

Review

Constraints on the expansion of organic farming in highly productive regions

Henrik G. Smith^{a,b,*}, Göran Bergkvist^c, Mark V. Brady^{a,g}, Romain Carrié^{a,h}, Sigrun Dahlin^c, Johan Ekroos^{a,d,e}, Christian Jörgensen^g, Ingrid Öborn^c, William Sidemo-Holm^a, Christine A. Watson^{c,f}

^a Centre for Environmental and Climate Science & Department of Earth and Environmental Sciences (MGeo), Lund University, Sweden

^b Department of Biology, Lund University, Sweden

^c Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden

^d Department of Agricultural Sciences, University of Helsinki, Helsinki, Finland

^e Helsinki Institute of Sustainability Science (HELSUS), University of Helsinki, Finland

^f School of Natural & Social Sciences, SRUC, Aberdeen, UK

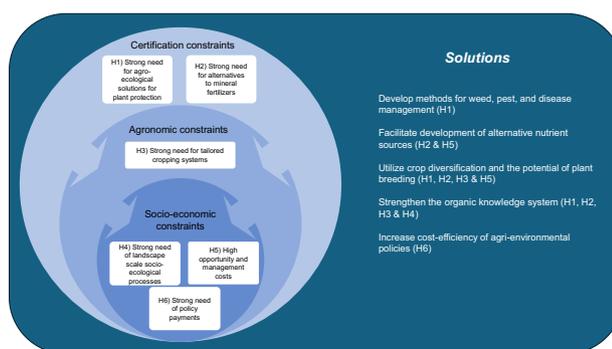
^g AgriFood Economics Centre, Swedish University of Agricultural Sciences & Lund University, Sweden

^h Dynafor, INRAE, University of Toulouse, Toulouse, France

HIGHLIGHTS

- A nested constraint hierarchy explains low uptake of organic farming in productive areas.
- Ameliorating constraints high in the hierarchy solve lower order constraints.
- In productive areas the need for alternative nutrient resources is critical.
- Based on our nested constraint hierarchy we propose solutions to increase organic uptake.
- Trans-disciplinary research and collaborative approaches needed to close knowledge gaps.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Mark van Wijk

Keywords:

Agri-environment schemes
Agroecology
Cropping systems
Ecological intensification
Functional biodiversity
Multi-actor approach
Nutrient management

ABSTRACT

CONTEXT: Uptake of organic farming falls short of stated sustainability targets, particularly in highly productive regions where adoption could mitigate environmental impacts of intensive farming. Several hypotheses have been advanced to explain the constraints on adoption, but these have not been assessed within an integrative, interdisciplinary framework.

OBJECTIVE: The objective was to develop a conceptual framework linking existing hypotheses on the constraints to the uptake of organic farming in highly productive agricultural regions, to review the supporting evidence and, based on this, to propose solutions for increasing adoption.

* Corresponding author.

E-mail address: henrik.smith@biol.lu.se (H.G. Smith).

<https://doi.org/10.1016/j.agsy.2026.104699>

Received 7 September 2025; Received in revised form 18 February 2026; Accepted 27 February 2026

Available online 7 March 2026

0308-521X/© 2026 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

METHOD: An interdisciplinary team developed a nested hierarchical framework of ecological, agronomic, and socio-economic processes influencing adoption of organic farming. They critically examined existing literature in relation to hypotheses and identified potential solutions to enhance adoption.

RESULTS AND CONCLUSIONS: We present a nested hypothesis hierarchy of interrelated constraints on organic conversion with special relevance to low uptake in highly productive regions dominated by arable crops. *Certification constraints* reflect fundamental needs for agroecological solutions for crop protection and nutrient supply, which are difficult to address in the absence of animal husbandry. The certification constraints give rise to *agronomic constraints*, driven by the greater divergence between organic and conventional crop rotations in such regions. While agronomic constraints are solvable, their solutions are limited by *socio-economic constraints*, including higher knowledge demands and opportunity costs for organic farmers, which current area-based policy-payments do not fully offset. Our review finds evidence for all constraint types, however, in highly productive areas the certification constraint *need for alternative nutrient resources* dominates, with downstream consequences for agronomic and socio-economic constraints. We demonstrate how our framework can guide solutions across the nested hierarchy: alleviating certification constraints through ecological intensification and alternative nutrient sources; addressing agronomic constraints by diversifying crop rotations; and overcoming socio-economic constraints by strengthening extension services and improving the spatial targeting of policy payments. Finally, we argue that persistent knowledge gaps call for stronger trans-disciplinary research to bridge the scale-related disconnect between academic research and farmer needs, as general approaches and small-scale experiments often fail to inform on-the-ground implementation.

SIGNIFICANCE: Given that expansion of organic farming in the EU is stalling, there is substantial interest in identifying strategies to enhance its uptake, particularly in regions where adoption remains limited. This study provides a basis for future research, informing management decisions, and guiding policy development for fostering the expansion of organic farming, and hence advance the overarching goal of increasing agriculture's sustainability.

1. Introduction

Long-term structural change in agriculture, driven by technological progress, economic growth and improved off-farm income opportunities, as well as public policies to increase food production, have resulted in agricultural specialization and intensification in many parts of Europe (Lefebvre et al., 2012; van Vliet et al., 2015). At the field level, it has resulted in increased use of agrochemicals, simplified crop rotations and more productive crops (Stoate et al., 2001; Emmerson et al., 2016). At the farm level, it has resulted in the conversion or abandonment of semi-natural habitats (Stoate et al., 2001; Török and Dengler, 2018). At regional scales, it has resulted in the separation of crop and livestock production (Peyraud et al., 2014; Garrett et al., 2020), and in agricultural land-use intensification in some regions and abandonment in others where farming is no longer economically viable (Terres et al., 2015; Ustaoglu and Collier, 2018).

The structural changes in European agriculture have entailed increased environmental externalities such as downstream eutrophication, spread of toxic chemicals, release of greenhouse gases, and biodiversity loss (Stoate et al., 2001; Emmerson et al., 2016). While it may be argued that some of these effects are offset by higher yields that reduce the demand for land (Green et al., 2005; Burney et al., 2010), environmental externalities are generally considered a major problem in need of mitigation (Stoate et al., 2009; Pe'er et al., 2022; Finger et al., 2024). Current developments also pose risks to the sustainability of agriculture itself, due to, e.g. evolving pesticide resistance (Heap, 2014; Gould et al., 2018), loss of ecosystem-service providers vital to pest control and crop pollination (Bianchi et al., 2006; Potts et al., 2016), and loss of soil carbon and associated soil fertility (Heikkinen et al., 2013; Harbo et al., 2026). The disconnection of crop and livestock production reduces the efficient use and recycling of nutrients (nitrogen, phosphorus etc.) at farm to regional scales and even globally because of feed imports, leading to nutrient losses through mechanisms such as erosion, leaching and volatilization, also with consequences for greenhouse gas emissions in the form of nitrous oxide (Peyraud et al., 2014; Nesme et al., 2015).

There is mounting pressure for European agriculture to reduce its environmental impacts and maintain landscape multifunctionality (European Commission, 2020; European Environment Agency, 2021; Leduc et al., 2021). Through various policy measures, some intensification trends have stabilized or even slightly reversed (e.g., Levers et al.,

2016), but measures have not been sufficient to meet environmental objectives and historical legacies of past management continue to drive environmental impacts today (Stoate et al., 2009; Pe'er et al., 2014; Grizzetti et al., 2021; Carvalho et al., 2025). Organic farming has been identified as a key measure for reducing environmental impacts (Eyhorn et al., 2019; European Commission, 2021; Gamage et al., 2023). Based on a set of principles – Principles of Health, Ecology, Fairness and Care – organic farming aims at producing sustainably (Luttikholt, 2007). These principles are, in turn, codified into rules that apply both for organic labelling of products and eligibility for public support, including prohibition of synthetic fertilisers and pesticides (Seufert et al., 2017; European Union, 2018). In turn, this way of producing food requires systematic changes to production systems, such as more complex crop rotations, to achieve ecological solutions to agricultural challenges (Watson et al., 2002a; Porter, 2009).

To increase the uptake of organic farming, multiple policy instruments have been enacted, such as policy payments to farmers for organic farming, public procurement of organic food, public support to research and development relevant to the organic sector, and soft governance measures (Stolze and Lampkin, 2009; Lampkin and Sanders, 2022). Plans to increase organic farming have been developed both in individual countries and for the EU through the new EU Action Plan launched in 2021 (European Commission, 2021). In addition, organic farming has benefitted from price premiums for organic produce (Crowder and Reganold, 2015; Eynade et al., 2021) and potentially promotion of organic products by retailers (Aigner et al., 2019). As a result, organic production in the EU has increased annually by 5.7% 2012-2020 to reach an area of 14.8 million ha (European Commission, 2023b). However, the target of having at least 25% of agricultural land under organic production by 2030 (European Commission, 2020), remains to be met, as the current area is 9% (Eurostat, 2023). Furthermore, area-based uptake in Europe is growing at a slower rate than the increase in European consumption of organic food (Willer et al., 2021). Current increases in food prices may also lead to reduced consumption of the more expensive organic produce (cf. Lindström, 2022 and references therein), threatening further expansion of organic farming as seen at the EU level (Fig. 1), and may even result in organic farms withdrawing from certification and returning to conventional practices (cf. Sahm et al., 2013), as already observed in Sweden (Fig. 1). The uptake also varies considerably between EU countries (from 2% in Ireland and

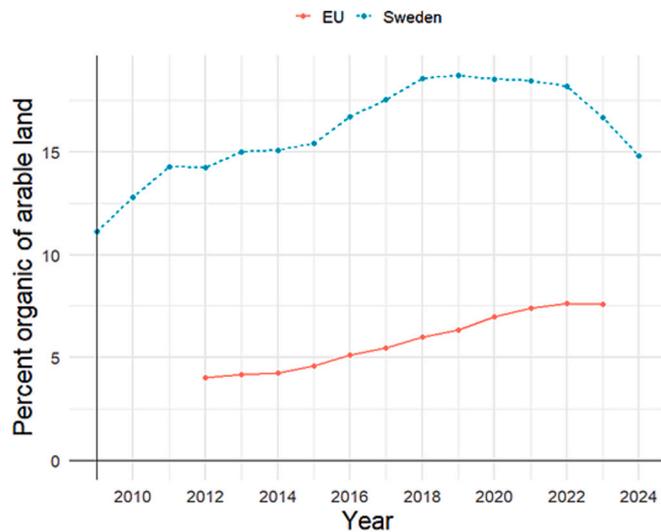


Fig. 1. Percent of arable land in EU managed using organic production methods and meeting the EU regulations (<https://eur-lex.europa.eu/eli/reg/2008/889/oj>) and that in Sweden reported to the Swedish Board of Agriculture by approved control bodies in the agricultural sector (SBA, 2025). Information downloaded from EUROSTAT (https://ec.europa.eu/eurostat/databrowser/view/org_cropar/) and the Swedish Board of Agriculture's statistical database (<https://statistik.sjv.se/PXWeb/pxweb/sv/Jordbruksverkets%20statistikdatabas/?rxid=5adf4929-f548-4f27-9bc9-78e127837625>).

Malta to over 20% in Austria, Estonia and Sweden, European Commission, 2023b) (Fig. 2), and is related to population density and educational level (Sandström et al., 2025). Within countries, there is evidence that uptake of organic farming is particularly constrained in regions characterized by high crop yields and often dominated by production of cash crops, which we refer to as *highly productive* regions. In a high-resolution analysis, Sandström et al. (2025) found that uptake was higher in areas with unfavourable biophysical conditions for agriculture, and in Sweden conversion to organic farming has predominantly occurred in regions characterized by relatively low crop yields and ruminant livestock farming dependent on arable-grass fodder production (Rundlöf and Smith, 2006; Basnet et al., 2018). Similar trends are observed in e.g. Germany (Schmidtner et al., 2012) and Great Britain (Gabriel et al., 2009). This is a concern, since it is in the highly productive areas that negative externalities of agriculture in terms of pollution from agrochemicals and loss of biodiversity are particularly high and most in need of amelioration (Stoate et al., 2009).

For the EU to reach its organic goal, it is necessary to understand what factors are constraining the expansion of organic farming, particularly in regions with low current uptake, specifically highly productive, intensively cropped regions with few ruminants. Several hypotheses have been posited to explain constraints to uptake (e.g., Rundlöf and Smith, 2006; Schmidtner et al., 2012; Läpple and Kelley, 2013; Dessart et al., 2019; Sapbamrer and Thammachai, 2021), but the hypotheses have rarely been comprehensively presented and jointly evaluated (but see Möhring et al., 2024 for a decision-oriented framework). One likely reason for this is that the hypotheses concern factors that have been investigated in a variety of disciplinary areas including: agronomic and ecological factors, economic preconditions for organic farming, design of policy instruments, private certification systems and socio-cultural constraints among farmers. Accordingly, it requires an interdisciplinary effort to deal with the complexity and inter-relatedness of these hypotheses, to identify main barriers that may be targets for research, management changes and policies aiming to increase uptake. In this review, we identify and evaluate six hypotheses relating to what constrains the uptake of organic farming in highly productive regions (Table 1), present the current state of evidence and examine how the

different hypotheses are interrelated. Based on this evaluation, we summarize the implications of current knowledge, suggest means to break constraints on uptake and identify research gaps.

