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Organic cropping systems balance environmental impacts and agricultural production

Hans-Martin Krause[1,4]✉, Paul Mäder[1,4]✉, Andreas Fliessbach[1], Klaus A. Jarosch[2], Astrid Oberson[3] & Jochen Mayer[2]

Agriculture provides food to a still growing population but is a major driver of the acceleration of global nutrient flows, climate change, and biodiversity loss. Policies such as the European Farm2Fork strategy aim to mitigate the environmental impact of land-use by fostering organic farming. To assess long-term environmental impact of organic food production we synthesized more than four decades of research on agronomic and environmental performance of the oldest system comparison experiment on organic and conventional cropping systems (DOK experiment). Two organic systems (bioorganic and biodynamic) are compared with two conventional (manure-based integrated and mineral-based) systems all with the same arable crop rotation including grass-clover, and manure from livestock integrated in all except the mineral-based system. Organic systems used 92% less pesticides and 76% less mineral nitrogen than conventional systems. Nitrogen use efficiency, that also considers biological nitrogen fixation, was above 85% for all systems. Organic fertilization with farmyard manure maintained or increased soil carbon and nitrogen stocks in the long term, especially in the biodynamic system with manure compost. Conventional mineral-based cropping reduced soil organic carbon and nitrogen stocks. Higher soil organic carbon stocks in organic cropping did not translate to increased N_2O emissions, which were the main driver for 56% lower soil-based, area-scaled climate impact compared to the integrated conventional system with manure. Organic cropping systems, especially compost-based biodynamic, showed enhanced soil health, richness of micro- and macrofauna and weed species. Highest yields were achieved in integrated conventional system, with highest total nitrogen inputs and enhanced soil health compared to pure mineral fertilization. Yet, these benefits come at the cost of lower nitrogen use efficiency and higher N_2O emissions. Despite a rigorous reduction of inputs yields of the organic systems achieved 85% of the conventional systems. We demonstrate at field level that organic cropping systems with reduced external nutrient inputs have less climate impact and a larger in-situ biodiversity, while providing a fertile ground for the future development of sustainable agricultural production systems.

Keywords Organic cropping systems, Nutrient cycles, Yields, Soil greenhouse gases, Soil biodiversity

Human activities have increasingly become a threat for the stability of the earth `s system[1]. Earths regulatory capacity, as captured by the concept of planetary boundaries, has already been crossed for critical impact categories such as nitrogen and phosphorus cycling, greenhouse gas emissions, biodiversity, and land use change[2]. Agricultural practices, developed during the period of the "green revolution" boosted food production and enabled global population growth, but are a major driver for ecosystem degradation and pose severe pressure on these critical impact categories by the transformation of natural habitats[3,4], acceleration of nutrient flows[5] and the emission of greenhouse gases[6].

In agricultural systems, nitrogen and phosphorus often limit crop growth, making the regulation of nutrient cycling in soils a prerequisite for long-term productivity. Although industrial, mineral nitrogen and phosphorus inputs largely increased food production, their overuse and the regional concentrated application of animal manures has exceeded the regulatory capacity of soils[7]. In 2010, nitrogen entered global croplands via mineral fertilizers (98 Tg N), manure (22 Tg N), biological nitrogen fixation (32 Tg N) and deposition (17 Tg N)[8]. Global mean nitrogen use efficiency (NUE) was 46% and growing nitrogen surpluses[8] accelerate the loss of nitrogen via

[1]Department of Soil Sciences, Research Institute of Organic Agriculture FiBL, Ackerstrasse 113, Frick 5070, Switzerland. [2]Department Agroecology and Environment, Agroscope, Reckenholzstrasse 191, Zurich 8046, Switzerland. [3]Institute of Agricultural Sciences, ETH Zurich, Eschikon 33, Lindau 8315, Switzerland. [4]Hans-Martin Krause and Paul Mäder contributed equally. ✉email: hans-martin.krause@fibl.org; paul.maeder@fibl.org

leaching and gaseous emissions causing eutrophication of natural ecosystems and the emission of greenhouse gases[9–11]. The production of mineral nitrogen fertilizers requires large amounts of energy and accounts for ~ 2.1% of global greenhouse gas emissions[12]. Thus, the focus on alternative nitrogen inputs via biological nitrogen fixation to ensure crop nitrogen supply is considered as a key element for sustainable agricultural systems.

Improved phosphorus cycling in arable systems is crucial for the long-term maintenance of soil fertility and crop production. Export of phosphorus from the soil-plant system can only be counteracted by the slow process of mineral weathering or requires replacement by external inputs via animal (or human) manures or mineral rock deposits[13]. The constant flow of phosphorus in minerally fertilized systems from rock deposits to soils, to freshwater bodies and oceans builds a constant threat for phosphorus shortages[13]. Also, regional concentration of most mineral phosphorus deposits[14,15] renders mineral based arable farming dependent from global fertilizer markets[16]. Thus, increasing nutrient efficiency by means of nitrogen and phosphorus cycling is the paramount challenge for sustainable agricultural systems and needs to be monitored also by nitrogen and phosphorus changes in soil stocks.

Since soils act as nutrient regulators, they also have an important function in the release and capture of the soil-borne greenhouse gases, carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4)[17,18]. The loss of soil organic matter causes CO_2 emissions and is one of the biggest threats to soil health, since it reduces their capacity to store nutrients, to act as a habitat for soil life, and to stabilize soils against erosion[19]. N_2O and CH_4 are trace gases with an estimated global warming potential 273 and 28 times greater than that of CO_2[6]. Agricultural N_2O emissions mainly stem from fertilized soils and occur in short lived peak events upon nitrogen fertilization or soil tillage inducing nitrogen mineralization. The availability of nitrogen is the most important factor driving N_2O emissions, but also soil organic carbon concentration, soil oxygenation status and soil pH can impact N_2O formation and consumption[20]. Agricultural CH_4 emissions mainly originate from ruminant husbandry and paddy soils, while well drained arable soils usually act as sink for CH_4[21].

Climate change accelerates the change of biodiversity that may result in the extinction of species, and systems with low biodiversity have a lower potential to adapt to climate extremes[3]. Through intensification of agricultural production and the loss of natural habitats via land use change, agriculture is the main contributor to biodiversity loss[22]. Biodiversity conservation and restauration are seen as measures to maintain and increase resilience and functionality of a landscape[23]. As more than a half of the earth habitable surface was transformed to agricultural land, there are mounting concerns about the environmental impact of agricultural practices that address the urgency for redesigned and sustainable agricultural practices[24,25]. The key challenge for future agricultural systems is to produce sufficient food for a still growing population while minimizing environmental impact of agricultural production, especially on nutrient cycles, biodiversity loss and greenhouse gas emissions.

Due to its focus on long-term soil fertility and the avoidance of mineral fertilizer inputs and chemical plant protection, organic agriculture is perceived as an environmentally friendly alternative to conventional cropping systems. Of the agricultural land, 1.6% globally (74.9 million ha), and 3.4% (16.5 million ha) within the European Union are currently managed organically[26]. The global market for organically produced products is growing[26] and there are further political efforts to increase shares of organic systems. For example, the EUs Farm2Fork strategy aims for 25% of farmland to be organically managed by 2030[27]. Organic systems rely on symbiotic nitrogen fixation, organic amendments, efficient nutrient cycling and self-regulatory processes for crop nutrition and plant protection[28]. By avoiding synthetic inputs in form of fertilizers and pesticides, organic cropping systems produce lower yields compared to conventional systems[29,30]. Yet, organic systems show beneficial environmental effects on soil fertility and soil organic matter[31–33], profitability, nutritional value, biodiversity and water quality[34]. In line with that, a recent study showed enhanced multifunctionality and provision of regulating ecosystem services in organic systems and conservation tillage, based on a short-term field experiment[35]. The most recent meta-analysis on environmental and agronomic performance of organic and conventional cropping systems still revealed high uncertainties especially for, nutrient cycling, the emission of greenhouse gases and the long-term impact on yield stability and land demand[34].

