetation: 10 comparisons). In only one pair of comparisons on arable flora, where the conventional system was managed very extensively, the number of species was lower under organic management. On average, species richness of arable flora was 95% higher under organic management. Inside the fields, the median even reached 304%. The organic variants showed on average 61% higher species richness for arable seedbank and 21% higher values for field margin vegetation. Flora abundance was higher under organic management in all of the 15 pairs compared (arable flora: 7 comparisons, arable seedbank: 6 comparisons, field margin vegetation: 2 comparisons). However, this result must be considered against the background of the relatively small number of studies and comparison pairs.

Differences between the management systems can mainly be explained by the fact that no chemical herbicides are applied in organic farming. Furthermore, no synthetic nitrogen fertilisers are used and the overall lower nutrient level results in a lower crop density and thus better living conditions for less competitive species.

a) Water protection



b) Soil conservation

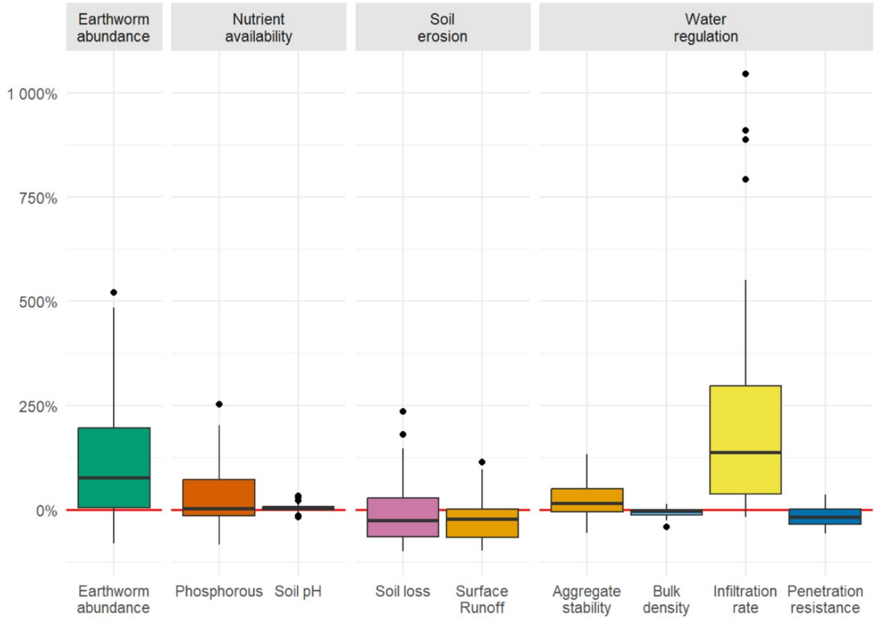
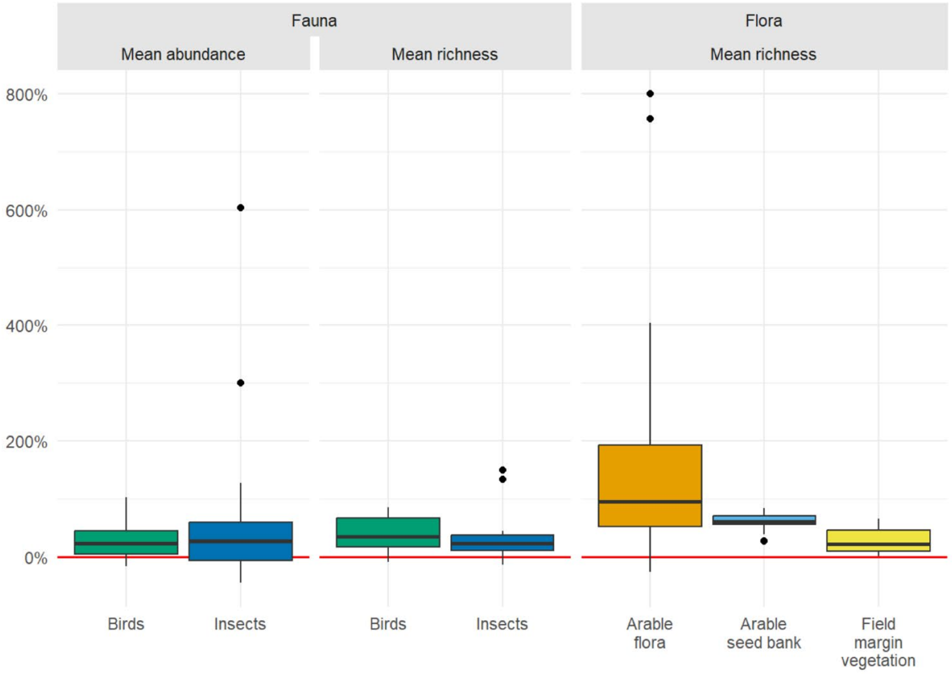