Because our scope is to conceptualize a hierarchy of ecological, agronomic and socio-economic processes affecting the uptake of organic farming, the review covers a wide range of topics across different disciplines. Therefore, instead of carrying out a systematic review which would have been unfeasible given the wealth of questions (cf. Haddaway and Westgate, 2019), we elected to perform a hermeneutic review where we critically interpret and make sense of the existing literature (Greenhalgh et al., 2018). This was enabled by creating a team of authors with a long-term experience of research on organic farming across disciplines.

2. Hypotheses

Conventional farmers considering converting to organic farming in highly productive agricultural regions face a series of challenges or *constraints* that reduce the likelihood that they will convert. We have identified six commonly hypothesised constraints on converting to organic farming from the scientific literature, particularly in regions dominated by conventional cash-crop farms (Table 1, Fig. 3).

Clearly, the foremost constraints on the expansion of organic agriculture in regions dominated by conventional arable farming are the needs to find agroecological solutions for crop protection and alternatives to synthetic fertilisers. These needs have been codified in labelling systems for certified organic production as prohibitions on the use of synthetic chemicals for protecting crops against weeds, pests and diseases, and restrictions on the use of synthetic fertilisers for meeting crop nutrient needs. These *certification constraints* are particularly severe in regions dominated by arable farms. First, cropping systems that have emerged from decades of conventional arable cropping tend to have small populations of natural enemies of crop pests and to be dominated by particularly problematic weed species, creating a vicious circle of reliance on synthetic chemicals (H1). Second, organic systems are dependent on organic nutrient sources such as farmyard manure, with limited availability in high-productive areas as a result of the regional specialization of agricultural production in recent decades (H2). Even so, these constraints can partially be alleviated, over time, through the introduction of more complex cropping systems, particularly using perennial grass-clover break crops between cash crops, and more diverse crop rotations (i.e., growing a greater variety of crops). However, this means that the organic-certification-constraints translate into *agronomic constraints*, in terms of using longer and more complex crop rotations. These cropping systems will differ more from conventional ones in highly productive areas where conventional farming is dominated by annual cash crops, making transition to organic management more demanding (H3).

Given appropriate agroecological methods, the agronomic constraints and the certification constraints on organic farming can be overcome, but what is agronomically possible may be counteracted by various *socio-economic constraints* faced by farmers. First, organic farming requires new or re-learning lost traditional knowledge, particularly how systems can be adapted to local conditions. Organic farming also requires different infrastructure, including advisors skilled in organic farming and supply chains for inputs and market chains for produce. Both knowledge building and exchange and access to relevant infrastructure is more difficult in productive regions where there are fewer neighbours practicing organic farming compared to where there are many adopters (H4). Second, organic management results in high opportunity costs both from loss of yields compared to conventional farming and the use of more complex crop rotations involving less cash crops. The higher profitability of cash cropping and the larger “yield gap” will pose larger constraints on organic farming in highly productive regions (H5).

Ultimately, these constraints could be overcome with adequate

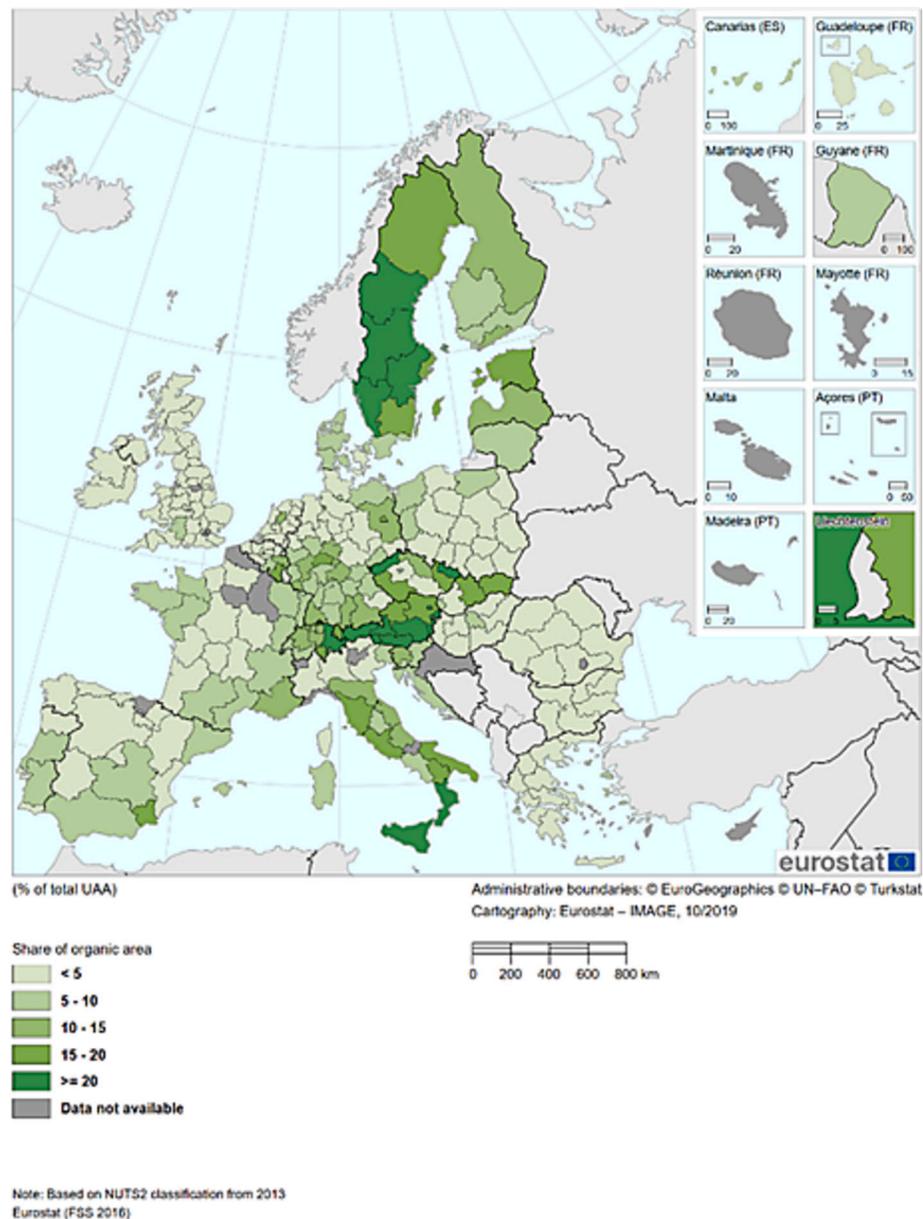


Fig. 2. Uptake of organic farming 2016 in the EU by national units of statistics (NUTS 2) regions, the intermediate of three levels used by Eurostat to present statistics. Reproduced from <https://ec.europa.eu/eurostat/web/products-eurostat-news/-/edn-20191016-1> under the Creative Commons Attribution 4.0 International licence.

policy payments to bridge the gap in profitability between conventional and organic systems. Indeed, such payments are offered for organic farming. However, today these uniform area-based payments are relatively low compared to the profitability of conventional cash crops in high-productive regions and thus reinforce the uptake of organic in less productive, mixed farming and livestock-dominated regions (H6).

H1. Stronger need for agroecological solutions for plant protection.

Organic farmers cannot control weeds, pests and diseases with synthetic crop protection products, and are thus mainly reliant on mechanical control measures, spatio-temporal isolation, and harnessing naturally occurring control agents and antagonists to avoid crop losses caused by weeds, pests and pathogens (Zehnder et al., 2007; van Bruggen and Finckh, 2016; Costa et al., 2023). This may be more challenging in highly productive areas where natural enemies to crop pests can be less abundant because: landscapes are structurally simple (cf. Bianchi et al., 2006; Chaplin-Kramer et al., 2011), cropping systems are

characterized by functionally simpler crop rotations (cf. Redlich et al., 2018; Guinet et al., 2023), particularly lacking perennial components (Chopin et al., 2026), and use of synthetic pesticides and fertilisers is pervasive (cf. Jonsson et al., 2012; Pandey et al., 2022).

Increased weed pressure is a key concern for converting to organic farming (Ferjani et al., 2010) and can be a major cause of loss of yield and its quality (e.g., Casagrande et al., 2009; Armengot et al., 2013). Landscape simplification may affect weed species richness less in organic compared to conventional farms (e.g., Roschewitz et al., 2005; Holzschuh et al., 2007), but the density of weeds species that are well adapted to disturbance has the potential to be higher in short and simple crop rotations characteristic of cash-crop landscapes (Liebman and Dyck, 1993; Scott and Freckleton, 2022), at least when sowing times and life cycles are similar among crops in the rotation (Weisberger et al., 2019).

Pests and diseases can also limit organic yields, particularly in high-value crops frequently grown in productive regions, such as oilseed rape

Table 1

Hypotheses about what constrains conversion to organic farming and why these constraints are particularly severe in highly productive regions dominated by arable farming, resulting in a heterogeneous uptake. For supporting references, see main text.

	Hypothesis	Constraint	Why more severe in productive regions
1	Strong need for agroecological solutions for plant protection	Farmers cannot use synthetic pesticides to protect crops from weeds, pests, and diseases	Lack of habitat supporting natural enemies of pests and lack of perennial crops in rotations compromise pest and weed suppression possibilities
2	Strong need for alternatives to mineral fertilisers	Farmers cannot use synthetic fertilisers to meet crop nutrient needs	Higher demand for imported nutrients when yield potential is high and little nutrients circulated through animals
3	Strong need for tailored cropping systems	Organic production requires crops and cropping systems resilient to low nutrient availability and high incidence of weeds, pests, and diseases	Need for considerable changes in cropping systems makes transition more demanding
4	Strong need of landscape scale socio-ecological processes	Lack of neighbouring organic farms constrains beneficial ecological processes at landscape scales and limits the reinforcement of knowledge-based and cultural feedback that support organic management	Fewer organic neighbours
5	High opportunity and management costs	Organic farming generally results in lower yields, and more costly measures to ensure nutrient availability and crop protection	Higher potential loss of yields both because conventional yields are higher and tools fewer to maintain high organic yields
6	Strong need of policy-payments	Price premiums not sufficient to compensate lower profits for organic farming	Higher opportunity costs related to yield losses and management not compensated by sufficient differentiation of area-based policy payments

and potatoes (Möller et al., 2006; Charles et al., 2020) and may contribute to the lower yield stability in organic compared to conventional farming (Knapp and van der Heijden, 2018). The generally lower abundance of natural enemies in highly productive agricultural landscapes, characterized by a high proportion of arable land, may be caused by spatio-temporal resource discontinuity related to strong disturbance regimes from intensive agricultural practises and low habitat heterogeneity resulting in a lack of source habitat (Jonsson et al., 2012; Smith et al., 2014). Structurally simple arable landscapes can also decrease possibilities to isolate disease vectors and pest pressures between crop fields (cf. Plantegeest et al., 2007; Clafin et al., 2017). There are, however, major idiosyncrasies in how natural enemies, crop pests and disease vectors respond to changes in agricultural methods and landscape structure (e.g., Karp et al., 2018; Mahas et al., 2025), and the impacts on plant health and crop yield are therefore difficult to predict (cf. Alexandridis et al., 2022).

To conclude, the evidence suggests that controlling weeds, pests, and diseases without the use of synthetic chemicals will be more challenging in highly productive areas, but there is a lack of evidence as to what extent it constrains conversion to organic farming.

H2. Strong need for alternatives to mineral fertilisers.

Organic farming restricts the import of mineral fertilisers because it aims to rely on supplying nutrients to crops through managing soil fertility via rotations and the use of on-farm manures and crop residues (Watson et al., 2002a). Organic farms may also to some extent import nutrients from outside the farm, but this is subject to certain restrictions (European Commission, 2023a). The import can come from different sources including manure from other farms, biogas digestate and food industry by-products, but animal manure is currently the key source (Carr et al., 2020; Döring and Neuhoﬀ, 2021). While stockless organic farms source more external nutrients than livestock farms, purchased feed may serve as a “hidden” source of nutrient inputs on organic livestock farms (Reimer et al., 2023). In highly productive regions with little livestock production, the opportunity to purchase (or exchange) manure from neighbours is limited (Nordin, 2021). The fact that few farms in these productive regions currently have livestock, particularly ruminants, constrains conversion to organic farming. This is because converting from arable conventional cash crop production to organic farming with both crops and livestock would require relevant knowledge, entail substantial investments in buildings and water supply, and result in high opportunity costs of forage production compared to cash crops (Martin et al., 2016) (see H3). Furthermore, the type of livestock production that is common in productive regions, such as pigs and poultry, requires specialist skills and infrastructure for organic production and is perceived more challenging in terms of conversion to organic than ruminant production (Hermansen et al., 2004).