The present study provides a quantitative base for the long-term effect of organic and conventional cropping systems on critical ecosystem services by synthesizing more than four decades of research in the world's oldest cropping system comparison trial - the DOK experiment[31]. This experiment compares two organic (bio-dynamic: BIODYN; bio-organic: BIOORG) with two conventional cropping systems (one with farmyard manure and mineral fertilizers: CONFYM, also called as integrated system; one with mineral fertilizers alone: CONMIN) since 1978 (Table 1, Fig S1). The cropping systems mainly differ in plant protection and fertilization strategy including a gradient of manure preprocessing intensity.

Our research objectives were to (i) quantify soil nitrogen and phosphorus stock changes in relation to nutrient balances to address the impact of cropping systems on nutrient flows, (ii) estimate the soil-based climate impact of cropping systems by integrating soil carbon stock changes with results from a greenhouse gas measurement campaign, (iii) identify the impact of cropping systems on soil biodiversity by linking measured biological soil health indicators with key results from soil biodiversity studies, (iv) quantify agricultural productivity in organic and conventional cropping systems, and (v) group indicators in critical impact categories of agricultural systems such as, biodiversity, soil health, climate, nutrient balances and yields, to discuss trade-offs and synergies as well as relative performance within organic and conventional cropping systems.

Results

Impact of cropping system on nutrient balances

To assess cropping system specific nutrient flows, nutrient balances were compared with changes in soil nitrogen and phosphorus stocks over 42 years (Fig. 1). Mean fertilizers inputs of total nitrogen, mineral nitrogen, phosphorus, and potassium to the organic systems, BIODYN and BIOORG, were 36%, 76%, 36%, and 27% lower compared to the conventional systems, CONMIN and CONFYM (Tab S1). Due to higher losses during

	Fertilizer types	Organic matter [kg OM/ha^{-1} a^{-1}]		Total *N* fertilization [kg *N*/ha^{-1} a^{-1}]		Mineral *N* fertilization [kg *N*/ha^{-1} a^{-1}]		Symbiotic *N* fixation [kg *N*/ha^{-1} a^{-1}]		Total *P* fertilization [kg *P*/ha^{-1} a^{-1}]		Total K fertilization [kg K/ha^{-1} a^{-1}]		Plant protection [kg ai/ha^{-1} a^{-1}]	
		mean	se	mean	se	mean	se	mean	se	mean	se	mean	se	mean	se
BIODYN	*slurry, manure compost*	1882	±72	94	±3	26	±1	122	±7	24	±3	177	±17	0.1	< 0.1
BIOORG	*slurry, rotten manure*	2032	±123	96	±8	30	±4	119	±7	25	±1	184	±20	0.3	±0.1
CONFYM	*mineral, slurry, stacked manure*	2314	±78	171	±6	113	±6	117	±7	38	±2	248	±7	2.8	±0.5
CONMIN	*mineral*	–	–	121	±6	121	±6	99	±8	38	±2	246	±9	2.6	±0.5

Table 1. Fertilizer types and mean annual inputs (and standard error) of organic matter, nitrogen (N), phosphorus (P), potassium (K) and plant protection across crop rotation periods 2–6 (1985–2019) for two conventional (mineral-based CONMIN and manure-based CONFYM) and two organic (bioorganic BIOORG and biodynamic BIODYN) cropping systems. "OM" refers to organic matter; "ai" refers to active ingredient equivalents; "Mineral fertilizer N" refers to the share of mineral nitrogen forms in synthetic fertilizers, slurry and manures within "total fertilizer N" inputs. "Symbiotic N fixation" was estimated based on ^{15}N isotope studies in grassclover[86] and soybean[52,53].

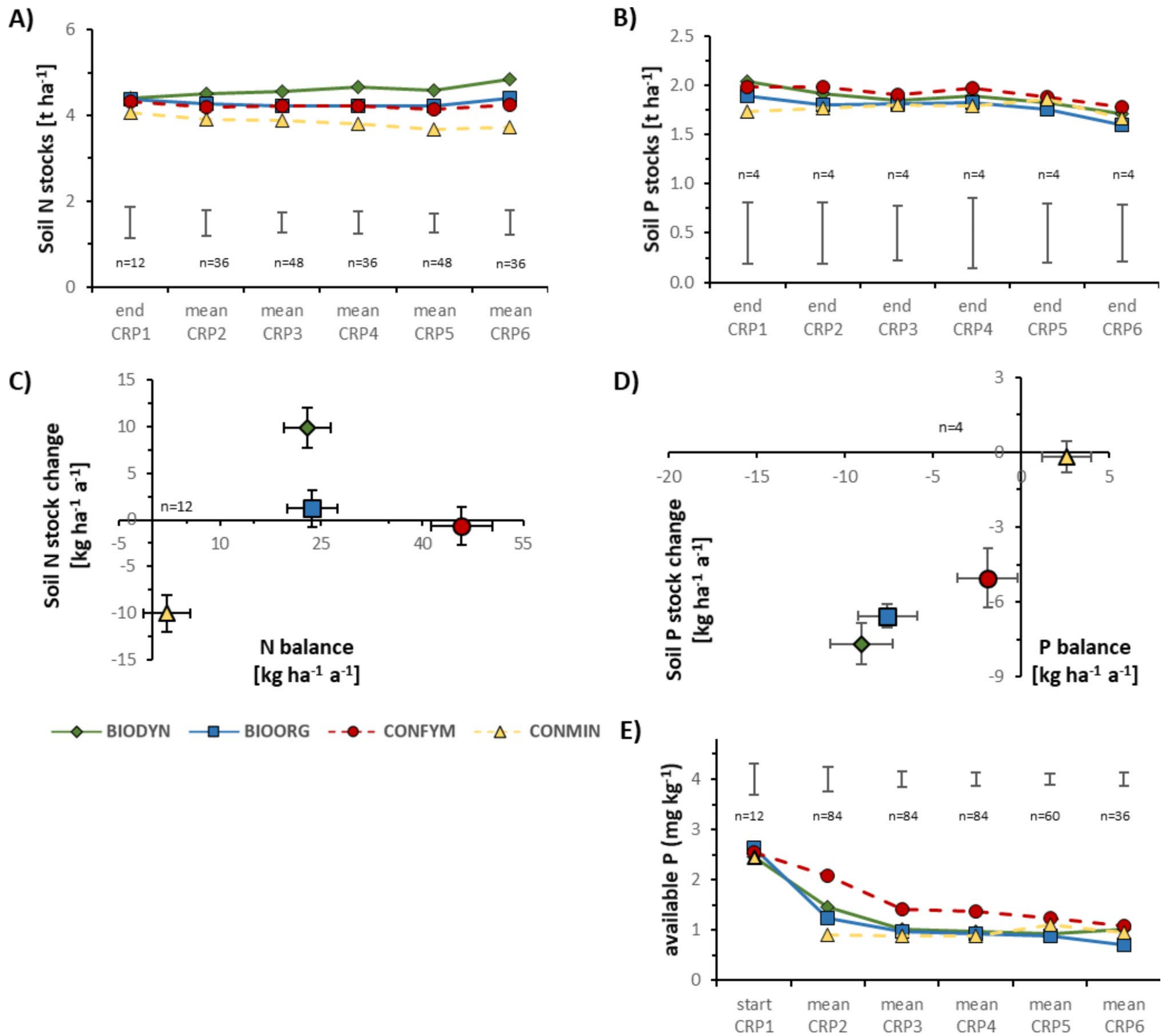

Fig. 1. Relationship of nitrogen and phosphorus balance and changes in soil nitrogen and phosphorus stocks and soluble (bioavailable) phosphorus, as influenced by cropping systems. Panels (A), (B) and (E) show the temporal development of soil nitrogen and phosphorus stocks and the available phosphorus contents in the arable layer (0–0.2 m soil depth) per crop rotation period (CRP), respectively. Error bars represent least significant difference between system in a given CRP. Prefixes "end" and "start" refer to data from one specific year, while the prefix "mean" refers to multiple measurement in the respective CRP. Panel (C) shows the means and standard deviation of soil nitrogen stock change and nitrogen balance from 2nd to 6th CRP (1984–2019). The nitrogen balance includes all outputs via harvest and inputs via fertilization, atmospheric deposition, seeds and nitrogen fixation. Panel (D) shows means and standard deviation of phosphorus stock changes and phosphorus balance from 2nd to 6th CRP (1984–2019). Panel (B) and (D) present data for iteration C (field subplot) only.