Fig. 2 Relative differences between organic and conventional farming (con = 0%) **a**) Water protection, **b**) Soil conservation, **c**) Biodiversity enhancement, **d**) Climate protection, **e**) Resource-use and efficiency

c) Biodiversity enhancement



d) Climate protection

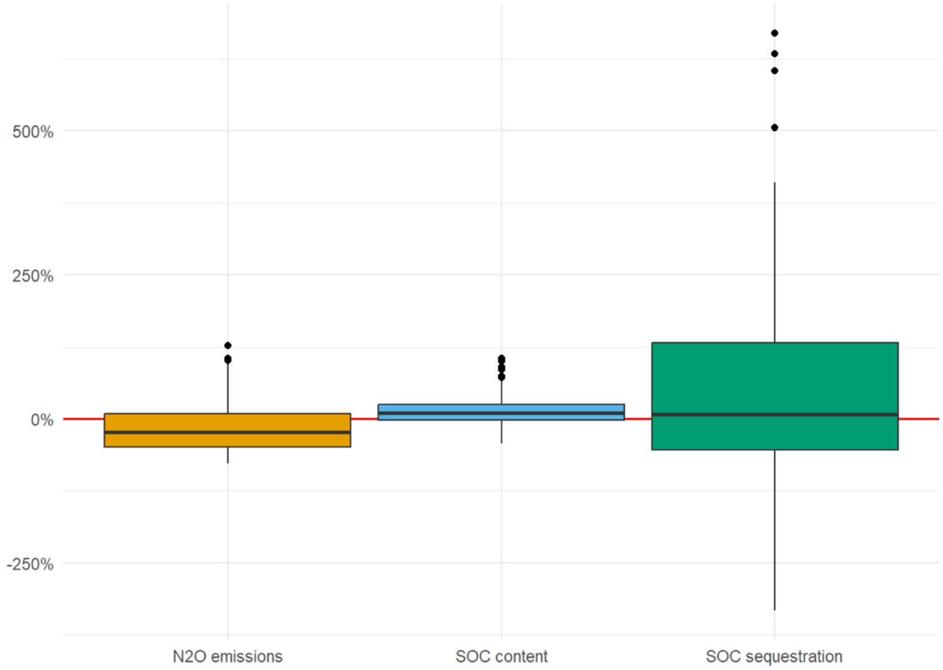
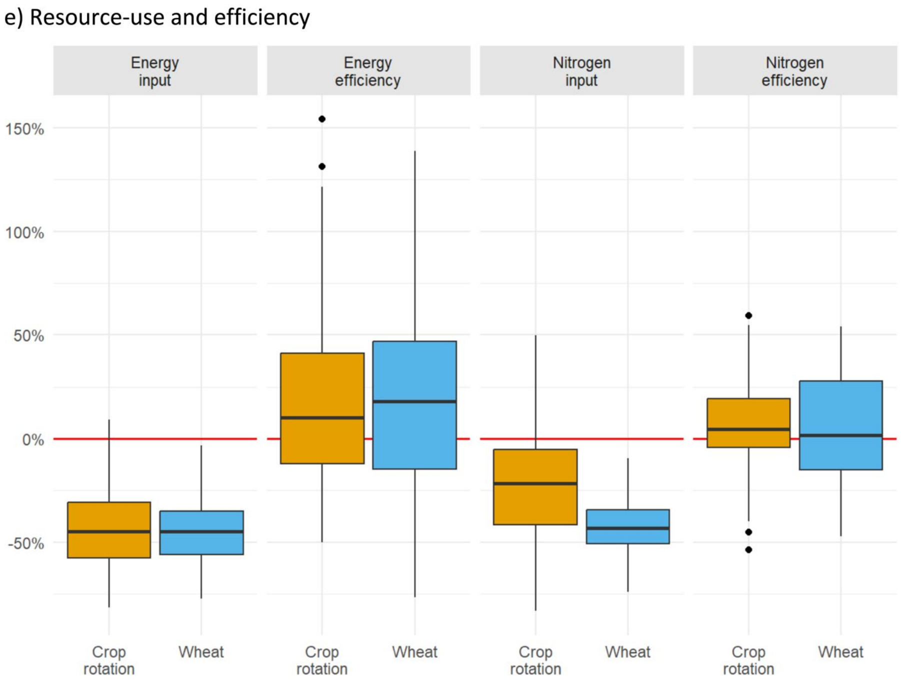