Biological fixation of atmospheric nitrogen (BNF) is a major source of nitrogen for organic farming through the inclusion of legumes in rotations. Forage legumes provide considerably larger net nitrogen input to the systems than grain legumes (Anglade et al., 2015). However, relying on BNF based on forage legumes without including animal husbandry would result in even higher opportunity costs, since short-term grass/legume leys and green manures in this case cannot be used for grazing and silage at the farm level (H3). Hence, this would likely require an alternative use of leys, e.g., for biogas or biorefinery (protein fractionation), to be economically viable (Tidåker et al., 2014; Micke et al., 2023).

Although nutrient budgets for organic farms in Europe are generally positive or neutral except for potassium, organic farms without livestock or imported manures frequently show lower surplus of nitrogen and negative balances of phosphorus and potassium (Reimer et al., 2020), indicating unsustainable mining of nutrient reserves with long-term negative consequences for crop yields and quality (Foissy et al., 2013). The severity of this will depend on soil type and historical management and may mostly be a long-term issue when converting to organic management (Watson et al., 2002b). Recent research also highlights the large spatial variability in phosphorus inputs and outputs, and the resulting phosphorus budgets for different production systems (Magaya et al., 2025). While sources of phosphorus that are recycled and of acceptable quality are limited in organic farming, rock phosphate is permitted within current EU regulations but usually solubilised in soil at a slow rate that cannot match crop demands (Edwards et al., 2010).

To conclude, the difficulties of finding economically viable solutions to nutrient demands is a key constraint to conversion to organic farming in highly productive agricultural regions currently dominated by arable farming.

H3. Strong need for cropping systems tailored to organic production.

For organic farmers, the design of the cropping system is critical to sustain long-term yields as the options to overcome challenges of, for example, weed and pest control as well as nutrient limitation are more limited than in conventional farming (H1, H2). Organic farmers thus rely on functionally diversified crop rotations, often related to livestock production, including the use of short-term grass-clover leys and grain legumes in crop rotations (Barbieri et al., 2023; Schaak et al., 2023). Arable farmers face the challenge of either including more leys in rotations to provide nitrogen and control weeds, or use of more inputs such

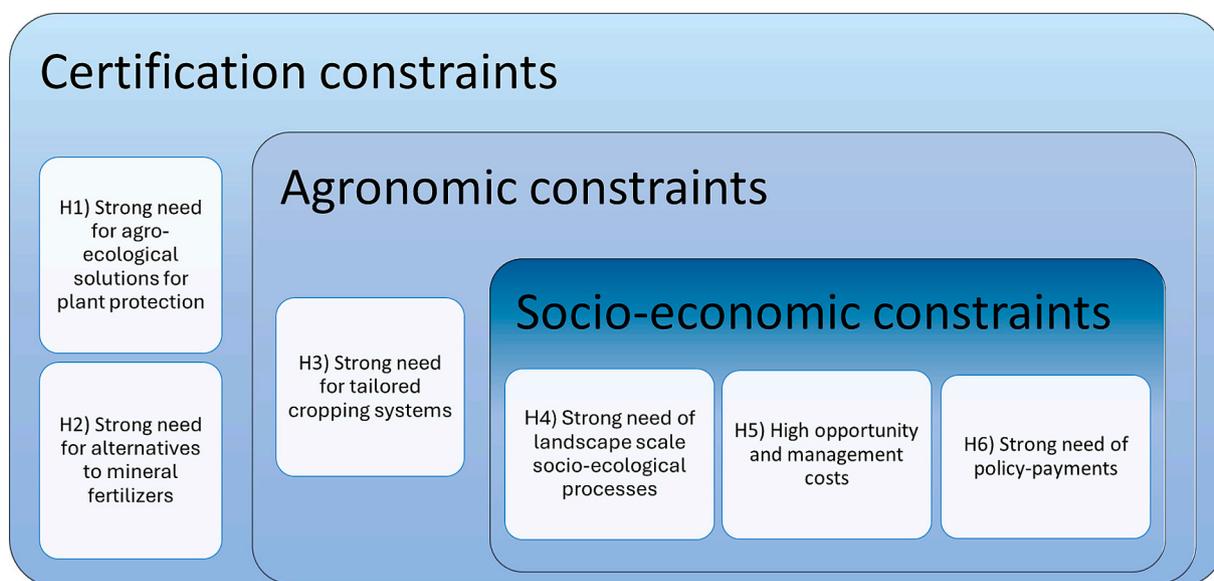


Fig. 3. Six hypotheses about constraints explaining the low uptake of organic farming that may be particularly important in highly productive agricultural regions dominated by conventional cash cropping, nested at three levels. *Low* in the hierarchy, the socio-economic constraints that directly affect farmers' decision making are contingent on the intermediate agronomic constraints that constitutes solutions to handle the certification constraints *high* in the hierarchy that are codified in organic production rules. Overcoming constraints high in the hierarchy will alter the likelihood that constraints lower in the hierarchy apply, whereas overcoming constraints lower in the hierarchy will leave those higher up unaffected.

as purchased organically approved nutrients and mechanical weed control to allow a higher proportion of cereal crops in the rotation (Chongtham et al., 2017). However, in highly productive regions, where crop production is less limited by soil conditions and climate, the economically optimal cropping system relies on production of the most profitable cash crops. Consequently, crop rotations in conventional systems are less likely to utilise short-term leys or have animal husbandry because the higher efficiency in resource use makes continuous growing of annual cash crops more attractive (Barbieri et al., 2017). Furthermore, when grown organically, the most valuable and demanding annual crops characteristic of more productive regions, such as winter wheat and oilseed rape, require suitable preceding crops that add nitrogen and other nutrients while not propagating weeds or diseases for subsequent crops (Melander et al., 2016; Ingver et al., 2019). Perennial forage crops can be particularly valuable in this respect (Martin et al., 2020).

As a result, the contrast between the cropping system for organic and conventional farming is larger in more productive regions (Reumaux et al., 2023), resulting in transition to organic farming being associated with a dramatic change in crop rotations and potentially inclusion of animal husbandry. Thus, when short-term grass-clover leys are not currently part of the farm enterprise, the degree of changes required to the cropping systems when converting to organic farming may pose a larger barrier. As clarified under H2, introducing ruminant animals on farms will result in considerable investment and opportunity costs. Opportunities to instead solve nutrient availability by other means may on the other hand be limited. For example, grain legumes suit organic rotations because they can fix their own nitrogen and leave some residual nitrogen to benefit the subsequent crop, but they are not good weed competitors (Melander et al., 2016) and might therefore trigger costly weed control measures, such as intensive soil cultivation between crops and repeated hoeing between crop rows in both the legume crops and in subsequent crops. Single-year green manure crops, often consisting of grass and clover, can be used in ruminant-free organic cropping systems to help in weed management and provide nitrogen to subsequent high value crops (Melander et al., 2020; Xu et al., 2025), but since these crops do not provide a revenue, they are often not economically viable. Hence, it is according to this hypothesis, not the

separation of livestock and cash-crop production per se that constrains transition to organic farming on highly productive land, but the unavailability of cropping systems that involve growing grass-clover break crops instead of annual cash crops.

To conclude, transition to organic farming will entail larger changes in the farm enterprise in highly productive areas where conventional farming is mostly based on production of annual cash crops, than in less productive areas with a higher prevalence of mixed farms with animal husbandry, posing a barrier to change.

H4. Strong need of socio-ecological processes at landscape scales.

An inevitable consequence of the lower uptake of organic farming in highly productive regions (Bichler et al., 2005; Rundlöf and Smith, 2006; Schmidtner et al., 2012) is that the average farm will have fewer organic neighbours. There are both ecological, agronomic, and cultural factors that may result in positive feedback and 'path dependency' between historical and future uptake of organic farming, with the lack of organic neighbours further constraining development of organic farming in highly productive regions (Simin and Janković, 2014; Allaire et al., 2015).

Ecological processes at large scales may be important for organic farming. Organic farming includes use of control of pests by natural enemies (Simon et al., 2014). Pest - natural enemy interactions are affected by both in-field and ex-field management, which is the ground for conservation biological control (Rusch et al., 2017). However, the ecological processes affecting pests and natural enemies occur at scales larger than individual farms (Bianchi et al., 2006) and is thus compounded by the existing fragmentation of farms (cf. Ntihinurwa and de Vries, 2021). Hence, pest pressure on organic farms will depend on how neighbouring farms are managed. For an organic farm, there may be both positive and negative consequences of being surrounded by organic farms, depending on whether the landscape-scale effects mostly pertain to weeds and pests or to their natural enemies. However, the net consequences of these opposing drivers of crop damage from amalgamation of organic farms have been sparsely investigated. Both weed species richness and density have been found to increase with the proportion of organic farming in the landscape, but the number of studies are limited and some did not find any effects (Brusse et al., 2024). For arthropod

pests and natural enemies, the data is slightly more extensive, demonstrating limited effects of organic farming at landscape scales (Petit et al., 2020; Brusse et al., 2024). We are not aware of evaluations of effects of organic neighbours on yield.

Relevant knowledge and proof-of-concept may be crucial for farmers to adopt new, but potentially more risky production practices, such as organic farming. Existence of neighbouring organic farms may promote conversion by facilitating knowledge-based feedback or by the existence of well-developed and knowledgeable extension services based on a broader customer base (cf. Sapbamrer and Thammachai, 2021). Similarly, access to specialized equipment, for example, inter row hoes, may be better if farms are located close together; in Hanson et al. (2004) organic farmers stated that they more than conventional farmers bonded with neighbours to share equipment and labour. In addition to knowledge spillover, collective behaviour may increase the conversion to organic farming through the creation of norms. Farmers' decisions are known to be affected by the practices and successes of colleagues (Dessart et al., 2019). Since the conversion to organic farming can be constrained by low social acceptance (Läpple and Kelley, 2013), the adoption may be affected by neighbours successfully transitioning to organic farming (but see Boncinelli et al., 2016 who concluded that information spillover was more important). These social mechanisms may result in positive feedback related to conversion that exacerbates other constraints on organic farming in highly productive regions (H1-H4).

To conclude, self-reinforcing neighbourhood effects, both ecological and social, potentially contribute to the highly heterogeneous uptake of organic farming, but the extent of this has not been quantified.

H5. High opportunity and management costs of replacing conventional production methods.

Lower yields compared to conventional farming can present substantial opportunity costs for farmers contemplating converting to organic in highly productive regions. Several recent meta-analyses have shown that organic farming on average produces 18-25% lower yields for given crops (de Ponti et al., 2012; Seufert et al., 2012; Ponisio et al., 2015; Alvarez, 2022; de la Cruz et al., 2023). The magnitude of expected yield-losses after conversion is hard to predict, because small-scale studies may underestimate yield differentials (Kravchenko et al., 2017) whereas analyses of commercial harvests showing similar (Kniss et al., 2016) or larger (Brückler et al., 2018) yield differences may be biased by higher uptake of organic farming in areas with lower productivity, and therefore yields (cf. Bichler et al., 2005; Rundlöf and Smith, 2006). Furthermore, estimates of yield differentials likely hide significant heterogeneities that reflect spatio-temporal variation in permissible practices as regulated by law and certification rules. However, in the context of this study, the critical issue is whether yield losses after conversion are larger in highly productive areas, which is expected based on H1-H3.

For a particular crop, the proportional yield loss associated with organic farming may be slightly higher in more productive regions (Ländell and Wahlstedt, 2020) and in contexts associated with productive areas such as simple crop rotations (Ponisio et al., 2015; Ponisio et al., 2017). However, a global meta-analysis found that yield differences between organic and conventional farming was at most weakly related to field size or conventional yields as a proxy for farming intensity (Smith et al., 2020). Furthermore, there are substantial heterogeneities in organic-conventional yield differences between crops (Ponisio et al., 2015), with yield differences tending to be larger for crops more prevalent in productive areas such as cereals and oilseed than for legume crops and grass-clover leys (de Ponti et al., 2012; Seufert et al., 2012; Kniss et al., 2016; Alvarez, 2022). Such crop-specific analyses will miss consequences related to changes in crop rotations caused by transitions to organic farming. Given the need for introducing leys for BNF and weed management in organic crop rotations (H2), the opportunity cost (i.e. forgone profit) will be larger than that indicated by crop-

specific analyses (Alvarez, 2022). In addition, global and continental studies have shown that crop selection by organic farmers differs from that of conventional farmers, with less focus on primary cereals (e.g. wheat, rice and maize) and greater focus on a wider range of crops including secondary cereals (e.g. spelt and barley) and grain legumes (Barbieri et al., 2019). Thus, opportunity costs for converting to organic are likely larger in highly productive areas dominated by production of annual cash crops.

Over and above the risks associated with any agricultural investment due to random weather events and price fluctuations, organic farmers face additional production risks, because they are not allowed to apply synthetic fertilisers or pesticides (H1 and H2) (Berentsen and van Asseldonk, 2016), which results in lower yield stability in organic systems (i.e. larger relative yield variability) (Knapp and van der Heijden, 2018; Smith et al., 2019). This suggests that there will be an additional (opportunity) cost in terms of greater risk on converting to organic farming in highly productive regions, because the organic system will be perceived as riskier to the farmer than continuing with the conventional system.