manure storage and composting, input of organic matter was on average 19% lower in organic systems compared to CONFYM (Tab S1). Mean annual nitrogen fixation was a major input in all cropping systems (99 to 122 kg ha^{-1} a^{-1}) and exceeded all other nitrogen inputs in BIODYN and BIOORG (Tab S2). Despite high nitrogen export through harvested products (> 210 kg ha^{-1} a^{-1}), inputs exceeded outputs and nitrogen balances were positive for all systems (Fig. 1, Tab S2). Cropping systems receiving organic inputs via liquid and solid manure maintained (BIOORG, CONFYM) or increased (BIODYN) top soil nitrogen stocks (Fig. 1C). Despite an even nitrogen balance (+ 2 kg N ha^{-1} a^{-1}), CONMIN soils lost 10 kg N ha^{-1} a^{-1}. Rising soil nitrogen stocks were observed in the BIODYN system although the system received less total nitrogen inputs compared to CONFYM and CONMIN. Unexpectedly high nitrogen use efficiencies were observed with 99% in CONMIN, 85% in CONFYM and ~ 90% in the organic systems (Tab S2). Phosphorus inputs were 36% lower in organic compared to conventional systems, yet, export of phosphorus from the field by harvested products differed only slightly and ranged from 33 kg ha^{-1} a^{-1} (BIODYN) to 39 kg ha^{-1} a^{-1} (CONFYM) (Tab S2). Phosphorus balances were slightly positive in CONMIN, even within the error margin in CONFYM and slightly negative in BIODYN and BIOORG (Tab S2). Top soil phosphorus stocks continuously decreased in all systems while plant-available phosphorus decreased mainly at the start of the field experiment in crop rotation period 1 (CRP1) and CRP2, yet to a greater extend in BIODYN and BIOORG (Fig. 1D and E).

Soil-based greenhouse gases

Soil carbon stocks increased in the BIODYN system, remained stable in BIOORG and CONFYM and decreased in CONMIN (Fig. 2A). Consequently, mean annual changes in soil organic carbon, expressed as CO_2 equivalent, was negative for BIODYN and positive for CONMIN (Fig. 2B). At the end of CRP6 differences in soil organic carbon stock were most prominent in the top soil (0–20 cm), but also the soil layer 20–30 cm showed enhanced carbon stocks in BIODYN compared to all other systems (Fig S3). N_2O emissions govern the area-scaled climate impact of cropping systems, with highest emissions in CONFYM followed by CONMIN, BIOORG and then BIODYN (Fig. 2C). Lowest N_2O emissions were found in BIODYN despite rising soil organic carbon stocks. The magnitude of N_2O emissions largely reflects total nitrogen inputs, which were greater than average fertilizer inputs during maize production, especially in CONFYM. Soil CH_4 emissions were negligible for all systems (Fig. 2C). Expressed on an annual base, climate impact for all soil-based greenhouse gases was 56% lower in organic (BIODYN and BIOORG) compared to conventional (CONFYM and CONMIN) systems.

Soil biodiversity and soil health

Reflecting the 100 m^2 plot scale of a replicated long-term field experiment, biodiversity assessment was restricted to soil-based biological entities and species richness was used as a measure of community diversity. For weeds, soil bacterial genotypes and soil faunal guilds, such as carabids, spiders and earthworms, greater richness was found in organic systems (Fig. 3). Little differences were found for fungal genotypes and *nematodae* while richness of *enchytraides* and microbial phenotypes was greater in systems receiving organic inputs compared to mineral fertilization in CONMIN. Biological indicators were assessed to characterize the impact of cropping systems on soil health[36]. Soil microbial biomass carbon and nitrogen increased in the order CONMIN < CONFYM < BIOORG < BIODYN. The same pattern was found for dehydrogenase activity which indicate microbial carbon cycling. Alkaline phosphatase activity, which is the main driver for biological cleavage of organically bound phosphorus was similar in BIOORG and CONFYM, and lowest and highest rates were found for CONMIN and BIODYN, respectively (Fig. 3).

Impact of cropping systems on yields

Food production is the primary objective of the agricultural sector and achieving high and stable yields is the benchmark for the economic viability of agricultural systems. Across the experimental period, mean yields of silage maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.) and potatoes (*Solanum tuberosum* L.) were 12%, 20% and 32% lower in the organic compared to the conventional systems (Fig. 4). Grass-clover yields in organic systems were 9% lower, while soya bean yields (*Glycine max* L.) were similar (Fig. 4). Yield trends over time were similar in all cropping systems and showed increasing yields for wheat. Despite lower inputs and the absence of

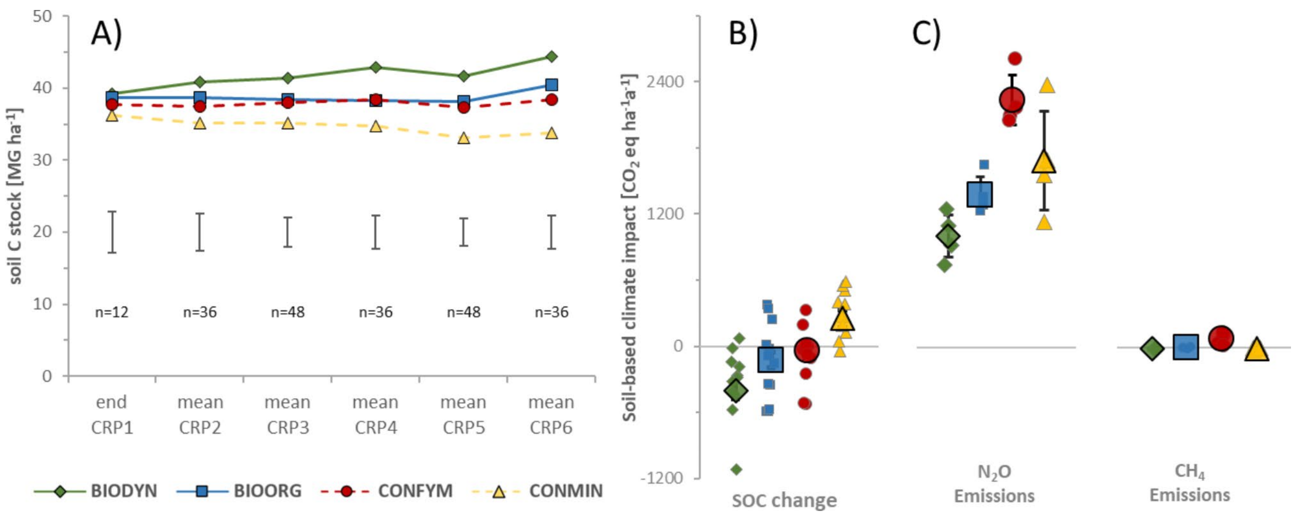

Fig. 2. Soil borne greenhouse gas emissions as influenced by cropping systems. Panel (A) shows soil organic carbon stock change from 2nd to 6th crop rotation period (CRP, 1984–2019). Error bars represent least significant difference between system in a given CRP. In panel (B) least square means of annual soil carbon stock (SOC) changes from 2nd to 6th CRP expressed as CO_2 equivalents ($n = 12 + SE$). (C) Least square means of annual area-scaled N_2O and CH_4 emissions across a grass-clover, maize and green manure sequence within 6th CRP[57] expressed as CO_2 equivalents ($n = 4 + SE$). Small symbols in panel (B) and (C) represent individual observations from experimental plots. System boundary for greenhouse gas emissions is the field site.