Fig. 2 (continued)



e) Resource-use and efficiency

Fig. 2 (continued)

The evaluation of 53 comparative pairs on fauna richness showed a differentiated picture. Considering the two investigated groups, birds and flower-visiting insects, the number of species in the organic variants was higher in 26 comparison pairs (birds: n = 11 comparisons, insects: n = 15 comparisons), while negative effects occurred for neither fauna groups. Taking all pair comparisons into account, the number of bird species and flower-visiting insects was 35% and 23% higher on organic farms (median values). In contrast to this, fauna abundance showed a higher variation. 41 of 92 pairs had higher values under organic farming (birds: 14 comparisons, insects: 27 comparisons), while 11 of the pairs from only one study showed negative effects. On average, fauna abundance was 23% (birds) and 26% (insects) higher under organic management, respectively.

It is worth mentioning that landscape structures also have a significant impact on biodiversity, especially on fauna. Many species of birds and insects use cultivated land only occasionally as a part of their habitat and depend greatly on the number and quality of landscape elements (e.g. Gabriel et al. 2010, Tuck et al. 2014). Therefore, this can outweigh the effects of land use.

Climate protection

The comparison of empirical results for soil-derived greenhouse gas emissions from organic and conventional agriculture in temperate climates showed positive effects from organic management. One of the main reasons for this is the ability of organic farming to store carbon in soils through the cultivation of legumes and the use of organic fertiliser. In total, in 134 of 270 pairwise comparisons soil organic carbon content was higher in the organic variant; however, there were no differences in 89 pairs and 47 pairs had a lower carbon content compared to the conventional variant. On average of all pairwise comparisons, organic carbon content was 10% higher.

The advantages of organic is even more pronounced regarding the sequestration rate. Here, 32 of 41 pairs indicatemore frequent use of intercrops leads to a higher carbon sequestration. Taking all pair comparisons into account, the annual carbon sequestration rate was on average also higher in the organically managed soils (275 kg ha^{1} compared with 40 kg ha^{1} in conventionally managed soils).

An important role for the interpretation of the above data is played by the sampling methods used in the studies. Differences in the sampling capacities (from 5 to 111 cm), sampling periods (between 3 and 70 years) and the frequency of sampling result in a certain heterogeneity of the data, which is, however, negligible as long as only the relative values resulting from the comparison of the pairwise comparisons are considered.

Of 35 pairwise comparisons, N_2O emissions were lower in the organic variant in 20 comparisons. On average, emissions were 24% lower according to the studies evaluated. Regarding CH_4 emissions, all agricultural areas included in the studies used in this analysis were able to absorb atmospheric methane; thus, the areas were emission sinks and not sources for this greenhouse gas. Comparing the uptake of organic and conventional variants, 4 of 6 pairs showed that the uptake rate was higher under organic management. However, due to the very limited data basis, this result needs to be interpreted with caution.

Using standard CO_2 equivalence from the IPCC and the results of all organic variants from the pairwise comparisons, the cumulative greenhouse gas reduction of organic farming was 1.082 kg CO_2e per hectare and year. The climate change mitigation performance of organic farming is strongly influenced by geographical (soil, climate, exposure and slope) and management factors. The latter include in particular (a) the farming history (including previous cultivation of legumes and duration of organic farming), (b) the tillage and (c) the type of crops grown.