In addition to yield losses, organic farms may also experience higher relative management costs in more productive regions. For a given effect, the costs of mechanical weed control (Moss, 2019) and management and opportunity costs of conservation biological control of pests (Griffiths et al., 2008) may be higher than that of chemical control, which may differentially affect organic farming in productive regions where weed and pest control are less supported by perennial crops and there is less undisturbed habitat for natural enemies (H1). However, research on the cost effectiveness of organically approved weed and pest control is scant, but a pan-European analyses showed that organic farms had lower costs for crop protection, while labour inputs were relatively similar to conventional farms, but with large heterogeneities (Blockeel et al., 2025). In addition, the scarcity of livestock and hence locally available manure may result in higher transport costs or the need to rely on more expensive nutrient sources (H2) (cf. Nordin, 2021).

In conclusion, the combination of larger yield reductions and higher risk and management costs in productive regions should result in substantially higher opportunity costs of converting to organic farming in these regions.

H6. Strong need of policy payments.

Policy payments supporting organic farming through the EU's Rural Development Programme have been pivotal for increasing uptake (Daugbjerg et al., 2011), and empirical evidence shows that adoption responds significantly to changes in payment levels (Le Gloux and Dupraz, 2024). However, these have contributed to heterogeneous uptake within countries due to very low conversion in high-productive regions (Fig. 1) (Rundlöf and Smith, 2006). Conversion in high-productive regions requires major structural changes and may result in large income losses compared to conversion in more extensive, low-productive regions (H5). Since payment schemes do not adequately reflect this spatial variation in the opportunity costs of organic farming—because they tend to consist of uniform area payments for the same type of production within countries—farmers in high-productive regions are offered insufficient compensation to make organic farming attractive (Häring et al., 2004). However, exceptions exist (Lampkin et al., 1999; Lampkin and Sanders, 2022), but it is unclear if these instances of regionally differentiated payments fully compensate for differences in opportunity costs.

Some costs of converting to organic farming may be unrelated to agricultural productivity, such as machinery investments. However, opportunity costs per unit area are magnified in high-productive regions for several reasons. First, if organic yields are a certain proportion of conventional yields, the per-unit-area yield loss will be larger in high-productive areas. This effect that is compounded if proportional yield losses are themselves larger in such areas (H5). Second, since conversion entails larger changes in crop production systems in highly productive

areas (H3), the introduction of more complex crop rotations (i.e., including grass and legumes) entails higher opportunity cost (Håring et al., 2004; Alvarez, 2022). Consequently, uniform area-based payments tend to overcompensate farmers in low-productive areas while being insufficient in high-productive areas.

Third, the opportunity cost of converting to organic farming on high-productive land, is further magnified by the obligatory transition period. Before farmers can sell their products as certified organic—and thus receive price premiums—they must, according to EU certification, pass through a transition period of one to three years (European Union, 2018). The forgone price premium constitutes an additional opportunity cost in the form of a fixed cost attributable to the transition period, which will be higher in high-yield regions due to higher organic yields. Overall, measures and budgets to support organic farming in the EU are considered insufficient to achieve the 25% goal for organic farmland (Willer et al., 2024).

To generate more geographically homogenous uptake, payments for converting to organic farming in high-productive regions must be sufficient to compensate for the higher opportunity costs associated with yield losses, management adjustments, production risk, and transition. Even if organic price premiums theoretically could fully compensate for these higher opportunity costs, it doesn't change the fact that uniform policy payments disfavour conversion of high-productive land.

3. Overcoming constraints

3.1. A hierarchy of solutions

We have outlined six hypotheses explaining the generally low uptake of organic farming in highly productive, intensively farmed landscapes. Our individual hypotheses are intended to clarify the complex set of factors constraining the expansion of organic farming, rather than to serve as unambiguous determinants, as they are, in several instances, interrelated. That said, they can be arranged hierarchically (Fig. 3): certification constraints related to the codification of organic farming (H1, H2), if not overcome, may require agronomic solutions (H3), which in turn may be more or less feasible depending on the regional farming context (H4). All these constraints ultimately affect farmers through consequences for profitability (H5) and through the construction of policies to promote organic farming (H6). Hence, overcoming constraints high in the hierarchy will alter the likelihood that constraints lower in the hierarchy apply, whereas overcoming constraints lower in the hierarchy will leave those higher up unaffected.

In this section, we discuss solutions to the low uptake of organic farming, with a focus on the situation in highly productive areas dominated by arable production of cash crops and relate the solutions to our hierarchy of constraints. Most of these solutions have been proposed previously but not presented in a systematic way that identifies the linkages between them.

3.2. Potential solutions

3.2.1. Develop sustainable approaches for weed, pest, and disease management and promotion of crop health (H1)

Because organic farming generally results in lower and more variable yields compared to conventional farming (de Ponti et al., 2012; Seufert et al., 2012; Ponisio et al., 2015; Smith et al., 2019; Alvarez, 2022; de la Cruz et al., 2023), and evidence suggests that best management practices substantially improve relative performance (Seufert et al., 2012; Ponisio et al., 2015), the potential for yield improvements is likely large (Karlsson, 2024). Ecological intensification (or eco-functional intensification) has been suggested as a general approach with specific relevance for reducing yield-losses from weeds, pests, and diseases with relevance to organic farming. It explicitly relies on better use of natural ecosystem processes to increase yields (or reduce environmental externalities) (Bommarco et al., 2013; Döring, 2019) by increasing planned and

associated biodiversity on arable land and maintaining non-crop habitat structures at the scales of farms and landscapes. Much is known about how weed abundance and species composition can be regulated (Bond and Grundy, 2001; MacLaren et al., 2020), such that the major obstacles are to overcome negative impacts of direct control measures on e.g. soil health and biodiversity as well as the management and opportunity costs these methods entail. Accounting for the positive effect of weeds on ecosystem processes that benefit yields may help lessen the incentive to reduce weeds at all costs (Bretagnolle and Gaba, 2015; Crochard et al., 2022). Whereas the empirical basis for the effect of ex- and in-field measures compatible with organic farming on pests and diseases is overwhelming, there is a context-dependence of the responses that makes it difficult for farmers to implement methods based on information in overarching syntheses (Karp et al., 2018). Recent efforts to organize a bewildering heterogeneity in results by defining archetypes, i.e. clusters of e.g. crop – pest – enemy systems that may respond similarly to eco-functional interventions, is a promising way forward (Alexandridis et al., 2022). Archetypes allow existing knowledge to be adapted to specific farm contexts, but developing such approaches requires stronger research on conservation biological control.

Methods based on input substitution rather than farming system redesign (Lamine and Bellon, 2009), can be promoted to control weeds, pests and diseases in organic production. These are technological alternatives to synthetic chemical inputs to control pests and diseases, such as the release of natural enemies for inundative biological control (Speiser et al., 2006), thermal or bacterial treatments for seeds (Lamichhane et al., 2022), or the use of natural insecticide or fungicide molecules (van Bruggen and Finckh, 2016). Precision approaches to weed and pest management in organic farming based on e.g. remote sensing and AI (Marino, 2023; Kaur et al., 2024) could improve efficiency and reduce costs. There is, however, a risk that the environmental benefits from organic farming are compromised because of such conventionalisation (Röös et al., 2018), which may even reduce the incentive for a system redesign paradigm that focus on natural regulation processes (cf. Lamine and Bellon, 2009). To secure the transformative potential of organic farming, priority should be given to strengthening the organic knowledge system (see section below) to support farmers in designing more sustainable production systems (cf. Darnhofer et al., 2010; Milardo, 2025).

3.2.2. Facilitate the development of alternative nutrient sources (H2 and H5)

To be sustainable, organic farming must replace macro- and micro-nutrients sold off in agricultural produce (H2). Traditionally, organic farming has relied on systems that include livestock. However, a sustainable future requires a shift towards more plant-based foods to mitigate climate change associated with the food system, particularly in Europe and North America (Henchion et al., 2021). Although global meat consumption may continue to rise, there is some evidence that more industrialized countries have reached peak meat consumption (Whitton et al., 2021). This may, in the long run, reduce the amount of nitrogen fixed in feed crops and nutrients recycled through animals. Organic farming thus needs to identify alternative and sustainable sources of nutrients, including nutrient-rich materials of urban origin such as human wastes. Fractionation allowing recovery of P as struvite is now accepted for organic production (European Commission, 2023a), whereas the use of human urine is still prohibited (EU 2018/848 Article 11 Regulation, Milestad et al., 2020). However, development of pelletized products enabling redistribution and application similar to other commercial fertilisers is ongoing (Kurniawati et al., 2023) and may be a future alternative to the currently marketed but costly fertilisers produced from food industry wastes (e.g. bone meal, blood meal) (H5). Contaminants, e.g. heavy metals and microplastics, remain a concern in materials recycled from society. However, a recent review on the use of these products in organic farming suggests that many soils can degrade certain pollutants, and that pollutant levels in many urban materials are

lower than in the past (Bünemann et al., 2024), or in the case of bioactive compounds, can be reduced with insect larvae (Lalander et al., 2025). Hence, there are ample opportunities to meet the nutrient demands of organic farming in a circular economy.

Lays are generally uneconomic on farms without livestock. However, farm-level to regional scale digestion of herbage to produce biogas can add additional income while at the same time improving the availability of the nutrients from the remaining digest (Koppelmäki et al., 2019). This enables greater precision in crop nutrient supply and higher nutrient use efficiency and yield quantity and quality (e.g., protein levels in bread wheat, Odlare et al., 2004; Möller et al., 2008; Magistrali et al., 2020; Reumaux et al., 2026). Life cycle analysis of systems integrating biogas with grain production have shown potential to enhance nutrient recycling, BNF, and energy efficiency on farms (Tidåker et al., 2014), but the environmental and economic benefits depend on handling systems, technologies for spreading of the digest, and collaboration between farms and with other societal and private enterprises. Biomass composition can have a major effect on the environmental impact of biogas production but mixing on-farm and off-farm residues is a way to manipulate this (Møller et al., 2022) and the net present value of such farm-level production of biogas and digestate was found positive with a smaller CO₂ footprint of the digestate compared to mineral fertilizer (Vikki et al., 2025). Quality-controlled biogas digestates produced from other feedstock such as food industry waste, household food wastes or livestock manures in municipality-level biogas plants can provide similar benefits (Gustafsson and Anderberg, 2023). The bulky character of the digestates limits the feasible transportation distance, but dehydration and fractionation of the digestates and further processing can increase this distance and allow redistribution of the contained phosphorus over a somewhat larger geographical area similar to fractionation of manure slurries (Pantelopoulos and Aronsson, 2021). Hence, a future biobased economy may significantly contribute to the possibilities to solve nutrient demands of organic farming.

3.2.3. Utilize crop diversification and the potential of plant breeding (H1, H2, H3 and H5)

Diversification of cropping systems in productive regions (H3) to increase BNF (H2) and suppress and manage weeds, pests, and diseases (H1) provides opportunities to introduce alternative (or reintroduce traditional) crop species, varieties and mixtures for human consumption, livestock feed and to improve soil health. Examples are different types of pulses (grain legumes) such as peas, beans, lentils and lupins, heritage cultivars of cereals as well as traditional roots, tubers, oil crops and vegetables (e.g., Revoyron et al., 2022; Ortman et al., 2023). To facilitate crop diversification and scale up the present small-scale production of alternative crops, obstacles of different nature (upstream, downstream of farm, farm level and institutional obstacles) need to be removed (cf. Meynard et al., 2018; Brannan et al., 2023), which requires stronger and expanded seed supply systems (Sandström et al., 2024), strengthening of farmer knowledge about how to grow and manage novel crops (Reckling et al., 2020), and improved output market chains including processing in highly productive regions (Messéan et al., 2021; Weituschat et al., 2023).

For optimal yields, organic farming generally needs varieties targeted to organic conditions, particularly high competition from weeds and low nutrient availability (Lammerts van Bueren et al., 2011). However, organic farming predominantly uses varieties bred for high availability of nutrients and efficient control of weeds, pests, and diseases emerging from crop breeding based on conditions mainly found in conventional farming (Lammerts van Bueren et al., 2011). Hence, there is potential to increase the quality and quantity of yields by more targeted plant breeding and variety testing (Lammerts van Bueren et al., 2011; Crespo-Herrera and Ortiz, 2015; Mitrović et al., 2023). However, conditions and goals differ among organic farms and farmers (e.g., Darnhofer et al., 2005; Lynch, 2022), challenging the very notion of “organic conditions”. In consequence, plant breeding for organic

production needs to target competitive ability under a broad range of management conditions, which may require a focus on multiple varieties tailored for specific farm conditions. Develop new variety mixtures is an option that may allow greater adaptability (Wuest et al., 2021). Furthermore, the way in which varieties are tested may require a different approach in organic systems. Kravchenko et al. (2017) demonstrate that the differences between field- and plot-scale experiments on crop yield are much larger in organic than conventional settings, such that field-scale evaluation of cultivars holds promise for better future variety selection (e.g., Participatory Plant Breeding, Colley et al., 2021; Ceccarelli and Grando, 2022).