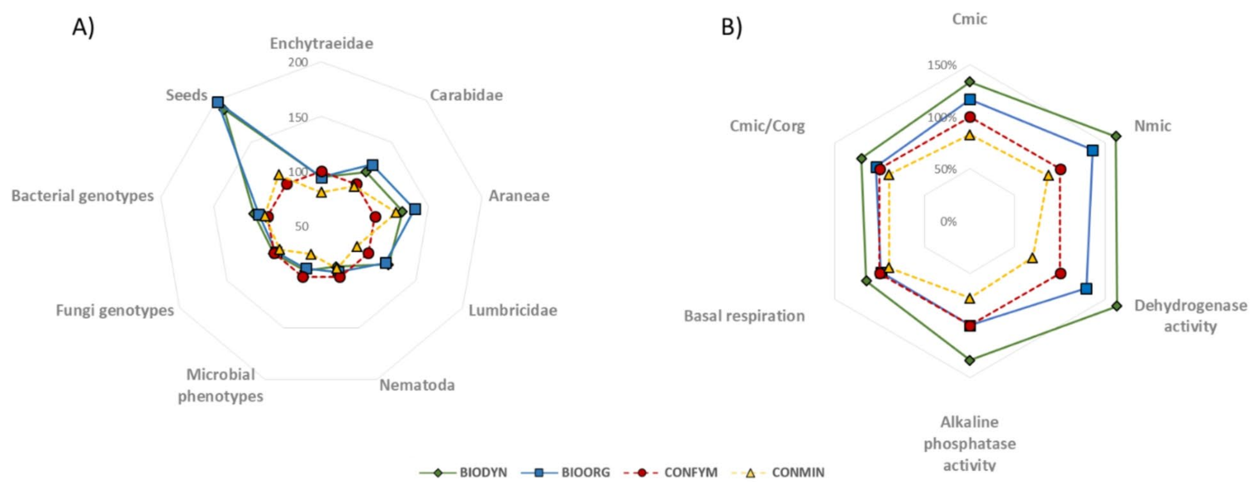

Fig. 3. Soil as habitat. (**A**) Richness of biological entities: soil faunal taxa relative to CONFYM (100%) as reported in studies investigating diversity of microbes, meso- and macrofauna and soil seed banks in the DOK experiment. (**B**) Soil biological quality indicators in relation to CONFYM (100%): microbial biomass carbon (Cmic), microbial biomass nitrogen (Nmic) dehydrogenase activity, alkaline phosphatase activity, basal respiration and the Cmic/Corg ratio.Source studies[63,76,87–90].

mineral fertilizers and synthetic pesticides, the yield reduction in organic systems (BIODYN and BIOORG vs. CONFYM and CONMIN) averaged across these five main crops in the 7-year crop rotation was 15% (Fig. 4)[37].

Relative performance of agronomic and environmental quality indicators

Relative performance indicators were assigned to critical impact categories such as yields, soil health, climate, biodiversity and nutrient balances (Fig. 5). While yield related indicators were clearly higher in the conventional system, indicators for biodiversity, soil health and climate were positively affected by organic cropping systems. Yet, it needs to be noted that the positive impact of organic systems on soil health and climate related indicators were mainly driven by the biodynamic system. Indicators related to nutrient balances showed mixed results. Nitrogen related indicators such as N balance or nitrogen use efficiency mainly differed between the two conventional systems CONFYM and CONMIN, while BIOORG and BIODYN were intermediate. Yet, more negative phosphorus balances in the organic systems were a major factor for overall lower performance of organic systems for this impact category (Fig. 5).

Discussion

Future agricultural systems must provide sufficient sustainable production in a changing environment and will face additional challenges such as decreasing soil-quality, environmental pollution, biodiversity loss and climate change adaptation. Unbalanced nutrient flows critically exceeded regulating capacity of the earth system, with globally increasing phosphorus and nitrogen use[2,38] and raising nitrogen surpluses, specifically in regions with excessive nitrogen inputs[39,40]. In this study we measured positive nitrogen balances for conventional and even organic systems, where nitrogen exclusively derives from farm internally recycled manure and biological nitrogen fixation, and no chemical nitrogen fertilizers are applied. Higher nitrogen inputs from biological nitrogen fixation compared to fertilizer nitrogen inputs in the organic systems underpin the pivotal role of legumes to secure a positive nitrogen balance and thus plant nutrition in organic cropping system, even when managed at 1.4 livestock unit per hectare fertilization intensity. Generally, positive nitrogen balances are needed to maintain crop growth since unavoidable losses occur via volatilization and leaching. Yet, the comparison of system specific nitrogen stock changes and nitrogen balances reveals a fundamental trade-off between efficiency and long-term soil health. High nutrient use efficiencies (NUEs) in the organically managed systems indicate that most of the nitrogen from liquid and solid manure and the fixed nitrogen became available to plants in the long term and thus demonstrates a huge potential to optimize fertilization management for an efficient use of nitrogen resources. An extremely high NUE, as observed in CONMIN, counteracts the retention of nitrogen in soil, limits soil organic matter build-up on the long run and indicates soil nitrogen mining[41]. In fact, soil nitrogen mining took place in the solely mineral fertilized soils in CONMIN, which lost 10 kg N ha^{-1} a^{-1} despite an even nitrogen balance (2 kg N ha^{-1} a^{-1}), while stable or rising soil nitrogen stocks were observed for all organically fertilized systems. Generally, high NUE in the DOK experiment might be linked to the favorable pedoclimatic conditions of a deep loess soil with good water retention capacities and sufficient precipitation[42]. Additionally, high nitrogen export in harvests might add to observed NUE, with greatest exports from grass-clover (393 kg N ha^{-1} a^{-1}), followed by maize (224 kg N ha^{-1} a^{-1}), soya (193 kg N ha^{-1} a^{-1}), winter wheat including straw (161 kg N ha^{-1} a^{-1}) and potato (117 kg N ha^{-1} a^{-1})[42].The nitrogen surplus of 47 kg ha^{-1} a^{-1} in CONFYM did not result in increasing soil nitrogen stocks, which denotes high potential of nitrogen losses and subsequent environmental