Due to the lack of robust, empirical comparative studies, yield-related climate change mitigation was assessed qualitatively. Here, due to lower yields, organic farming is considered to have similar emissions from soil and plants per kg of output to conventional agriculture. In addition, metabolism-related methane emissions per kg of milk in organic dairy farming are probably higher than in conventional dairy farming. Total GHG emissions per kg of milk from organic and conventional milk production are considered to be comparable.

Resource-use efficiency

Resource-use efficiency was investigated based on nitrogen and energy. For both topics, the comparisons were carried out for the whole crop rotation and for a single crop only (wheat). Considering the crop rotation level with 63 pairs in total, nitrogen input was clearly lower in the organic variant than in the conventional variant for 42 pairs. Although nitrogen outputs and balances were also lower due to lower yields, nitrogen efficiency was clearly higher under organic management in 30 out of 64 pairwise comparisons. In 20 pairs however, no differences were found and in 14 pairs the efficiency was lower in the organic variant. On average, nitrogen input at the crop rotation level was 22% lower under organic management, while nitrogen efficiency was 5% higher. Furthermore, the relative advantages of organic practices were slightly more pronounced at farm level compared to crop rotation level and more pronounced on farms compared to field experiments, respectively. Similar results were found for the crop level (wheat). Nitrogen input was lower in organic variants in 17 out of 19 pairwise comparisons. Nitrogen efficiency was higher in organic variants for wheat in 7 out of 18 pairwise comparisons and similar in 6 pairs respectively.

A similar picture emerged for energy input and efficiency. In total, energy input was lower under organic management in 53 out of 57 pairwise comparisons at crop rotation level. For wheat, energy input was lower under organic management in 51 out of 53 pairwise comparisons. For the crop rotation, energy efficiency was higher in the organic variant in 22 out of 41 pairs, whereas in 11 pairs the conventional variant had a better input–output ratio. At the crop level (wheat), energy efficiency was higher in the organic variant in 16 out of 28 pairs, whereas in 7 pairs the conventional variant had a better input–output ratio. On average, 45% less energy was used under organic management and the energy efficiency was 10% higher. Again, these advantages of organic farming were more pronounced at the farm level.

For both resource categories, the differences between organic and conventional production were primarily due to the specific type of on-farm processes (N_2-fixation by legumes, humus management, building soil fertility, nutrient mobilisation and nutrient cycling) of organic farming. In contrast, in conventional systems the production of mineral fertiliser nitrogen often represented the most significant nitrogen and energy input.

Animal welfare

Following Fraser (2008), who described animal welfare with a multi-dimensional model comprising “basic health and functioning, natural living/natural behaviour and affective states", the differences between organic and conventional animal husbandry in terms of animal welfare were assessed using animal health, animal behaviour and emotional state. Across all livestock species, the results did not provide a clear picture of whether organic husbandry is more welfare-friendly than conventional husbandry. It is worth noting, that most of the comparative analyses we found dealt with dairy cows (278 of 445 pairs), while very few compared the animal welfare status for other livestock.

The analysis showed that animal health was better in the organic variant in 129 of 420 pairwise comparisons. No clear differences were found in 208 pairs; the conventional variant had less animal health problems in 83 pairs. The analysis of the literature reveals that organic farms perform better if the main risk factors for animal health problems are addressed within the EU Organic Regulations. For example, the requirements regarding litter and space have a positive effect on lameness and leg health. On the other hand, the review points out that health risks in organic farming are different. This can be illustrated by the provision of outdoor access and grazing which poses a higher risk in terms of parasite contamination. Thus, management factors are of greater importance than production system.

As far as animal behaviour and emotional state are concerned, the studies indicated that organic livestock husbandry was advantageous, e.g. due to greater space allowances or access to pasture, but the empirical basis was very weak. In total, 5 of 9 pairs showed that the affective state of livestock was better under organic management. Regarding natural living (in particular animal behaviour), 7 of 16 pairs showed advantages for organic farming, while no differences were found in 7 pairs.

To sum up, organic farming offers great potential for good animal welfare, but the current legislative framework does not guarantee it. Therefore, no general statements can be made on the impact of the farming method on animal welfare as a whole and in particular on animal behaviour and the emotional/ affective states.