New breeding techniques have been proposed as a way to close the yield gap in organic farming, e.g. by reintroducing lost genetic variability (Andersen et al., 2015). However, crops derived from genetic engineering are currently not allowed in organic farming (EU Regulation (EU) 2018/848 Article 11 Regulation), since it is considered incompatible with its principles (Altieri, 2005; but see Andersen et al., 2015). The use of new genomic techniques in organic farming will be continued to be banned according to the recent proposal by the European Commission (European Commission, 2023c). However, that does not mean lack of room for utilization of other modern techniques, e.g. combining biotechnology with traditional breeding, that could foster faster development of crop plants optimal for organic conditions (Nuijten et al., 2017) and openness for novel developments could help make organic farming more competitive (Purnhagen et al., 2021). IFOAM has compiled a list of breeding techniques that are deemed compatible with organic farming principles and that could help to foster varieties and breeds suitable for organic conditions (IFOAM, 2017).

3.2.4. Strengthen the organic knowledge systems (H1, H2, H3, H4)

Organic farming is knowledge intensive and thus benefits from scientific advice, but also requires local, place-based solutions since the idea that the cropping system should fit the local conditions is embedded in its principles. The existing variation in how advisory support and extension services are organized, for example in the EU, from being embedded in conventional systems to separate and specialised services (Lampkin et al., 1999; Padel and Lampkin, 2007), provide a rich foundation to understand how to best combine accessibility, in depth scientific evidence on organic farming per se, and local agroecological knowledge. Promising developments are the development of organic farmers’ own peer supported knowledge exchange mechanisms (Šūmane et al., 2018; Malusà et al., 2022) and the OrganicAdviceNetwork funded by the EU, aiming for a network of 1000 organic advisers across all Member States and seven other European countries (<https://cordis.europa.eu/project/id/101134850>). However, if the uptake of organic farming is to increase, developments are required across the whole food system. Moschitz et al. (2021) suggested that the Agricultural Knowledge and Information Systems for organic farming need to be developed into Food and Agricultural Knowledge and Innovation Systems. We contend that this could be beneficial to conversion in the often densely populated highly productive regions if it helps to create market opportunities or direct connections into catering through public procurement or restaurants.

Advice on organic farming must be tailored to the specific needs of different contexts (Milardo, 2025), which must include those of highly productive regions. For example, Swedish specialist arable farms have relied mainly on mineral fertilisers and pesticide inputs to maintain crop yield and quality. Converting to organic arable farming thus requires alternative management solutions for nutrient management as well as weed, pest and disease control using agroecological management practices such as intercropping (Bedoussac et al., 2015) or service crops (Lagerquist et al., 2022). This transition calls for novel on-farm demonstrations, exchange visits for farmers and advisors, and vocational training adapted to the local conditions. Integration of livestock into specialist crop production in highly productive areas, requires advisors as well as farmers to be familiar with managing both crop and livestock

enterprises and to understand the benefits and challenges of integration from both financial and biophysical perspectives (see Vermunt et al., 2022; Moojen et al., 2023) and to account for the need for specialized knowledge (see Moojen et al., 2023) and infrastructure (see Hermansen et al., 2004). One possibility to facilitate integration of crops and livestock farming is to reduce administrative and legal barriers to partnerships between livestock. In such partnerships, businesses could be financially separate, but the use of the farmland and resources is improved through integration of forage and grazing into the landscape (Martin et al., 2016).

3.2.5. Increase the cost efficiency of agri-environmental policies (H6)

Agri-environmental policy payments have been crucial for fostering conversion to organic farming, but current payment levels are too low to achieve substantial conversion in highly productive areas (H6). As has been argued for other agri-environmental measures (Hanley et al., 2012; Wätzold et al., 2016), spatial targeting is generally necessary to achieve environmental goals cost-effectively. Furthermore, it is important how goals for organic area are formulated for achieving environmental goals, e.g. the EU's 25% goal (Kremmydas et al., 2025), as well as minimizing potentially negative net welfare effects on developing countries (Mével et al., 2023). Such targeting can be achieved by addressing both the environmental problems associated with conventional agriculture and the environmental benefits of organic farming. Any policy instrument that restricts or internalizes costs (e.g., environmental taxes) of using inorganic fertilisers and pesticides will benefit organic farming by reducing the opportunity cost of organic farming (Michalke et al., 2023), particularly in highly productive regions where opportunity costs are higher (H5). Similarly, any spatial differentiation in agri-environmental payments that directly or indirectly relates to the environmental benefits of organic farming, will increase cost efficiency (cf. Hanley et al., 2012; Reed et al., 2014). If larger uptake in highly productive areas would increase environmental benefits, e.g. because marginal benefits are higher when uptake is low or because the contrast between organic and conventional farming is larger, spatial differentiation would increase cost efficiency (Sidemo Holm et al., 2024) (but see Gabriel et al., 2009). However, such differentiation may have social implications, such as perceived fairness, that need to be considered (Markova-Nenova et al., 2023).

An action-based agri-environmental scheme based on very generalized measures may suffer both from the context-dependence not being considered (Rundlöf and Smith, 2006) and "conventionalisation", where intensification to increase profits undermines the intended environmental benefits (Röös et al., 2018). A drastic solution to improve cost-efficiency, would therefore be to replace payments for organic farming with payments for the intended environmental and social benefits it provides. One proposal to do this is using result-based payments (Herzon et al., 2018) which, in theory, could deliver similar benefits to society as certified organic farming, but with higher precision and lower costs attributable to spatial targeting. However, result-based schemes face several challenges, including i) uncertainty in achieving results and thus risk of not receiving payments, which can constrain uptake (OECD, 2022), ii) issues of fairness if the same action generate different support depending on context (OECD, 2022), iii) difficulties in identifying credible indicators (Elmiger et al., 2023), iv) high cost of credible monitoring of the range of benefits that organic farming is expected to provide (e.g. biodiversity, environmental quality, soil health, circularity) (Burton and Schwarz, 2013; Bartkowski et al., 2021), and v) the fact that results may manifest at spatial scales larger than the farm (cf. Lindborg et al., 2017). A possible way to preserve the benefit of a broad principle-based scheme such as organic farming, while increasing cost effectiveness, would be to provide context-specific payments for actions, for example using a bonus based on modelled benefits, to maintain or improve environmental conditions (Sidemo-Holm et al., 2018; Bartkowski et al., 2021).

3.2.6. Target markets, develop value chains and food systems (H5)

Economic constraints on the uptake of organic farming could be alleviated by measures targeting the entire food chain, including consumers, that increase demand, potentially raising farm revenue if they reduced downstream costs and/or increased consumers' willingness to pay a premium for organic food. Such measures could be driven by both the private sector (Brouwer et al., 2018) and demand-side policy instruments, such as green public procurement (GPP) and consumer information (Daugbjerg, 2023). Related policy instruments include public funding of marketing efforts (Stolze and Lampkin, 2009) and raising consumer awareness of organic production (European Commission, 2023b). However, it is a challenge to use such measures to disproportionately promote uptake specifically in productive arable regions. For example, Lindström et al. (2020) and Jørgensen (2021) found that GPP increases the area of organic farmland in Sweden by increasing demand, but the latter study also highlighted the difficulty of targeting specific areas. Subsidizing processing, marketing, and distribution of organic agricultural produce specifically in highly productive regions may, though, result in better spatial targeting of uptake as farming, processing, and distribution are geographically inter-linked. Still, downstream instruments remain indirect and cannot be as target efficient as directly subsidizing organic farm practices in highly productive areas, although a policy mix may be the most efficient strategy (Sanders et al., 2011). However, a geographical dimension either in private initiatives (e.g., retailer-driven) or in public procurement may help targeting organic produce in densely populated arable areas and break the current negative correlation between population density and organic farming uptake in the EU (Krajewski et al., 2024). However, the farm-economic impact of short food supply chains remains inconclusive (Chiaverina et al., 2023), highlighting the need to further evaluate downstream policies promoting locally produced organic food.

Agriculture in highly productive regions is often dominated by arable crop production, which as we have shown constitutes a challenge for organic farmers (H2, H3). The increased need for and interest in a shift from animal to plant protein in human consumption to mitigate climate change provides a challenge for organic farming in general, but potentially also an opportunity to use an increased demand for pulses, including organic pulses, to generate synergistic effects for BNF on organic farms (cf. Herridge et al., 2008; van Loon et al., 2023). Current economic challenges of increasing production of pulses in highly productive arable regions (Reckling et al., 2016), may be partly overcome if a "protein shift" affects market prices of pulses. A French study of consumers indicates that organic consumers already have a comparably large interest in pulses as their diets are richer in plant-based foods than non-organic consumers (Kesse-Guyot et al., 2021). Such a protein shift may, however, require additional research into novel methods for processing plants (Wanasundara et al., 2024).

3.2.7. Upscaled multi-actor research across space and time (H1, H2, H3, H4, H5, H6)

Organic farming has historically been subject to low research and development investments (Niggli, 2015). This has resulted in knowledge gaps, such that additional research is required to allow the development of organic farming without compromising its sustainability ambitions. We here highlight two such gaps: the need to cover processes over large spatio-temporal scales and the need for trans-disciplinary research.

When evaluating our hypotheses, it is important to consider spatial scales, because solutions can be implemented at the level of fields, farms, landscapes, or society at large. Whereas many studies on the certification constraints have been carried out at plot or field scales, there is increasing evidence of consequences of agricultural management at larger scales (Griffiths et al., 2008; Tschamtké et al., 2012). If landscape-scale processes – ecological or social – are crucial for the opportunity costs of organic farming, it will require enhanced focus on farmer collaboration (Sutherland et al., 2012; Sūmane et al., 2018). Upscaling solutions evaluated at small spatial scales may also not always be

feasible (Leifeld et al., 2016), e.g. because of regional availability of manure only being sufficient to a limited number of farms, or scale-dependent pest-natural enemy relationships. Ultimately, upscaling in the most productive regions will be related to identifying solutions that are sustainable at large spatial scales without relying on major structural changes in the agricultural sector such as the reintroduction of livestock production. Thus research needs to consider the constraints to uptake of organic farming using relevant system boundaries. Furthermore, while we in our review mostly considered short time horizons because most evidence pertains to that timescale, it has been argued that organic farming may face long-term issues, not the least related to ongoing climate change which may increase issues of weeds and pests (Wirehn, 2018) with relevance for the possibility to farm organically in productive regions. Hence, there is a need to climate-proof organic farming to handle weeds, pests, and extreme weather events, e.g. capitalizing on knowledge about agroecological methods (Biswas and Das, 2024).

Moving forward, transdisciplinary research where practitioners and scientists together design and implement farming and food systems research is one way to create new actionable knowledge both in relation to management practices and policy support. Co-designed research which involves farmers, researchers and other stakeholders in the problem formulations and let farmers play a key role in designing the solutions, is a mechanism for engaging farmers in how to redesign farming systems to meet desired goals (Lacombe et al., 2018). Approaches such as Living Labs (Cascone et al., 2024) could be gainfully employed to support transition to organic farming in highly productive regions if they are based on a bottom-up approach engaging motivated farmers. Trans-disciplinary research may also bridge the current scale-related disconnect between academics and farmers, where general approaches and small-scale studies fail to inform farming in practice (Kleijn et al., 2019). Such efforts can integrate research and practice through, for example, farmer innovation tracking, multi-actor design of research, and public funding of field-scale trials (Maas et al., 2021; Salembier et al., 2021). However, at the same time this research must be embedded in a system-level understanding of farming across the spatio-temporal scales most relevant for farming activities and ecosystem processes underpinning pest, disease and weed control, and explore costs and benefits for farms and production regions pinning pest, disease and weed control, and explore costs and benefits for farms and production regions (cf. Kleijn et al., 2019; Salliou et al., 2019). A possible way to achieve this would be to allow scientific evaluation of agri-environment schemes to be an integral part of national implementation of such schemes, e.g. as part of the Common Agricultural Policy in Europe (Smith et al., 2016).

4. Conclusions and outlook

Agriculture is essential for the production of food, feed, fibre, and biofuels, but at the same time causes pervasive environmental externalities, including biodiversity loss, eutrophication, chemical contamination, and the weakening of regulating ecosystem services (Vitousek et al., 1997; Power, 2010). While organic farming offers a pathway to more sustainable food production, we have summarized a suite of challenges (“Hypotheses”) that may constrain its expansion in regions where uptake is currently low, but where it may also be most needed because of its potentially high environmental benefits. These challenges can be hierarchically arranged, so that addressing more fundamental and often agronomic considerations may help to reduce challenges more related to socio-economic processes and policy (“Overcoming constraints”). Currently there is a range of options to do this by adhering to a knowledge-based development of organic farming targeting the specific challenges (“Solutions”). However, it is important to realize two major constraints on such developments. The first is that organic farming may only be a partial solution to sustainability issues in agriculture, because of certification constraints (e.g. nutrient supply) and the infeasibility of growing certain crops profitably. The second is to find solutions that do

not undermine the sustainability of organic farming itself, but rather further develop the concept and practices building on ecological principles to narrow the ‘ecological yield gap’ by increasing the delivery of ecosystem services to support crop growth and substitute external inputs (van Ittersum et al., 2025). One potentially promising avenue is the utilization of new plant breeding techniques; while the current standpoint is that GMO-techniques and new genomic techniques are incompatible with organic farming principles, there are opportunities to use other modern breeding techniques (Nuijten et al., 2017; Purnhagen et al., 2021). Finally, organic farming is strongly dependent on being, and being perceived as, a sustainable solution. With the interest in climate change spiralling because of the inability of nations to meet the Paris agreement on climate change, it may be pivotal for organic farming to increasingly focus on how agricultural methods can better target climate change mitigation and adaptation.