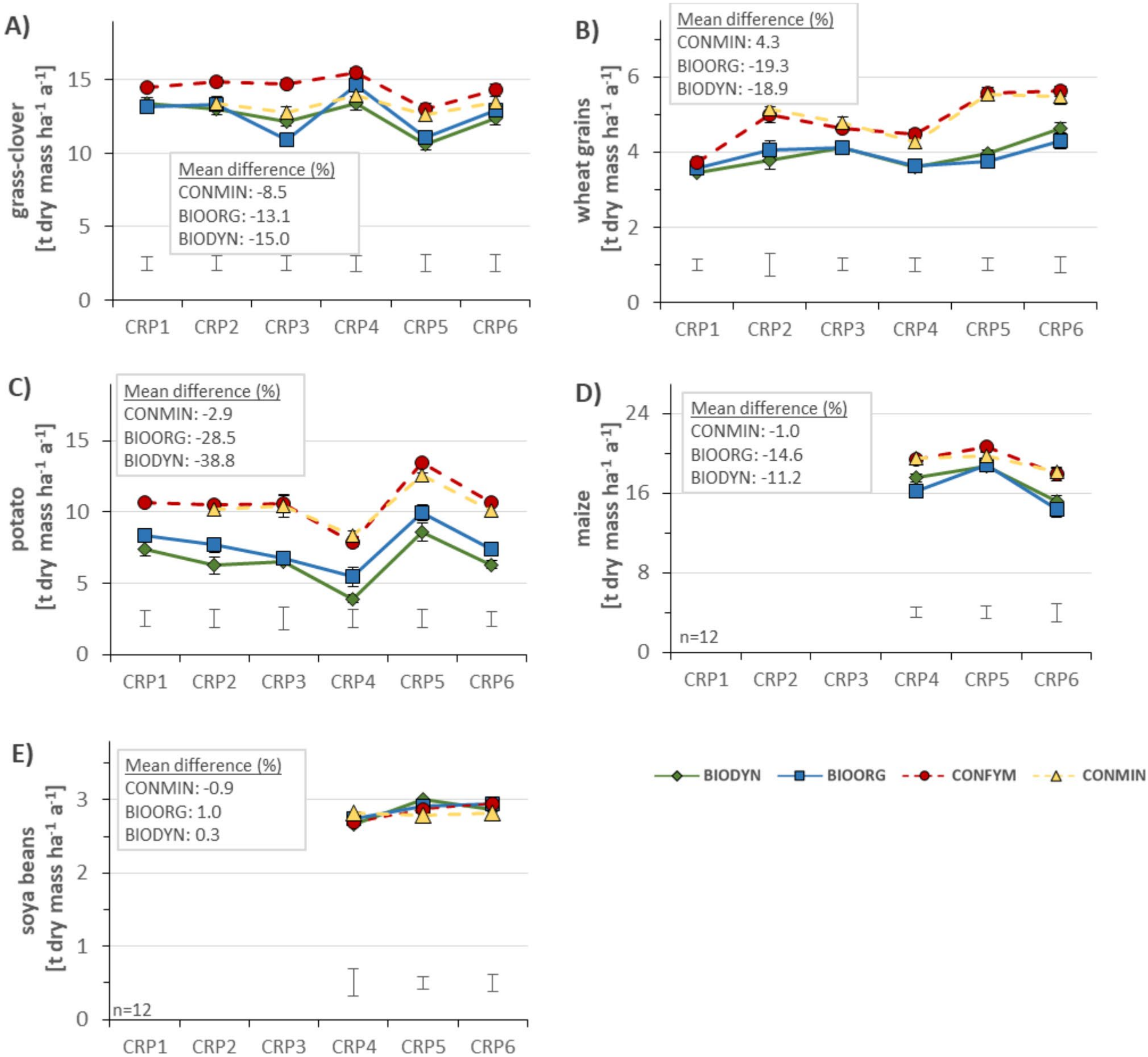

Fig. 4. Yield development over six crop rotation periods (CRP) of the five main crops (**A**) grass-clover, (**B**) winter-wheat, (**C**) potato, (**D**) maize and (**E**) soybean. Soybean and maize were grown for the first time in the 4th CRP. Data show mean yields per CRP and error bars represent least significant difference between system in a given CRP. The CONMIN system only took effect in the 2nd CRP, being left unfertilized before. Mean differences in percentages refer to relative yield differences to CONFYM.

impacts[9]. Indeed, highest N_2O emissions stem from the CONFYM system receiving organic and mineral nitrogen fertilization. Rising soil nitrogen stocks in BIODYN, receiving less nitrogen compared to CONFYM and CONMIN, reveal the positive effect of manure composting for the long-term build-up of soil nitrogen. Thus, our study shows that the substitution of mineral nitrogen by nitrogen fixing crops and in the form of manure can be achieved in organic cropping system, securing stable yields over several decades. However, strong reliance on biological nitrogen fixation in organic farms often is accompanied by phosphorus export as organic fertilizers capable of balancing crop nitrogen and phosphorus demands are still scarce[43]. Nitrogen availability and de-facto nutrient transfer from conventional to organic farms[44] might limit the widespread adoption of organic cropping systems. However, with 1.6% of global organic cropland area[26] and nitrogen surpluses in national and global cropland balances[8], this limit has not been reached yet[45].

Phosphorus efficiency is a major issue for agricultural production as 30% of global croplands suffer from phosphorus deficits with decreasing soil phosphorus stocks[46]. Here we could show that decreasing phosphorus stocks in the plough layer were not limited to organic systems, but also occurred in conventional systems. Declining phosphorus stocks cannot be explained by crop export alone as phosphorus balances (e.g. CONFYM) were only slightly negative. Transport of phosphorus into deeper soil layers[47] and leaching of dissolved

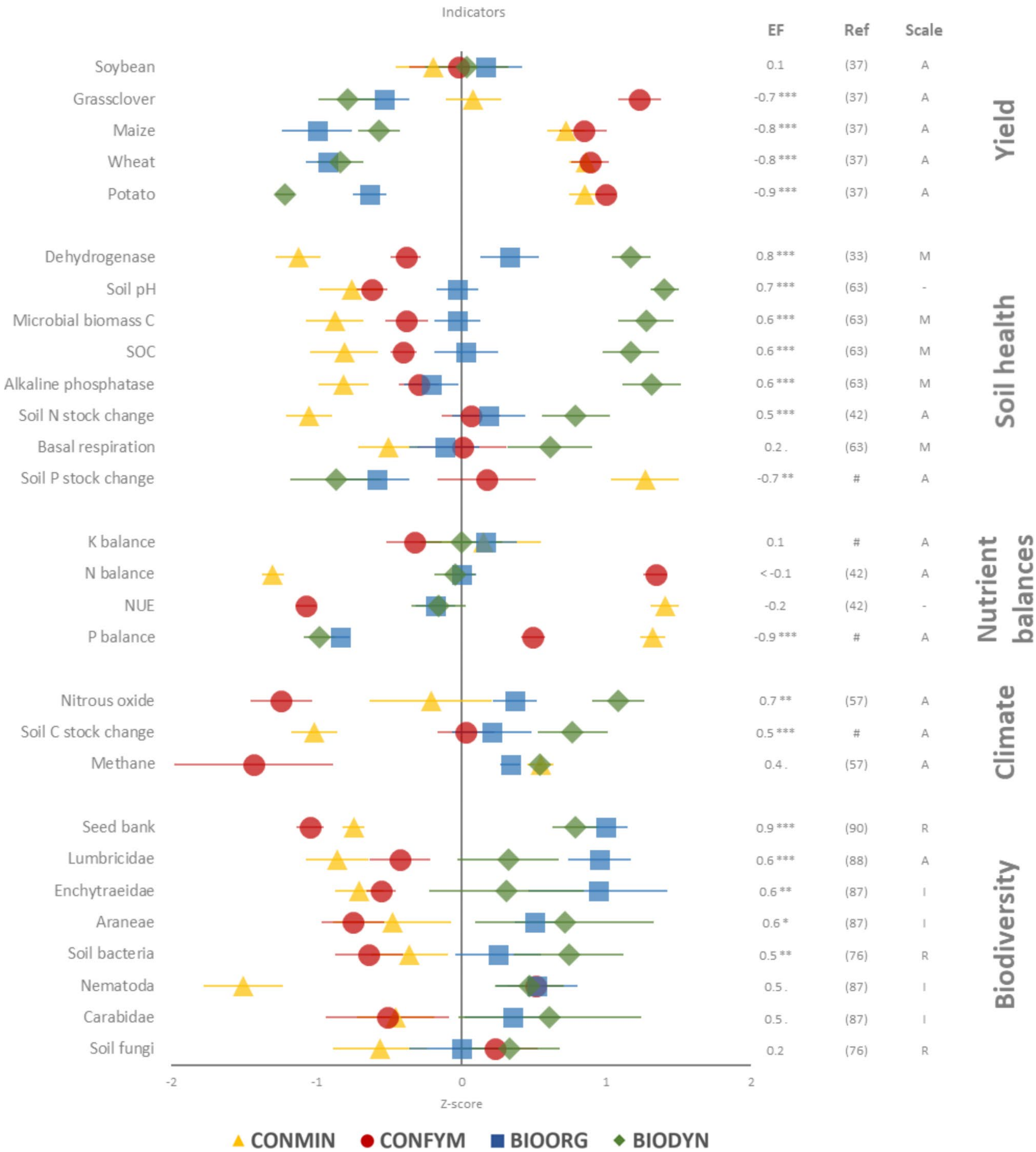

Fig. 5. Relative system performance based on z-transformation and standard errors of 28 indicators assigned to critical impact categories and ranked according effects size (EF) between organic (BIOORG and BIODYN) and conventional (CONFYM and CONMIN) systems. Impact of farming system was assessed by one-way Anova with * $p<0.05$, ** $p<0.01$ and *** $p<0.001$. Nitrous oxide and methane emissions were inversely calculated, resulting in positive z-scores for low emissions. Scales of indicators varied between area scaled (A) and mass scaled (M) indicators, while richness (R) and number of individuals (I) was used for biodiversity assessments. For soil pH and nitrogen use efficiency (NUE) none of these scales are applicable. Further details for each indicator can be retrieved from the cited publications. # refers to unpublished data and details are given in supplementary information.

phosphorus might have added to decreasing soil phosphorus stocks[48] and might also explain the sharp decrease of available phosphorus in the start phase of the field experiment. Even in the CONMIN system with a positive phosphorus balance, an enhanced phosphorus uptake and export via crops in the beginning of the field experiment could not be observed[47]. The impact of lower phosphorus inputs on plant nutrition in the organic systems might partly be compensated by increased phosphatase activity, cleaving organically bound phosphorus and making it potentially available for plant uptake. Indeed, organically managed soils were found to have higher gross organic mineralization rates than soils under CONMIN[49], yet organic phosphorus added via fertilization seems to be generally mineralized quickly as no differences in organic phosphorus stocks and composition were detected[50]. Also, a greater incidence of mycorrhiza in organic systems might contribute to crop phosphorus supply[51]. In organic systems, soil phosphorus stocks decreased to a greater extent than in conventional systems, which highlights the need for additional phosphorus fertilizers for organic farming. Yet, plant tissue analyses, so far did not indicate plant phosphorus deficiency symptoms in any system of the DOK experiment[52,53]. Still, decreasing phosphorus stocks in the plough layer in conventional and organic cropping systems emphasize the fundamental need to utilize yet unused phosphorus resources to avoid phosphorus limitation on the long term. Especially the recycling of phosphorus on a regional scale that aims to connect rural and urban phosphorus flows is discussed as most promising approach to mitigate phosphorus losses in the food system[54].