Discussion

The main aim of this systematic review was to describe and quantify differences between organic and conventional agriculture regarding the impact of both production systems on water protection, soil conservation, biodiversity enhancement, climate protection, resource-use efficiency as well as animal welfare. Our literature search yielded 463 studies that met our criteria, comprising 2141 pairwise comparisons. It is by far the most comprehensive study of its kind comparing organic and conventional agriculture. To our knowledge, animal welfare was assessed for the first time in our study using pairwise comparisons between organic and conventional livestock husbandry. However, a lack of data made clear conclusions impossible.

The evaluation of the scientific literature found that, across all indicators for the fields of environmental protection and resource conservation, organic management showed advantages over conventional management in 60% of the pairs analysed. No differences were found for 26%, and in 14% of the comparison pairs, the conventional management was more advantageous. Furthermore, no clear picture could be drawn regarding animal welfare. Organic management showed advantages across all animal species and production types in 32% of the pairs, whereas conventional management performed better in 19% of the pairs. No substantial differences were found between organic and conventional livestock in 49% of the comparison pairs.

The study results are in line with the outcomes of previous thematic reviews on the impact of organic farming on (a) water (e.g. Stolze et al. 2000; Haas 2001; Tuomisto et al. 2012; Meier et al. 2015; Mondelaers et al. 2009; Seufert and Ramankutty 2017; Gomiero et al. 2011), (b) soil (e.g. Siegrist et al. 1998, Armstrong Brown et al. 2000; Mäder et al. 2002, Gattinger et al. 2012, Tuomisto et al. 2012, Lori et al. 2017, Kremen and Miles 2012, Seufert and Ramankutty 2017), (c) biodiversity (e.g. Tuck et al. 2014; Rahmann 2011; Mondelaers et al. 2009; Bengtsson et al. 2005; Hole et al. 2005), (d) climate (Mondelaers et al. 2009; Tuomisto et al. 2012; Gattinger et al. 2012; Skinner et al. 2014), (e) resource-use and efficiency (e.g. Gomiero et al. 2011, Dalgaard et al. 2000, Jespersen et al. 2017, Hülsbergen et al. 2022) as well as (f) animal welfare (Sundrum 2001; Hovi et al. 2003; Lund &

Algers 2003; van Wagenberg et al. 2017; Åkerfeldt et al. 2021).

Due to this study's comprehensiveness the results can be interpreted in a larger context – in particular regarding the evaluation of organic farming as a system, the relevance of the functional unit in comparative studies as well as the lack of data. These aspects are discussed in the following sections.

Systems approach as an explanation for the provision of public goods

The differences between organic and conventional agriculture in the provision of public goods are in particular a result of the system approach pursued in organic farming. This approach is characterized in particular by (a) the linking of individual agro-ecological system elements and the use of synergy effects, as well as (b) the consideration of natural system boundaries and capacities. Typically, this leads to diverse crop rotations (Barbieri et al. 2017), a lower production intensity (Tuck et al. 2014) and a simultaneous provision of multiple public goods (Jespersen et al. 2017; Seufert and Ramankutty 2017). These can be illustrated by the nutrient management in organic farming. According to the Regulation (EU) 2018/848, the total amount of livestock manure used in organic production shall not exceed 170 kg of nitrogen per year/hectare. Furthermore, synthetic nitrogen fertilisers shall not be used. Due to the lower N input, the risk of environmentally relevant N losses is significantly reduced. The relatively low N fertilization level also gives rare and low-competitive weeds the chance to develop and not to be displaced by the crop. The flowering of these weeds in turn attracts beneficial insects to the crop and contributes to an enhancement of biodiversity. Because mineral nitrogen fertiliser cannot be used, organic nutrient management relies at least in part on legumes, which have multiple positive effects on the entire agroecosystem. They are involved in humus formation and nutrient uptake, fix nitrogen, store atmospheric carbon in soils, keep weeds below agriculturally acceptable thresholds, promote soil life and soil aggregate stability, and much more (Gattinger et al. 2012; Lori et al. 2017). Finally, perennial legumes prevent erosion (Auerswald et al. 2021) and provide year-round habitats and an important food base for insects and other fauna species (Benton et al. 2003; Duflot et al. 2014).