We have outlined the evidence supporting the different hypotheses and demonstrated support for all of them, but with varying strengths and quality of the evidence. It is, however, important to consider that both conventional and organic farming are dynamic systems, such that the validity of the hypotheses may vary over both space and time. For example, increased demand for sustainability in conventional farming, with increasing restrictions on the use of inorganic fertilisers and pesticides (e.g., European Commission, 2020; Wesseler, 2022), may indirectly reduce the certification constraints of organic farming with consequences throughout the hierarchy of hypotheses. Likewise, the certification constraints of organic farming will depend on how permissive certification schemes are for e.g. the use of pesticides (cf. Larsen et al., 2021; Tschardt et al., 2021), affecting the need for organically tailored crop rotations. Organic farming, as other farming systems, is also experiencing rapid technological development, which may substantially increase production (Darnhofer et al., 2010; Sidemo-Holm et al., 2021), implying that certification constraints may be highly time-dependent.

Organic certification is also a constantly evolving process (see for example <https://ec.europa.eu/transparency/expert-groups-register/screen/expert-groups/consult?lang=en&groupID=3794>) and as new technologies become available, the value of such technologies to organic farming will need to be considered in the context of organic farming principles. Furthermore, the spread of agroecological knowledge and practices, not the least to extension services, will reduce the opportunity costs of organic farming. Finally, the volatility of markets and policy can quickly and radically impact the magnitudes of constraints to organic farming. For instance, food price increases, or an increasing share of customers avoiding animal produce because of perceived climate effects, will reduce consumer demand for organic dairy and other livestock products and raise opportunity costs of organic crop rotations (H3), while putting additional pressure on organic farmers to find innovative ways to overcome certification constraints if they are to remain in business.

Thirty-five years after introducing public support to organic farming in Europe (Sanders et al., 2011), it is still only a minority of farmland and mainly in low-productive regions that has been converted. The wider certification constraints of farming may also mean that it will never become the sole solution to sustainability issues in farmland. Still organic farming can make a significant contribution to the sustainability of the whole agricultural sector and may serve as an inspiration for agroecological solutions in conventional farming (Eyhorn et al., 2019). However, to maintain that role, the constraints we have outlined need to be overcome with implementation of best management, better use of existing knowledge and technology, better designed public policy and transdisciplinary research and development involving multiple stakeholders from design to implementation.

CRedit authorship contribution statement

Henrik G. Smith: Writing – review & editing, Writing – original

draft, Funding acquisition, Conceptualization. **Göran Bergkvist:** Writing – review & editing, Writing – original draft, Conceptualization. **Mark V. Brady:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Romain Carrié:** Writing – review & editing, Writing – original draft, Conceptualization. **Sigrun Dahlin:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Johan Ekroos:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **Christian Jörgensen:** Writing – review & editing, Writing – original draft, Conceptualization. **Ingrid Öborn:** Writing – review & editing, Writing – original draft, Funding acquisition, Conceptualization. **William Sidemo-Holm:** Writing – review & editing, Writing – original draft, Conceptualization. **Christine A. Watson:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

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

Acknowledgments

Funding: This work was supported by grant 2018-02396 from the Swedish Research Council FORMAS. We thank Pernilla Borgström, Pierre Chopin, Yann Clough, Melanie Karlsson, Martin Nordin, Rafaele Reumaux, and Johanna Wetterlind, as well as the members of our stakeholder reference group (Karin Ullvén, Jan Hill, Eve Roubinet, Anna Backlin, Erika Olsson, Emelie Ekholm, Anna Redner, and Jenny Möller) for valuable discussions inspiring this work. This research is a contribution to the strategic research area BECC. AI was sometimes used for checking language with results carefully checked by authors.

Data availability

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

References

- Aigner, A., Wilken, R., Geisendorf, S., 2019. The effectiveness of promotional cues for organic products in the German retail market. *Sustainability* 11, 6986.
- Alexandridis, N., Marion, G., Chaplin-Kramer, R., Dainese, M., Ekroos, J., Grab, H., Jonsson, N., Karp, D.S., Meyer, C., O'Rourke, M.E., Pontarp, M., Poveda, K., Seppelt, R., Smith, H.G., Walters, R.J., Clough, Y., Martin, E.A., 2022. Archetype models upscale understanding of natural pest control response to land-use change. *Ecol. Appl.* 32, e2696.
- Allaire, G., Poméon, T., Maigné, E., Cahuzac, E., Simioni, M., Desjeux, Y., 2015. Territorial analysis of the diffusion of organic farming in France: between heterogeneity and spatial dependence. *Ecol. Indic.* 59, 70–81.
- Altieri, M.A., 2005. The myth of coexistence: why transgenic crops are not compatible with agroecologically based systems of production. *Bull. Sci. Technol. Soc.* 25, 361–371.
- Alvarez, R., 2022. Comparing productivity of organic and conventional farming systems: a quantitative review. *Arch. Agron. Soil Sci.* 68, 1947–1958.
- Andersen, M.M., Landes, X., Xiang, W., Anyshchenko, A., Falhof, J., Østerberg, J.T., Olsen, L.I., Edenbrandt, A.K., Vedel, S.E., Thorsen, B.J., Sandøe, P., Gamborg, C., Kappel, K., Palmgren, M.G., 2015. Feasibility of new breeding techniques for organic farming. *Trends Plant Sci.* 20, 426–434.
- Anglade, J., Billen, G., Garnier, J., 2015. Relationships for estimating N₂ fixation in legumes: incidence for N balance of legume-based cropping systems in Europe. *Ecosphere* 6, 37.
- Armengot, L., José-María, L., Chamorro, L., Sans, F.X., 2013. Weed harrowing in organically grown cereal crops avoids yield losses without reducing weed diversity. *Agron. Sustain. Dev.* 33, 405–411.
- Barbieri, P., Pellerin, S., Nesme, T., 2017. Comparing crop rotations between organic and conventional farming. *Sci. Rep.* 7, 13761.
- Barbieri, P., Pellerin, S., Seufert, V., Nesme, T., 2019. Changes in crop rotations would impact food production in an organically farmed world. *Nat. Sustainability* 2, 378–385.
- Barbieri, P., Starck, T., Voisin, A.-S., Nesme, T., 2023. Biological nitrogen fixation of legumes crops under organic farming as driven by cropping management: a review. *Agric. Syst.* 205, 103579.
- Bartkowski, B., Droste, N., Ließ, M., Sidemo-Holm, W., Weller, U., Brady, M.V., 2021. Payments by modelled results: a novel design for agri-environmental schemes. *Land Use Policy* 102, 105230.
- Basnet, S.K., Manevska-Tasevska, G., Surry, Y., 2018. Explaining the process for conversion to organic dairy farming in Sweden: an alternative modelling approach. *Ger. J. Agric. Econ.* 67, 14–30.
- Bedoussac, L., Journet, E.-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L., Justes, E., 2015. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. *Agron. Sustain. Dev.* 35, 911–935.
- Berentsen, P.B.M., van Asseldonk, M.A.P.M., 2016. An empirical analysis of risk in conventional and organic arable farming in The Netherlands. *Eur. J. Agron.* 79, 100–106.
- Bianchi, F.J.J.A., Booij, C.J.H., Tschamntke, T., 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proc. R. Soc. Lond. B Biol. Sci.* 273, 1715–1727.
- Bichler, B., Lippert, C., Haring, A.M., Dabbert, S., 2005. The determinants of the spatial distribution of organic farming in Germany. *Ber. uber Landwirtschaft.* 83, 50–75.
- Biswas, S., Das, R., 2024. Organic farming to mitigate biotic stresses under climate change scenario. *Bull. Natl. Res. Cent.* 48, 71.
- Blockeel, J., Grovermann, C., Finger, R., 2025. Organic crop farming in the European Union: Impacts on farm-level input costs, labour, and income. *Q. Open* 5.
- Bommarco, R., Kleijn, D., Potts, S.G., 2013. Ecological intensification: harnessing ecosystem services for food security. *Trends Ecol. Evol.* 28, 230–238.
- Boncinelli, F., Bartolini, F., Brunori, G., Casini, L., 2016. Spatial analysis of the participation in agri-environment measures for organic farming. *Renew. Agric. Food Syst.* 31, 375–386.
- Bond, W., Grundy, A., 2001. Non-chemical weed management in organic farming systems. *Weed Res.* 41, 383–405.
- Brannan, T., Bickler, C., Hansson, H., Karley, A., Weih, M., Manevska-Tasevska, G., 2023. Overcoming barriers to crop diversification uptake in Europe: a mini review. *Front. Sustain. Food Syst.* 7.
- Bretagnolle, V., Gaba, S., 2015. Weeds for bees? A review. *Agron. Sustain. Dev.* 35, 891–909.
- Brouwer, F., Mantino, F., Polman, N., Short, C., Sterly, S., Rac, I., 2018. Private sector actions to valorise public benefits from agriculture and forestry. *EuroChoices* 17, 16–22.
- Brückler, M., Resl, T., Reindl, A., 2018. Comparison of organic and conventional crop yields in Austria. *Bodenkultur* 68, 223–236.
- Bruse, T., Tougeron, K., Barbottin, A., Henckel, L., Dubois, F., Marrec, R., Caro, G., 2024. Considering farming management at the landscape scale: descriptors and trends on biodiversity. A review. *Agron. Sustain. Dev.* 44, 30.
- Bünemann, E.K., Reimer, M., Smolders, E., Smith, S.R., Bigalke, M., Palmqvist, A., Brandt, K.K., Möller, K., Harder, R., Hermann, L., Speiser, B., Oudshoorn, F., Løes, A. K., Magid, J., 2024. Do contaminants compromise the use of recycled nutrients in organic agriculture? A review and synthesis of current knowledge on contaminant concentrations, fate in the environment and risk assessment. *Sci. Total Environ.* 912, 168901.
- Burney, J.A., Davis, S.J., Lobell, D.B., 2010. Greenhouse gas mitigation by agricultural intensification. *Proc. Natl. Acad. Sci. USA* 107, 12052–12057.
- Burton, R.J.F., Schwarz, G., 2013. Result-oriented agri-environmental schemes in Europe and their potential for promoting behavioural change. *Land Use Policy* 30, 628–641.
- Carr, P.M., Cavigelli, M.A., Darby, H., Delate, K., Eberly, J.O., Fryer, H.K., Gramig, G.G., Heckman, J.R., Mallory, E.B., Reeve, J.R., Silva, E.M., Suchoff, D.H., Woodley, A.L., 2020. Green and animal manure use in organic field crop systems. *Agron. J.* 112, 648–674.
- Carvalho, R., Guedes, P., Mateus, E.P., Silva, V., Tyrologou, P., Koukouzas, N., Ribeiro, A. B., Couto, N., 2025. Soil contamination in Europe unveiled: a review of pesticides and metabolites to watch. *Open Res. Eur.* 5, 257.
- Casagrande, M., David, C., Valantin-Morison, M., Makowski, D., Jeuffroy, M.-H., 2009. Factors limiting the grain protein content of organic winter wheat in south-eastern France: a mixed-model approach. *Agron. Sustain. Dev.* 29, 565–574.
- Cascone, G., Scuderi, A., Guarnaccia, P., Timpanaro, G., 2024. Promoting innovations in agriculture: living labs in the development of rural areas. *J. Clean. Prod.* 443, 141247.
- Ceccarelli, S., Grando, S., 2022. Return to agrobiodiversity: participatory plant breeding. *Diversity* 14, 126.
- Chaplin-Kramer, R., O'Rourke, M.E., Blitzer, E.J., Kremen, C., 2011. A meta-analysis of crop pest and natural enemy response to landscape complexity. *Ecol. Lett.* 14, 922–932.
- Charles, R., Baux, A., Dierauer, H., Daniel, C., 2020. Organic rapeseed in Switzerland: 20 years of practice. *OCL Oils. Fat. Crop. Li.* 27, 68.
- Chiaverina, P., Drogué, S., Jacquet, F., Lev, L., King, R., 2023. Does short food supply chain participation improve farm economic performance? A meta-analysis. *Agric. Econ.* 54, 400–413.
- Chongtham, I.R., Bergkvist, G., Watson, C.A., Sandström, E., Bengtsson, J., Öborn, I., 2017. Factors influencing crop rotation strategies on organic farms with different time periods since conversion to organic production. *Biol. Agric. Hortic.* 33, 14–27.
- Chopin, P., Hermouet, S., Watson, C., Öborn, I., Bergkvist, G., 2026. A novel framework to study the evolution of crop rotation diversity reveals changes towards regional crop type specialisation in Sweden. *Eur. J. Agron.* 172, 127848.
- Claflin, S.B., Jones, L.E., Thaler, J.S., Power, A.G., 2017. Crop-dominated landscapes have higher vector-borne plant virus prevalence. *J. Appl. Ecol.* 54, 1190–1198.
- Colley, M.R., Dawson, J.C., McCluskey, C., Myers, J.R., Tracy, W.F., Lammerts van Bueren, E.T., 2021. Exploring the emergence of participatory plant breeding in countries of the Global North – a review. *J. Agric. Sci.* 159, 320–338.