The agricultural sector is a major contributor to total greenhouse gas emissions[6], and agricultural systems have to adapt to a changing climate. The sector can contribute to the mitigation of greenhouse gas emissions, by stabilizing soil organic carbon stocks and minimizing N_2O and CH_4 emissions[18]. The observation that soil borne greenhouse gas emissions were mainly driven by N_2O emissions across all cropping systems emphasizes the need for optimized nitrogen management for sustainable agricultural production. Rising soil organic carbon stocks, as observed for organically fertilized systems, is discussed as a negative carbon dioxide emission technology effectively offsetting emitted carbon[55,56]. Despite the fact that N_2O emissions mainly stem from heterotrophic activity of soil microbes[20], lower N_2O emissions in organic systems were observed along with elevated soil organic carbon stocks and increased microbial biomass and activity. Lower N_2O emission were most likely linked to stable soil pH and amount and type of nitrogen fertilizers[57]. We could not confirm the proposed effect of enhanced soil organic carbon being compensated by raising N_2O emission[58]. Instead our data suggests that, N_2O emissions rather than changes of soil organic carbon contents drive area scaled climate impact and that reduced N_2O emissions can go together with enhanced soil organic carbon stocks to reduce overall area-scaled climate impact of organically managed soils. Similarly, Autret et al. (2019)[59] found lower climate impact of organic vs. conventional farming in a 19-year field site with the organic system even acting as a sink for soil borne greenhouse gas emissions. Yet, nitrogen fertilization levels were drastically lower in the organic system with a mean annual fertilizer nitrogen input of 9 kg ha^{-1} a^{-1} and a much higher yield reduction[59]. In line with our study a global meta-analysis showed lower area scaled N_2O emissions in organic versus conventional systems[60]. No significant differences were found in yield-scaled emissions in the DOK experiment[57] and a yield increase of 9% in organic systems would be needed to equalize yield-scaled emissions on a global base to mitigate additional land demand in organic agriculture[60]. While the climate impact of the food systems relies on multiple factors such as stocking densities, consumer diets and food waste[61], our study shows that the adoption of organic agricultural practice reduces the in-situ emissions of greenhouse gases and the area-scaled impact of food production.

Rising soil organic carbon stocks in organically fertilized systems also offer benefits for soil health and soil biology[62,63]. However, soil organic carbon concentrations evolve slowly and it took 22 years until significant differences were observed between BIODYN and CONFYM[63]. Notably, composting of manure in BIODYN, resulted in higher losses during organic fertilizer preparation and 19% less organic matter input compared to stacked manure application in CONFYM, which highlights the long-term value of manure composting for soil carbon management. Furthermore, the results demonstrated that the enhanced soil health indicators were significantly higher in the BIODYN compared to the BIOORG. Following a system comparison approach, we cannot fully disentangle the factors driving these differences, but composting of manure inputs in BIODYN and the use of copper in BIOORG might contribute to the observed differences. On the other hand, decreasing soil organic carbon stocks in CONMIN might be related to missing organic matter imports compared to organically fertilized systems. Enhanced soil organic carbon contents in organically managed system were also demonstrated in a global meta-analysis[32] and other case studies[35]. While enhanced soil organic carbon contents provide multiple benefits for soil health, organic fertilization does not necessarily translate to net CO_2 removal due to possible leakage effects[64]. In addition to that, density and size fractionation revealed that stable soil organic matter fractions, associated with minerals (MOAM) remained unchanged over the experimental period of the DOK experiment, and solely the particulate organic matter fractions (POM) were enhanced in BIODYN[65]. As POM fractions are considered rather labile and prone to losses upon changes in soil management[66], organic systems require constant effort to manage soil carbon stocks. Apart from manures, above and belowground plant residues and root exudates are major inputs of fresh organic matter to soils[67]. Concomitant to higher yields in the conventional systems, higher carbon input via roots and root exudates might be expected. However, a recent ^{13}C pulse-label study in wheat and maize in the DOK experiment showed rhizodeposition and roots carbon inputs was decoupled from aboveground biomass. In maize, even higher carbon allocation trough rhizodeposition and roots was found for BIOORG compared to CONFYM[68]. Thus, evolution of soil organic carbon stock cannot be explained by carbon balances alone but also needs to consider input quality and biological transformation and stabilization processes[69,70]. Summarizing, we found organic cropping systems to contribute to climate change mitigation and adaptation by stabilization of soil organic carbon stocks, while organic nitrogen fertilization strategy results in less N_2O emissions.

Enhanced soil organic carbon stocks in organic cropping systems come along with enhanced indicators for soil biological and habitat quality as well as greater richness of certain soil faunal and microbial guilds.

Interestingly, soil heterotrophic activity and rising soil organic carbon stocks were closely connected, suggesting biological activity to be a major driver for raising soil organic carbon stocks[63]. While there is increasing evidence that agrochemicals and fertilizers exert a strong effect on soil biodiversity[71–74] reduced nutrient and pesticide inputs to organic cropping systems help to minimize soil biodiversity loss below ground and above ground and thus maintain multifunctionality of agriculturally managed soils. Especially mycorrhizal fungi, crucial for crop phosphorus supply were enhanced in organic systems of the DOK experiment[51] and in crop- and grassland across Europe with low pesticide application[73]. Also in farm sites organically managed soils show lower pesticide loading compared to conventional, but a strong legacy effect fortifies the need for long-term management to sustain soil biodiversity[75]. Generally, soils in the DOK experiment exhibit distinct community structure of soil fungi and bactria[76]. Supporting the theory of enhanced soil multifunctionality and resilience, in organic cropping systems improved water-use efficiency of crops[77], plant pathogen suppression[78] and a greater capacity to mineralize organic nitrogen under drought conditions was observed[79]. Cropping system specific capacity for nitrogen mineralization under drought conditions could further be linked to distinct bacterial communities active in proteolysis in the DOK experiment[79].

As any plot experiment, the DOK study results are in a strict sense restricted to the site conditions, with a fertile soil and to the specific management practices applied in each system and cannot include landscape effects. While our results highlight the close linkage between soil health and soil biodiversity we recognize that a main threat to biodiversity, the loss of natural habitats, is largely driven by land demand[3,80]. Also, the fact that enhanced aboveground biodiversity can translate in enhanced weed pressure and competition for light and nutrient sources highlights the need for sophisticated management to maintain high and stable yield in organic cropping systems.