In this context, it is important to note that organic farming is a multifaceted and very heterogeneous system approach. By comparison, however, conventional farming is even more heterogeneous. While the European Regulation on Organic Farming (European Commission 2018) sets clear boundaries for organic farming, there is no corresponding unified framework for conventional farming. In fact, existing regulations that govern activities on agricultural land are generally broader and less standardized compared to those for organic systems. Sumberg and Giller (2022) argue that the term "conventional agriculture" is misleading as an overarching concept, as it overlooks the diversity of individual farming practices within this category. They advocate for evaluating and improving specific practices for sustainability of agriculture, rather than comparing farming systems. While this perspective is valid and improving individual practices is an important step, the strength of organic agriculture lies in its systems-based approach, which offers overarching sustainability benefits. As described above, the systems approach is an essential part of organic agriculture, and breaking it down into individual farming practices does not capture the entirety of its benefits. To effectively evaluate organic agriculture, it must be compared against a comparable reference system. As most studies use conventional agriculture as a baseline, this serves as the primary comparator in reviews such as ours. It is likely, that some of the heterogeneity observed in our results is due to the variability of the conventional systems studied.

Relevance of the functional unit

Most comparative studies that examine the environmental and social benefits of organic agriculture compared to conventional agriculture consider only direct effects by relating impacts only to the agricultural area or the farm animal. From a technical perspective, this approach is obvious because of the original context. For example, soil loss occurs on agricultural land. Flora and fauna also refer to a spatially delimited habitat. Animal welfare is considered to be inseparable. This may explain why there are only few pairwise comparisons that collect and consider not only environmental data but also information on yields. Regardless of this, however, due to the yield gap between organic and conventional farming, critics repeatedly put forward the argument that, considering possible leakage effects, the advantages of organic farming are reduced (Kirchmann et al. 2016; Meemken and Qaim 2018). From a theoretical perspective, this objection is valid. In practice, however, it is important to consider the fact that yield gaps between organic and conventional management differ substantially and depend also very much on crop species and specific site conditions. This makes it difficult to observe and specify leakage effects. However, if the organic farming area will increase substantially as politically desired (European Commission 2020), it will be important that the existing yield gaps decrease or become less relevant. This could be achieved by changes in consumption habits (consumption of fewer animal products, less food waste) resulting in lower food demand (Mueller et al. 2017) or an increase in yields in organic cropping systems, which, however, should be based on organic principles. Furthermore, it is likely that the yield gap will shrink, because of decreases in the conventional yields as affected by stronger regulations of pesticide and fertiliser application as part of the farm-to-fork strategy (e.g. Wilbois and Schmidt 2019).

Regardless, a general determination of the functional unit (i.e. area or yield) to assess environmental impacts does not do justice to the complexity of this relationship. Rather, a differentiated assessment is required, concerning in which context and what manner resource use or conservation should be prioritised and therefore which parameter is best suited. To this end, the spatial approach to reducing environmental problems (i.e. focusing on environmental performance locally or globally to mitigate degradation), the regional extent of the environmental problem (i.e. the scarcity of individual environmental goods in a region) and the context-specific yield level and therewith the extent of leakage effects should be considered. Furthermore, it is important not only to focus on single environmental effects, but also to consider the aggregated impacts, when evaluating the advantages or disadvantages of a farming practice. As described above, organic farming has clear advantages here due to its systems approach.

Limitations of the study

We close this discussion with a reflection on the quality of the data set and the statistics used for this work. Despite the comprehensive literature search and data evaluation and compilation from the last three decades of agricultural research, there are some limitations concerning the relevance and the transferability of our findings.

Our aim was to include all papers that were found using the systematic literature search syntax and that met our eligibility criteria (see Materials & Methods section). This approach allowed us to improve the statistical power by increasing the total sample size and avoiding biases. Nevertheless, there is a risk that studies were included, in which the investigated farming systems contain unrealistic management practices such as unusual crop rotations, fertilisation amounts, or plant protection measures. To give an example, the biodiversity studies include a comparison between traditional (conventional) farming and modern organic farming in Hungary (Knudsen et al. 2017), where traditional farming with low fertilization and without pesticides was the more extensive system, which, if at all, might be representative only for low percentage of conventional farming in Hungary. The fact that, unlike for organic farming, no clear definition of conventional farming exists, means such comparisons can be misleading. Yet, despite the different origin and background of the studies as well as their varying context, the results of the comparisons in the meta-analysis are in line with the results from real farms (Chmelíková et al. 2021). Nevertheless, the differences are not so clear in practice, due to data heterogeneity and the differing experiment designs.