- Costa, C.A., Guiné, R.P.F., Costa, D.V.T.A., Correia, H.E., Nave, A., 2023. Chapter 3 - Pest control in organic farming. In: Sarathchandran, U.M.R., Sabu, T., Meena, D.K. (Eds.), *Organic Farming*, Second edition. Woodhead Publishing, Cambridge, US, pp. 111–179.
- Crespo-Herrera, L.A., Ortiz, R., 2015. Plant breeding for organic agriculture: something new? *Agric. Food Secur.* 4, 25.
- Crochard, L., Julliard, R., Gaba, S., Bretagnolle, V., Baude, M., Fontaine, C., 2022. Weeds from non-flowering crops as potential contributors to oilseed rape pollination. *Agric. Ecosyst. Environ.* 336, 108026.
- Crowder, D.W., Reganold, J.P., 2015. Financial competitiveness of organic agriculture on a global scale. *Proc. Natl. Acad. Sci. USA* 112, 7611–7616.
- Darnhofer, I., Schneeberger, W., Freyer, B., 2005. Converting or not converting to organic farming in Austria: farmer types and their rationale. *Agric. Hum. Values* 22, 39–52.
- Darnhofer, I., Lindenthal, T., Bartel-Kratochvil, R., Zollitsch, W., 2010. Conventionalisation of organic farming practices: from structural criteria towards an assessment based on organic principles. A review. *Agron. Sustain. Dev.* 30, 67–81.
- Daugbjerg, C., 2023. Using public procurement of organic food to promote pesticide-free farming: a comparison of governance modes in Denmark and Sweden. *Environ. Sci. Pol.* 140, 271–278.
- Daugbjerg, C., Tranter, R., Hattam, C., Holloway, G., 2011. Modelling the impacts of policy on entry into organic farming: evidence from Danish–UK comparisons, 1989–2007. *Land Use Policy* 28, 413–422.
- de la Cruz, V.Y.V., Tantriani Cheng, W., Tawarayama, K., 2023. Yield gap between organic and conventional farming systems across climate types and sub-types: a meta-analysis. *Agric. Syst.* 211, 103732.
- de Ponti, T., Rijk, B., van Ittersum, M.K., 2012. The crop yield gap between organic and conventional agriculture. *Agric. Syst.* 108, 1–9.
- Dessart, F.J., Barreiro-Hurlé, J., van Bavel, R., 2019. Behavioural factors affecting the adoption of sustainable farming practices: a policy-oriented review. *Eur. Rev. Agric.* 46, 417–471.
- Döring, T.F., 2019. Eco-functional intensification of organic farming. In: Köpke, U. (Ed.), *Improving Organic Crop Cultivation*. Burleigh Dodds Science Publishing Limited, London.
- Döring, T.F., Neuhoff, D., 2021. Upper limits to sustainable organic wheat yields. *Sci. Rep.* 11, 12729.
- Edwards, A.C., Walker, R.L., Maskell, P., Watson, C.A., Rees, R.M., Stockdale, E.A., Knox, O.G.G., 2010. Improving bioavailability of phosphate rock for organic farming. In: Lichtfouse, E. (Ed.), *Genetic Engineering, Biofertilisation, Soil Quality and Organic Farming*. Springer, Netherlands, Dordrecht, pp. 99–117.
- Elmiger, B.N., Finger, R., Ghazoul, J., Schaub, S., 2023. Biodiversity indicators for result-based agri-environmental schemes – Current state and future prospects. *Agric. Syst.* 204, 103538.
- Emmerson, M., Morales, M., Oñate, J., Batáry, P., Berendse, F., Liira, J., Aavik, T., Guerrero, I., Bommarco, R., Eggers, S., 2016. How agricultural intensification affects biodiversity and ecosystem services. *Adv. Ecol. Res.* 55, 43–97.
- European Commission, 2020. Farm to Fork Strategy. For a Fair, Healthy and Environmentally-friendly Food System. European Union, Brussels.
- European Commission, 2021. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on an Action Plan for the Development of Organic Production. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0141R%2801%29> (Accessed 6 May 2022). Brussels.
- European Commission, 2023a. Commission Implementing Regulation (EU) 2023/121 of 17 January 2023. European Commission, Brussels.
- European Commission, 2023b. Organic Farming in the EU – A Decade of Organic Growth, January 2023. European Commission, DG Agriculture and Rural Development, Brussels.
- European Commission, 2023c. Proposal for a Regulation of the European Parliament and of the COUNCIL on Plants Obtained by Certain New Genomic Techniques and their Food and Feed, and Amending Regulation (EU) 2017/625. European Commission Brussels.
- European Environment Agency, 2021. Rethinking-agriculture. European Environment Agency.
- Regulation (EU) 2018/848 of the European Parliament and of the Council of 30 May 2018 on Organic Production and Labelling of Organic Products and Repealing Council Regulation (EC) No 834/2007 (OJ L 150, 14.6.2018), 2018. European Union.
- Eurostat, 2023. Organic Crop Area by Agricultural Production Methods and Crops. Eurostat. https://ec.europa.eu/eurostat/databrowser/view/ORG_CROPAR_custom_2190595/bookmark/table?lang=en&bookmarkId=e2e1e28b-6c43-4665-ada8-262b7a902dd2.
- Eyhorn, F., Muller, A., Reganold, J.P., Frison, E., Herren, H.R., Luttkikholt, L., Mueller, A., Sanders, J., Scialabba, N.E.-H., Seufert, V., Smith, P., 2019. Sustainability in global agriculture driven by organic farming. *Nat. Sustainability* 2, 253–255.
- Eyinate, G.A., Mushunje, A., Yusuf, S.F.G., 2021. The willingness to consume organic food: a review. *Food Agric. Immunol.* 32, 78–104.
- Ferjani, A., Zimmermann, A., Reissig, L., 2010. Organic agriculture: why so few farms convert. *Agrar. Schweiz* 1, 238–243.
- Finger, R., Schneider, K., Candel, J., Möhring, N., 2024. Europe needs better pesticide policies to reduce impacts on biodiversity. *Food Policy* 125, 102632.
- Foissy, D., Vian, J.-F., David, C., 2013. Managing nutrient in organic farming system: reliance on livestock production for nutrient management of arable farmland. *Org. Agric.* 3, 183–199.
- Gabriel, D., Carver, S.J., Durham, H., Kunin, W.E., Palmer, R.C., Sait, S.M., Stagl, S., Benton, T.G., 2009. The spatial aggregation of organic farming in England and its underlying environmental correlates. *J. Appl. Ecol.* 46, 323–333.
- Gamage, A., Gangahagedara, R., Gamage, J., Jayasinghe, N., Kodikara, N., Suraweera, P., Merah, O., 2023. Role of organic farming for achieving sustainability in agriculture. *Farming Syst.* 1, 100005.
- Garrett, R.D., Ryschawy, J., Bell, L.W., Cortner, O., Ferreira, J., Garik, A.V.N., Gil, J.D.B., Klerkx, L., Moraine, M., Peterson, C.A., dos Reis, J.C., Valentim, J.F., 2020. Drivers of decoupling and recoupling of crop and livestock systems at farm and territorial scales. *Ecol. Soc.* 25.
- Gould, F., Brown, Z.S., Kuzma, J., 2018. Wicked evolution: can we address the sociobiological dilemma of pesticide resistance? *Science* 360, 728–732.
- Green, R.E., Cornell, S.J., Scharlemann, J.P.W., Balmford, A., 2005. Farming and the fate of wild nature. *Nature* 307, 550–555.
- Greenhalgh, T., Thorne, S., Malterud, K., 2018. Time to challenge the spurious hierarchy of systematic over narrative reviews? *Eur. J. Clin. Investig.* 48, e12931.
- Griffiths, G.J.K., Holland, J.M., Bailey, A., Thomas, M.B., 2008. Efficacy and economics of shelter habitats for conservation biological control. *Biol. Control* 45, 200–209.
- Grizzetti, B., Vigiak, O., Udias, A., Aloe, A., Zanni, M., Bouraoui, F., Pistocchi, A., Dorati, C., Friedland, R., De Roo, A., Benitez Sanz, C., Leip, A., Bielza, M., 2021. How EU policies could reduce nutrient pollution in European inland and coastal waters. *Glob. Environ. Chang.* 69, 102281.
- Guinet, M., Adeux, G., Cordeau, S., Coursion, E., Nandillon, R., Zhang, Y., Munier-Jolain, N., 2023. Fostering temporal crop diversification to reduce pesticide use. *Nat. Commun.* 14, 7416.
- Gustafsson, M., Anderberg, S., 2023. Great expectations—future scenarios for production and use of biogas and digestate in Sweden. *Biofuels* 14, 93–107.
- Haddaway, N.R., Westgate, M.J., 2019. Predicting the time needed for environmental systematic reviews and systematic maps. *Conserv. Biol.* 33, 434–443.
- Hanley, N., Banerjee, S., Lennox, G.D., Armsworth, P.R., 2012. How should we incentivize private landowners to 'produce' more biodiversity? *Oxf. Rev. Econ. Policy* 28, 93–113.
- Hanson, J., Dismukes, R., Chambers, W., Greene, C., Kremen, A., 2004. Risk and risk management in organic agriculture: views of organic farmers. *Renew. Agric. Food Syst.* 19, 218–227.
- Harbo, L.S., Pihlap, E., Barančíková, G., Don, A., Schneider, F., Poeplau, C., 2026. Soil organic carbon changes in agricultural areas of Europe—synthesis of repeated regional soil surveys. *Eur. J. Soil Sci.* 77, e70263.
- Häring, A., Dabbert, S., Aurbacher, J., Bichler, B., Eichert, C., Gambelli, D., Lampkin, N., Offermann, F., Olmos, S., Tuson, J., 2004. Organic Farming and Measures for European Agricultural Policy. Universität Hohenheim.
- Heap, I., 2014. Global perspective of herbicide-resistant weeds. *Pest Manag. Sci.* 70, 1306–1315.
- Heikkinen, J., Ketoja, E., Nuutinen, V., Regina, K., 2013. Declining trend of carbon in Finnish cropland soils in 1974–2009. *Glob. Chang. Biol.* 19, 1456–1469.
- Henchion, M., Moloney, A.P., Hyland, J., Zimmermann, J., McCarthy, S., 2021. Review: trends for meat, milk and egg consumption for the next decades and the role played by livestock systems in the global production of proteins. *Animal* 15, 100287.
- Hermansen, J.E., Strudsholm, K., Horsted, K., 2004. Integration of organic animal production into land use with special reference to swine and poultry. *Livest. Prod. Sci.* 90, 11–26.
- Herridge, D.F., Peoples, M.B., Boddey, R.M., 2008. Global inputs of biological nitrogen fixation in agricultural systems. *Plant Soil* 311, 1–18.
- Herzon, I., Birge, T., Allen, B., Povellato, A., Vanni, F., Hart, K., Radley, G., Tucker, G., Keenleyside, C., Oppermann, R., Underwood, E., Poux, X., Beaufoy, G., Pražan, J., 2018. Time to look for evidence: results-based approach to biodiversity conservation on farmland in Europe. *Land Use Policy* 71, 347–354.
- Holzschuh, A., Steffan-Dewenter, I., Kleijn, D., Tschamtker, T., 2007. Diversity of flower-visiting bees in cereal fields: effects of farming system, landscape composition and regional context. *J. Appl. Ecol.* 44, 41–49.
- IFOAM, 2017. Position Paper: Compatibility of Breeding Techniques in Organic Systems. Bonn, Germany.
- Ingver, A., Tamm, Ü., Tamm, I., Tamm, S., Tupits, I., Bender, A., Koppel, R., Narits, L., Koppel, M., 2019. Leguminous pre-crops improved quality of organic winter and spring cereals. *Biol. Agric. Hortic.* 35, 46–60.
- Jonsson, M., Buckley, H.L., Case, B.S., Wratten, S.D., Hale, R.J., Didham, R.K., 2012. Agricultural intensification drives landscape-context effects on host–parasitoid interactions in agroecosystems. *J. Appl. Ecol.* 49, 706–714.
- Jørgensen, C., 2021. Stimulating green production through the public procurement of final products. In: Working Paper 2021, 2. Agrifood Economics Centre, Lund, Sweden.
- Karlsson, M., 2024. In: *Developing organic farming: agroecological challenges for sustainable intensification*. PhD-thesis. Lund University, Lund, Sweden. https://lucris.lub.lu.se/ws/portalfiles/portal/183523261/Melanie_Karlsson_-_WEBB.pdf.
- Karp, D.S., Chaplin-Kramer, R., Meehan, T.D., Martin, E.A., DeClerck, F., Grab, H., Gratton, C., Hunt, L., Larsen, A.E., Martínez-Salinas, A., O'Rourke, M.E., Rusch, A., Poveda, K., Jonsson, M., Rosenheim, J.A., Schellhorn, N.A., Tschamtker, T., Wratten, S.D., Zhang, W., Iverson, A.L., Adler, L.S., Albrecht, M., Alignier, A., Angelella, G.M., Zubair Anjum, M., Avelino, J., Batáry, P., Baveco, J.M., Bianchi, F.J. J.A., Birkhofer, K., Bohnenblust, E.W., Bommarco, R., Brewer, M.J., Caballero-López, B., Carrière, Y., Carvalho, L.G., Cayuela, L., Centrella, M., Četković, A., Henri, D.C., Chabert, A., Costamagna, A.C., De la Mora, A., de Kraker, J., Desneux, N., Diehl, E., Diekötter, T., Dormann, C.F., Eckberg, J.O., Entling, M.H., Fiedler, D., Franck, P., Frank van Veen, F.J., Frank, T., Gagic, V., Garratt, M.P.D., Getachew, A., Gonthier, D.J., Goodell, P.B., Graziosi, I., Groves, R.L., Gurr, G.M., Hajian-Forooshani, Z., Heimpel, G.E., Herrmann, J.D., Huseeth, A.S., Inclán, D.J.,