The main challenge for organic cropping systems are lower yields due to reduced nutrient and pesticide inputs[30]. The mean yield reduction between organic (BIODYN and BIOORG) and conventional (CONFYM and CONMIN) systems after CRP3 was 20%[31]. Yet, in this study the yield reduction declined to 15% after the inclusion of maize and soya from CRP 4 onwards (Fig. 4, Fig. S5-9). This yield gap is lower compared to the range of published meta-analyses on a global scale[30], which might be explained by the restrictions in pesticide and fertilizer use of Swiss Integrated Production systems, which lowers the intensification level of conventional cropping systems[81]. Moreover, total nitrogen inputs (i.e., stocking density) in the organic systems is at the higher end of reports from European farms and/or field experiments[42]. Stable yields in all systems of the DOK experiment show that, also mixed organic cropping systems, recycling animal manure at a rate of 1.4 livestock units per hectare can sustain yields for more than four decades. However, it needs to be noticed that due to lower yield levels in the organic systems, the relative yield stability was lower compared to conventional systems[37]. Out of the crops which were cultivated over all six crop rotations, yields increased in all systems for wheat, but stagnated or decreased for grass-clover[37]. Silage maize and soybean were only cultivated for three crop rotation periods, and showed slightly declining and increasing yields in all systems, respectively. Details on statistical analysis of yield stability in the cropping system of the DOK experiment can be reviewed in Knapp et al. (2023)[37]. Similar yields in soybean and little differences in grass-clover yield might be explained by the relatively high share of nitrogen-fixing clover in the mixture, and the lack of severe pest and diseases in soybean. Winter wheat and silage maize, two *Gramineae* densely rooted and with a long growth period, manifested 12% and 20% lower yields in organic systems. In the organic systems wheat had a higher affinity for symbiosis with mycorrhiza, which likely contributed to crop phosphorus supply and might have limited organic yield decrease[82]. The crop with the largest yield depression in organic was potatoes which have a high nutrient demand in a short growth period and are susceptible to pest and diseases. The effect of copper use in BIOORG is reflected in somewhat higher yields compared to BIODYN. The remarkable increase in wheat yields in CRP5 and CRP6 in the BIODYN system might be attributable to a new wheat variety bred under organic conditions (var. Wiwa). Importantly, out of the five main crops planted in the DOK experiment, grass-clover and silage maize are used as feed for animals to mimic a mixed cropping system at 1.4 livestock units per hectare. In turn, wheat, potatoes and soybean are cultivated as food for human consumption. Still raising yields in organic cropping systems are crucial to avoid additional land demand and thus negative impacts on climate and biodiversity[80,83]. Such efforts include technical and biological options like breeding for nutrient use efficiency and resistance against pests and diseases, circular economy using recycled fertilizers, and adaption of mixed crop-livestock systems. Last but not least, these changes need to be accompanied with changing consumer behavior and healthy diets with more plants and less meat[61,84].

In summary, we found that with drastic reduction of synthetic fertilizers and pesticide inputs in organic systems reduce pressure on soil health, biodiversity and climate related indicators with moderate yield losses (Fig. 5). The lack of mineral nitrogen and phosphorus input in organic systems contribute substantially to safeguard phosphorus stocks and reduces dependencies on external inputs with high energy demand for nitrogen fertilizers and thus renders organic systems more resilient to supply chain crises. For the long-term sustainability of organic and conventional cropping systems integration of livestock and crop rotation including legumes are conducive factors. Slowly decreasing soil phosphorus stocks, also in systems with a positive balance, urge for alternative phosphorus sources that connect urban and rural nutrient flows and balance regions with nutrient deficits and surpluses, especially in organic cropping systems. Although raising soil organic carbon stocks are relevant in view of soil health, our results point to the importance of N_2O as decisive greenhouse gas in arable cropping systems. Organic nitrogen fertilization and composting of farmyard manure can raise soil organic carbon stocks without increasing soil N_2O emissions. Enhanced soil health together with higher richness of microbiota and macrofauna in organic systems, also translates to higher microbial nitrogen mineralization under drought stress. Despite lower yields in organic systems, the yield reduction decreased from 20% after three crop rotations to 15% across six rotations, highlighting the potential of organic cropping systems to provide stable yield with low external inputs in the long term.

In conclusion, we observed that the reduction of synthetic fertilizers and pesticide inputs in organic cropping systems reduced the pressure on critical impact categories such as soil health, biodiversity and soil-based greenhouse gas emissions. These benefits are accompanied by a moderate yield loss. While there is a trade-off between yields and biodiversity, the widespread implementation of organic farming systems requires systemic changes that focus on sustainable intensification and the integration of livestock and perennial crops. This is necessary in order to take full advantage of the benefits on climate and biodiversity, and to provide fertile ground for the development of sustainable agroecosystems.

Materials and methods

Field site description and experimental setup

The DOK experiment was set up in 1978 in the vicinity of Basle (Therwil (BL), Switzerland; 47° 30.158'N, 7° 32.347'E), 308 m above sea level. DOK stands for bio-**D**ynamic, bio-**O**rganic and **K**onventionell (German, for conventional). Average yearly precipitation was 840 mm and mean temperature was 10.5 °C (climate norm 1991–2010). The soil type is a haplic luvisol on deep deposits of alluvial loess. Averaged across all field plots it contains 12% sand, 72% silt and 16% clay, and had an initial pH (H_2O) of 6.3 and a soil organic carbon content of 15 g kg^{-1}. Four cropping systems are compared, differing mainly with respect to fertilization and plant protection strategy (Tab S3). The DOK experiment can be described as a split-strip-plot design (Fig. S1). Each cropping system was replicated in four blocks and three iterations (A, B and C) resulting in a total of 12 observations per cropping system ($n = 12$). In the iterations A, B and C, identical crop rotations were planted, but iterated in time to account for seasonal variability. One crop rotation period (CRP) lasted seven years. Individual plot size was 5 m x 20 m. The bio-dynamic (BIODYN) and bio-organic (BIOORG) organic systems were fertilized with farmyard manure and slurry corresponding to 1.2 (CRP1 and CRP2) and 1.4 (CRP3-CRP6) livestock units per hectare (Tab S3). The fertilization intensity of the organic systems was based on the fodder produced in the respective crop rotation and reflects the intensity typically found on swiss mixed farms. One conventional system (CONFYM) was fertilized with the same amount of farmyard manure and slurry as the organic systems and, on top, with mineral fertilizers up to the level of the plant-specific Swiss standard recommendation[81]. The other conventional system (CONMIN) was introduced as a solely mineral fertilized control in CRP2 and was left unfertilized during CRP1. Both organic systems and the CONFYM system represent typical mixed cropping systems with arable crops and livestock, while the CONMIN system is purely based on mineral nutrient inputs. Since 1985, the conventional systems have been farmed according to the Swiss national regulations for integrated plant production, representing one type of good agricultural practice. The inputs of nitrogen, phosphorus and potassium of the four systems are shown in Table 1.

Plant protection in the organic systems was conducted according to bio-dynamic and bio-organic farming standards. Since management in the DOK experiment aims to mimic certified cropping systems, the plant protection strategy in the conventional systems was adjusted after the founding of Integrated Production Suisse label in 1989, which lowered annual pesticide use from CRP3 onwards (Fig S2). Still, across CRP2-6 pesticide use, expressed in active components equivalents, was 97% lower in BIODYN and 86% lower in BIOORG compared to CONFYM and CONMIN (Fig. S2). In the organic systems, weeds were controlled mechanically, and biocontrol (*Bacillus thuriengiensis var tenebrionis*) was applied to control Colorado beetles (*Leptinotarsa decemlineata*). Copper was applied only in BIOORG to potatoes as a fungicide. The seven years crop rotation was identical in all systems, including root crops, cereals and grass-clover ley (Tab S4). The same rotations were planted on three iterations A, B and C in the field (subplots), but displaced in time. Green manure and winter fodder crops were planted in all systems. To represent common agricultural practice in Switzerland, the crop rotation, and also management practices, were adjusted after each CRP[85]. In the last three CRPs, the crops remained constant but changed in order. The varieties of the different crops also changed over the duration of the experiment to be in parallel with common practice and to deal with possible break-downs of resistances. Soil tillage was similar in all treatments. The soils were ploughed to a depth of 15 to 20 cm before planting potatoes, winter wheat, cabbage, beetroots, soybean or maize. The grass-clover mixture was sown in drills after rotary harrowing the cereal stubble field and consisted of a mixture of *Dactylis glomerata*, *Festuca pratensis*, *Phleum pratense*, *Lolium perenne*, *Trifolium pratense*, and *Trifolium repens*.

Organic fertilizer quantification

Dry matter dependent nutrient contents in treatment-specific organic fertilizers such as slurry and manure were quantified each year. Briefly, nitrogen contents of fertilizers were determined according to Kjeldahl method with chemical oxidation and subsequent steam distillation. Organic matter contents were determined through incineration and photometric analysis of ash extract was used to quantify potassium and phosphorus contents. Relative nutrient inputs were calculated on mean annual inputs compared to CONFYM.