In fact, the main limitation of the approach is the lack of data and the correspondingly high variability of the results. Nitrate leaching for instance, shows a high variability, as some studies found higher, other lower levels of nitrate leaching in the organic system. This can be due to numerous factors besides the farming system, but as further factors could not be evaluated, the result shows a mixed signal. Similar trends can be seen for Nutrient availability, fauna abundance, SOC content and nitrogen efficiency, to name a few. A low number of overall studies and varying results reduce the interpretative power of the analyses. With our approach, we enable comparisons between the systems, but the sample size and variability of the data set should always be considered when interpolating these results to the system level.

This heterogeneity also prevented us from following a traditional meta-analysis approach. As all systems varied to a certain extent, no uniform control (conventional) or treatment (organic) could be discerned. Additionally, the broad range of different units used to inform each indicator meant that only a small subsample of studies could potentially be used for a meta-analytical approach. Additionally, the necessary data to calculate the within and between study heterogeneity and consequent weighing of individual comparisons necessary for a meta-analysis was rarely given (namely sample size (n) and error variable (SD or SE)). These limitations ultimately led us to forego the classical approach of a meta-analysis in order to retain the most of the extracted data.

We hoped to avoid this issue and other problems regarding experimental design and the robustness of the analytical methods applied (Kirchmann et al. 2016) by only including mainly peer-reviewed papers. However, as Kusche et al. (2019) showed, additional quality checks carried out to ensure a high degree of comparability and representativeness resulted in a lower sample size along with changes in the scale of the effect sizes, as also observed in previous meta studies (Gattinger et al. 2012).

In contrast to previous global meta studies on organic and conventional agriculture (e.g. Gattinger et al. 2012; Seufert et al. 2012; Lori et al. 2017), we did not include further explanatory criteria in our dataset. We therefore refrained from analyses such as meta regressions or in-depth evaluations based on categorical variables or factors (Gattinger et al. 2012; Lori et al. 2017). Further, we did not weight single studies, as the heterogenic nature of the studies, indicators and measurement units made this type of quantification of indicators impossible. In addition, there is a slight redundancy in the pairwise comparisons in aggregated indicators as some studies contributed to several subtopics.

With regard to individual public goods, major limitations in the dataset were observed for animal welfare. This may at least partially explain why animal welfare has not yet been the subject of a quantitative literature analysis, although it is an area that has had a lot of public attention for many years and is prominently addressed in the EU organic regulations. Animal welfare encompasses the three aspects health, natural living and affective states (Fraser 2008). However, individual studies only very rarely include and analyse all three dimensions. The studies we used focused mostly on health-related aspects, thus we conducted a semiquantitative evaluation instead. Further, most papers studied cattle, while only few studied monogastric livestock and small ruminants. We expected more pronounced differences between organic and conventional animal husbandry for monogastric livestock (poultry and pigs), as the husbandry systems differ more than in dairy cattle husbandry (WBA 2015).

For climate impacts, we focussed on studies that measured soil carbon and greenhouse gas data only. Therefore, climate footprint or carbon footprint assessments based on life cycle assessments (LCA) of organic and conventional products were excluded as comparative LCAs on agricultural products often do not adequately differentiate between specific characteristics of the respective farming system in the definition of the goal and scope and in the inventory (Meier et al. 2015). For instance, modelled N emissions in LCAs often do not correspond with the actual amount of N left in the system (Meier et al. 2015). Furthermore, N_2O emissions from conventionally managed soils seemed to be influenced mainly by total N inputs, whereas for organically managed soils other variables such as SOC and pH seemed to be more important, which reinforces the need for system-specific emission factors (Skinner et al. 2014, 2019).

While there is a good knowledge base on soil carbon under organic and conventional management, there have so far been only a few scientific publications on the greenhouse gases (GHG) N_2O and CH_4 in contrasting plant-soil systems. A reason for the relatively low number of eligible GHG studies might be that monitoring of GHG fluxes in soil–plant systems generally requires sophisticated analytical skills and is time-consuming (Skinner et al. 2014). The same holds true for CH_4 emissions from organic and conventional cattle husbandry. There are no comparative measurements of CH_4 emissions from organic and conventional cattle farming systems (dairy, beef), although CH_4 from enteric fermentation in cattle is one of the largest GHG sources in agriculture globally. It is assumed that the emission factors for CH_4 and N_2O differ between organic and conventional cattle husbandry because of differences in the feeding regime and husbandry conditions (Meier et al. 2015).

Biodiversity, mainly the occurrence of fauna species, is highly influenced by landscape structures, which may interact with management in different ways or even superimpose the effects of farming systems (e.g. Gabriel et al. 2010, 2013; Winqvist et al. 2012; Ricci et al. 2019). Moreover, comparative studies do not include the most intensively managed conventional farms because no comparison pair is available (Gabriel et al. 2010) or concentrate on single crops, solely (mainly winter wheat, e.g. Batary et al. 2017), which does not represent e.g. the positive effects of whole crop rotations with perennial leys as common in organic systems (Stein-Bachinger et al. 2021, 2022).

Some indicators, in particular nitrogen leaching, species richness and abundance, aggregate stability, surface runoff and soil loss, involved data collection using a wide range of methods and measurement units. This lack of harmonization meant the results were difficult to compare and may have affected allocation to the categories "clear effects" versus "no clear difference". The soil related indicators combine pairwise comparisons from studies from plot to regional scale, from field and laboratory measurements and partly modelled comparisons. As a consequence, the units and the magnitude of the reported systems differences are not fully comparable. While the qualitative systems differences in our analysis can be assessed robustly, the quantitative system differences are quite sensitive to which studies are included in the assessment. This heterogeneity in the underlying data does, however, not change the clear overall finding that organic farming provides more environmental goods than conventional farming.

The aforementioned limitations are not unusual in review studies on ecosystem services. A certain level of unexplained variability is inherent when studying complex systems, as comparability between studies cannot be perfect, when relevant factors (such as the climate, management practices, etc.) vary. Nevertheless, some improvements are possible. Given the potential of meta-analyses to identify effects that go beyond the scope of individual studies with study-specific conditions, it would be beneficial for agricultural scientists to consider potential future reviews when publishing data and results. This would also help to overcome publication biases or the so-called "file drawer problem" (Rothstein et al. 2005).

It is vital, that key information is provided, including agricultural data such as crop rotations, all interventions (e.g. harvest, tillage, fertilization), and the timing of these interventions. Weather data, all relevant and potentially explanatory parameters, should also be reported, as well as clear information on the methodology employed. Additionally, it is important to include information on the statistical data, especially mean, standard deviation (or standard error), and sample size (n). While many studies report mean values and a test of significance (typically p-value), they rarely provide all of those essential data. Furthermore, the data should be made available in numerical format, as publishing results only in graphical form complicates extracting data. If including such data in the main manuscript is not feasible, they should be provided as supplementary material. Additionally, designing experiments to have a comparable control to the system evaluated strengthens the interpretive power of the results and enables comprehension on the system level. Reviews and meta-analyses can be a very beneficial for agricultural studies. By considering their requirements when publishing experimental data, these studies can become more accurate, comprehensive and impactful.

Conclusions

Organic farming clearly provides a range of environmental benefits. Consequently, it may contribute to solving current challenges in this field and is rightly considered a key approach for sustainable land use. In contrast to this, no clear conclusion can be drawn regarding animal welfare and in particular animal health, indicating that farm-specific management factors are of greater importance than the production system (organic vs conventional). Future research needs to take specific aspects more into consideration by comparing whole farming systems, e.g. different intensities of cropping systems and the surrounding landscape. This may allow new visions of sustainable land use including new technologies and management practices. Should there be a further expansion of organic farming in the medium-term, it will be important to focus research on yield optimisation based on organic principles and by altering their relevance through changes in consumption.

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Declarations

Conflicts of interest The authors declare no competing interests.

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