Soil carbon, nitrogen and phosphorus stock changes

Soil samples were taken from soil depth 0–20 cm. In order to assess changes in soil carbon and nitrogen stocks, carbon and nitrogen concentrations in archived soil samples were reanalyzed using dry combustion at 900 °C (Elementar, Vario Max Cube). Inorganic soil carbon content, although negligible in most samples, was analyzed in a separate subsample at 500 °C combustion temperature and used for the calculation of soil organic carbon concentration. Analyses were performed in analytical duplicates using 1 g of homogenized subsamples. Due to limited availability of samples from the first years of the field experiment, samples from 1984 served as baseline measure for CRP1. From the 2nd to 6th crop rotation (1985–2019) archive samples from every second year were reanalyzed with $n = 12$ per system and year. Soil total phosphorous was determined at the end of each CRP on dried and milled soil samples (0–20 cm sampling depth) with the ignition method. For that, 1 g of soil was ignited for 5 h at 550 °C, extracted with 1 M sulphuric acid for 16 h and the filtrate (Whatman 40) analyzed for the concentration of orthophosphate. Only soil from iteration C was analyzed for total P. Labile soil phosphorous was annually or bi-annually (2006 onwards) monitored by phosphorous extraction with CO_2 saturated water and subsequent colorimetric phosphorous determination.

Soil carbon, nitrogen and phosphorous stocks were calculated using plot-specific soil masses of the 0–20 cm layer based on mean bulk densities assessed three times during CRP1. For quantification of soil organic carbon in deeper soil layers (20–30 cm and 30–50 cm) an additional sampling of bulk density was carried out in spring 2019 at the end of CRP6 (Fig S3)[86]. Least square means of annual changes in soil organic carbon and nitrogen stocks per hectare were calculated using linear regression. As the CONMIN was effectively put into practice after the CRP1, data from CRP2 to CRP6 was used for regression analysis for all treatments. The effect of cropping systems on soil carbon stock changes was determined by ANOVA and subsequent Tukey posthoc test with clay contents as co-variable.

Nitrogen balance

The nitrogen balance was calculated as the difference between treatment-specific inputs and outputs for each experimental plot ($n=12$) as described in[42]. Inputs include atmospheric deposition, seeds, fertilizers and symbiotic N_2 fixation. Details on type and amount of nitrogen inputs are displayed in Tab S1 and Tab S2. Symbiotic N_2 fixation by soya bean and clover grown in the DOK experiment has been assessed using ^{15}N techniques[52,53], including estimates of belowground legume nitrogen inputs via roots and rhizodeposition[86], and transfer of fixed nitrogen from clover to associated grasses[53]. For nitrogen inputs via atmospheric deposition, 20 kg N ha^{-1} a^{-1} were assumed on the base of regional models. The nitrogen contained in seed was estimated based on available records on amounts of seeds applied per plot (kg ha^{-1}) and seed nitrogen concentrations by suppliers or from reference data[81] (Tab S2). Nitrogen outputs include all harvested products from 1984 to 2019 (CRP2-CRP6). In the case of cereals this meant from grain and straw, as straw was removed from the plots. Nitrogen concentrations of harvested products were assessed via dry combustion after milling and homogenizing harvested products and associated plant material separately. Nitrogen balance does not account for nitrogen losses through ammonia volatilization, nitrate leaching, and gaseous nitrogen losses due to denitrification and uses the field trial as system boundary. Nitrogen use efficiency was calculated by dividing outputs through inputs.

Phosphorus balance

The treatment-specific phosphorus balance was calculated similarly to the nitrogen balance, including phosphorus fertilizers and seeds as phosphorus inputs and harvested products as phosphorus outputs from 1984 to 2019. The phosphorus balance does not account for atmospheric phosphorus deposition and phosphorus losses through, e.g., leaching and erosion. The phosphorus balance was calculated for the whole experiment and for iteration C separately, since soil total phosphorus values are only available for iteration C. Differences in phosphorus balance between iterations A, B and C were negligible. Phosphorus use efficiency was calculated by dividing outputs through inputs.

Soil-based climate impact

Area scaled climate impact was assessed via N_2O and CH_4 emissions during a 571 days measurement campaign across a grass-clover, maize, green manure cropping sequence within CRP 6 [57] and soil carbon stock changes across the experimental period. To compare greenhouse gases, soil emissions were expressed as CO_2 equivalents. The system boundary was limited to the experimental field site and does not account for emissions during mineral fertilizer production, livestock husbandry and/or manure treatments. Annual changes in soil organic carbon stocks were converted to CO_2 equivalents to compare the relative impact of greenhouse gases. N_2O-N and CH_4-C emissions were quantified in a field campaign from 2012 to 2014 using static chambers with analytical duplicates[57]. The field campaign covered 256 days of grass clover, 140 days of maize followed by 175 days of green manure (*Brassica chinensis x Brassica rapa*) cultivation within field iteration C ($n=4$). Cumulative N_2O and CH_4 emissions were normalized to annual emissions and converted to CO_2 equivalents assuming global warming potential of 273 and 27.9 for a 100-year period[6]. Annual soilborne greenhouse gas emissions for each cropping system were calculated by summarizing means of net soil organic carbon stock changes, N_2O emissions and CH_4 emissions on the basis of CO_2 equivalents.

Biodiversity

The impact of cropping systems on biodiversity was synthesized from published studies. As it is inherently challenging to assess the effect of cropping systems on landscape biodiversity in a replicated field experiment we restricted our analysis to soil-related taxa of micro- to macrofauna, and seed bank analyses of weeds. Briefly, number of individuals and species richness of *carabidae* and *araneae* was assessed in samples from pitfall traps which were left open for 14 days from 3 to 17 May in 2005 during wheat cultivation[87]. Number of individuals and species richness of *nematodae* and *enchytreidae* was assessed from homogenized soil cores samples taken on 9 May 2005 using Oostenbrink elutriators and a combination of cold and hot funnel extraction[87]. Richness of *lumbricidae* was assessed four times between 1990 and 1992 by hand-sorting a soil block of 40 cm x 40 cm x 40 cm, after wheat, potato and beetroot[88]. Microbial phenotypes were assessed via analysis of phospholipid derived fatty acids in soil samples taken in March 2003 during winter wheat[89]. Richness of soil bacterial and fungal genotypes was analyzed in soil samples taken during winter wheat and grassclover in march 2000 and march 2007, each, and analyzed using DNA based sequencing and clustering of operational taxonomic units at 97% sequence identity[76]. Richness of seedbank diversity was assessed in spring 2009 in wheat and maize, by taking undisturbed soil cores from each experimental plot and subsequent incubation to enhance germination[90].

Yields

Yield assessments are described in detail in[37]. Briefly, 16 plots were harvested (4 systems x 4 field replicates) per crop, year and iteration. Per crop rotation, there were 6 harvests of grass-clover, 3 of silage maize, 3 of soya bean, 6 of winter wheat, and 3 of potatoes across all three iterations. In CRP3 there were 9 harvests of grass clover due to a 3rd year of grass-clover cultivation. Yields were expressed as dry matter per hectare. Effects of cropping systems on average yield in each CRP were assessed by analysis of variance and subsequent Tukey post hoc tests (Tab S5-9). Influence of seasonal and variability was assessed by including experimental blocks and iterations as additional factors.

Relative system performance

Indicators for agronomic and environmental performance of cropping systems were retrieved from peer-reviewed studies investigating all four main cropping systems (CONMIN, CONFYM, BIOORG and BIODYN) of the DOK field experiment. For all indicators, z-transformation of parcel-specific values and one-way Anova was used to calculate the impact of organic (BIOORG and BIODYN) vs. conventional (CONMIN and CONFYM) cropping systems using the stats package v4.2.2 in R. Subplot was used as covariable except for biodiversity assessment, soil phosphorus stock change, nitrous oxide and methane emissions, when not all subplots were investigated[57,87,88,90]. To quantify impact strength of each indicator, effect size between organic (BIOORG and BIODYN) and conventional (CONFYM and CONMIN) cropping systems were calculated using Cohens D approach. To account for critical challenges of agroecosystems, indicators were additionally assigned to impact categories, which were defined as agronomic yields, soil health, nutrient cycling, biodiversity and climate impact (Fig. 5).

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Author contributions
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Declarations

Competing interests
The authors declare no competing interests.

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Correspondence and requests for materials should be addressed to H.-M.K. or P.M.