- Ingrao, A.J., Iv, P., Jacot, K., Johnson, G.A., Jones, L., Kaiser, M., Kaser, J.M., Keasar, T., Kim, T.N., Kishinevsky, M., Landis, D.A., Lavandero, B., Lavigne, C., Le Ralec, A., Lemessa, D., Letourneau, D.K., Liere, H., Lu, Y., Lubin, Y., Luttermoser, T., Maas, B., Mace, K., Madeira, F., Mader, V., Cortesero, A.M., Marini, L., Martinez, E., Martinson, H.M., Menozzi, P., Mitchell, M.G.E., Miyashita, T., Molina, G.A.R., Molina-Montenegro, M.A., O'Neal, M.E., Opatovsky, I., Ortiz-Martinez, S., Nash, M., Östman, Ö., Ouin, A., Pak, D., Paredes, D., Parsa, S., Parry, H., Perez-Alvarez, R., Perović, D.J., Peterson, J.A., Petit, S., Philpott, S.M., Plantegenest, M., Plečaš, M., Pluess, T., Pons, X., Potts, S.G., Pywell, R.F., Ragsdale, D.W., Rand, T.A., Raymond, L., Ricci, B., Sargent, C., Sarthou, J.-P., Saulais, J., Schäckermann, J., Schmidt, N.P., Schneider, G., Schüepp, C., Sivakoff, F.S., Smith, H.G., Stack Whitney, K., Stutz, S., Szendrei, Z., Takada, M.B., Taki, H., Tamburini, G., Thomson, L.J., Tricault, Y., Tsafack, N., Tschumi, M., Valantin-Morison, M., Van Trinh, M., van der Werf, W., Vierling, K.T., Werling, B.P., Wickens, J.B., Wickens, V. J., Woodcock, B.A., Wychukhys, K., Xiao, H., Yasuda, M., Yoshioka, A., Zou, Y., 2018. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. *Proc. Natl. Acad. Sci. USA* 115, E7863–E7870.
- Kaur, R., Sharma, D., Saini, C., 2024. Smart farming: empowering organic agriculture with AI. *Int. J. Res. Appl. Sci. Eng. Technol.* 12, 805–809.
- Kesse-Guyot, E., Lairon, D., Allès, B., Seconda, L., Rebouillat, P., Brunin, J., Vidal, R., Taupier-Letage, B., Galan, P., Amiot, M.-J., Péneau, S., Touvier, M., Boizot-Santai, C., Ducros, V., Soler, L.-G., Cravedi, J.-P., Debrauwer, H., Hercberg, S., Langevin, B., Pointereau, P., Baudry, J., 2021. Key findings of the French BioNutriNet project on organic food-based diets: description, determinants, and relationships to health and the environment. *Adv. Nutr.* 13, 208–224.
- Kleijn, D., Bommarco, R., Fijen, T.P.M., Garibaldi, L.A., Potts, S.G., van der Putten, W.H., 2019. Ecological intensification: bridging the gap between science and practice. *Trends Ecol. Evol.* 34, 154–166.
- Knapp, S., van der Heijden, M.G.A., 2018. A global meta-analysis of yield stability in organic and conservation agriculture. *Nat. Commun.* 9, 3632.
- Kniss, A.R., Savage, S.D., Jabbour, R., 2016. Commercial crop yields reveal strengths and weaknesses for organic agriculture in the United States. *PLoS One* 11, e0161673.
- Koppelmäki, K., Parviainen, T., Virkkunen, E., Winquist, E., Schulte, R.P.O., Helenius, J., 2019. Ecological intensification by integrating biogas production into nutrient cycling: modeling the case of agroecological symbiosis. *Agric. Syst.* 170, 39–48.
- Krajewski, S., Żukovskis, J., Gozdowski, D., Cieślinski, M., Wójcik-Gront, E., 2024. Evaluating the path to the European Commission's organic agriculture goal: A multivariate analysis of changes in EU countries (2004–2021) and socio-economic relationships. *Agriculture* 14, 477.
- Kravchenko, A.N., Snapp, S.S., Robertson, G.P., 2017. Field-scale experiments reveal persistent yield gaps in low-input and organic cropping systems. *Proc. Natl. Acad. Sci. USA* 114, 926–931.
- Kremmydas, D., Beber, C., Baldoni, E., Ciaian, P., Fellmann, T., Gocht, A., Hristov, J., Pignotti, D., Vicario, D.R., Stepanyan, D., Tillie, P., 2025. The EU target for organic farming: potential economic and environmental impacts of two alternative pathways. *Appl. Econ. Perspect. Policy* 47, 602–623.
- Kurniawati, A., Toth, G., Ylivainio, K., Toth, Z., 2023. Opportunities and challenges of bio-based fertilizers utilization for improving soil health. *Org. Agric.* 13, 335–350.
- Lacombe, C., Couix, N., Hazard, L., 2018. Designing agroecological farming systems with farmers: a review. *Agric. Syst.* 165, 208–220.
- Lagerquist, E., Menegat, A., Dahlin, A.S., Parsons, D., Watson, C., Ståhl, P., Gunnarsson, A., Bergkvist, G., 2022. Temporal and spatial positioning of service crops in cereals affects yield and weed control. *Agriculture* 12, 1398.
- Lalander, C., Lopes, I.G., Gyftopoulos, N., Vinnerås, B., 2025. The impact of scale and frass recirculation on pathogen inactivation dynamics in black soldier fly larvae bioconversion. *Front. Microbiol.* 16.
- Lamichhane, J.R., Corrales, D.C., Soltani, E., 2022. Biological seed treatments promote crop establishment and yield: a global meta-analysis. *Agron. Sustain. Dev.* 42.
- Lamine, C., Bellon, S., 2009. Conversion to organic farming: a multidimensional research object at the crossroads of agricultural and social sciences. *A review. Agron. Sustain. Dev.* 29, 97–112.
- Lammerts van Bueren, E.T., Jones, S.S., Tamm, L., Murphy, K.M., Myers, J.R., Leifert, C., Messmer, M.M., 2011. The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: a review. *NJAS-Wagen. J. Life Sc.* 58, 193–205.
- Lampkin, N., Sanders, J., 2022. Policy Support for Organic Farming in the European Union 2010–2020. Thünen Working Paper.
- Lampkin, N., Foster, C., Padel, S., 1999. The Policy and Regulatory Environment for Organic Farming in Europe: Country Reports. Universität Hohenheim, Stuttgart-Hohenheim.
- Ländell, G., Wahlstedt, G., 2020. Production of Organic and Non-organic Farming 2019 - Cereals, Dried Pulses, Oilseed Crops, Table Potatoes and Temporary Grasses - JO 14 SM 2001. Statistics Sweden.
- Läpple, D., Kelley, H., 2013. Understanding the uptake of organic farming: accounting for heterogeneities among Irish farmers. *Ecol. Econ.* 88, 11–19.
- Larsen, A.E., Powers, L.C., McComb, S., 2021. Identifying and characterizing pesticide use on 9,000 fields of organic agriculture. *Nat. Commun.* 12.
- Le Gloux, F., Dupraz, P., 2024. Upscaling environmental incentives in the common agricultural policy: an assessment of the potential of transfers from the first to second pillar. *Bio-based Appl. Econ. J.* 13, 27–48.
- Leduc, G., Manevska-Tasevska, G., Hansson, H., Arndt, M., Bakucs, Z., Bohm, M., Chitea, M., Florian, V., Luca, L., Martikainen, A., Pham, H.V., Rusu, M., 2021. How are ecological approaches justified in European rural development policy? Evidence from a content analysis of CAP and rural development discourses. *J. Rural. Stud.* 86, 611–622.
- Lefebvre, M., Espinosa, M., Gomez y Paloma, S., 2012. The Influence of the Common Agricultural Policy on Agricultural Landscapes. JS A. P. Report, European Commission, Joint Research Center, p. 7.
- Leifeld, J., et al., 2016. Current approaches neglect possible agricultural cutback under large-scale organic farming. A comment to Ponisio. *Proc. R. Soc. Lond. B Biol. Sci.* 283.
- Levers, C., Butsic, V., Verburg, P.H., Müller, D., Kuemmerle, T., 2016. Drivers of changes in agricultural intensity in Europe. *Land Use Policy* 58, 380–393.
- Liebman, M., Dyck, E., 1993. Crop rotation and intercropping strategies for weed management. *Ecol. Appl.* 3, 92–122.
- Lindborg, R., Gordon, L.J., Malinga, R., Bengtsson, J., Peterson, G., Bommarco, R., Deutsch, L., Gren, Å., Rundlöf, M., Smith, H.G., 2017. How spatial scale shapes the generation and management of multiple ecosystem services. *Ecosphere* 8, e01741.
- Lindström, H., 2022. The Swedish consumer market for organic and conventional milk: a demand system analysis. *Agribusiness* 38, 505–532.
- Lindström, H., Lundberg, S., Marklund, P.-O., 2020. How green public procurement can drive conversion of farmland: an empirical analysis of an organic food policy. *Ecol. Econ.* 172, 106622.
- Luttikholt, L.W.M., 2007. Principles of organic agriculture as formulated by the International Federation of Organic Agriculture Movements. *NJAS-Wagen. J. Life Sc.* 54, 347–360.
- Lynch, D.H., 2022. Soil health and biodiversity is driven by intensity of organic farming in Canada. *Front. Sustain. Food Syst.* 6, 826486.
- Maas, B., Fabian, Y., Kross, S.M., Richter, A., 2021. Divergent farmer and scientist perceptions of agricultural biodiversity, ecosystem services and decision-making. *Biol. Conserv.* 256, 109065.
- MacLaren, C., Storkey, J., Menegat, A., Metcalfe, H., Dehnen-Schmutz, K., 2020. An ecological future for weed science to sustain crop production and the environment. *A review. Agron. Sustain. Dev.* 40, 24.
- Magaya, S., Magid, J., Hermann, L., Schulp, C.J.E., 2025. Phosphorus removal and use in organic crop farming in the EU. *Nutr. Cycl. Agroecosyst.* 130, 91–110.
- Magistrali, A., Vavera, R., Janovska, D., Rempelos, L., Cakmak, I., Leifert, C., Grausgruber, H., Butler, G., Wilkinson, A., Bilsborrow, P., 2020. Evaluating the effect of agronomic management practices on the performance of differing spelt (Triticum spelta) cultivars in contrasting environments. *Field Crop Res.* 255, 107869.
- Mahas, J.W., Wilson, A.E., Steury, T.D., Jacobson, A.L., 2025. Association of plant pathogen vectors and vector-borne plant pathogens with landscape composition: a meta-analysis. *Environ. Entomol.* 55.
- Malušá, E., Furmanczyk, E.M., Tartanus, M., Brouwer, G., Parveaud, C.-E., Warlop, F., Kelderer, M., Kienzle, J., Alcazar Marin, E., Dekker, T., Vávra, R., Verrastro, V., Lindhard Pedersen, H., Boutry, C., Friedli, M., Schlüter, M., 2022. Knowledge networks in organic fruit production across Europe: a survey study. *Sustainability* 14, 2960.
- Marino, S., 2023. Understanding the spatio-temporal behavior of crop yield, yield components and weed pressure using time series Sentinel-2-data in an organic farming system. *Eur. J. Agron.* 145, 126785.
- Markova-Nenova, N., Wätzold, F., Sturm, A., 2023. Optimizing agri-environment schemes for cost-effectiveness, fairness or both? *Q. Open* 3.
- Martin, G., Moraine, M., Ryschawy, J., Magne, M.-A., Asai, M., Sarthou, J.-P., Duru, M., Therond, O., 2016. Crop-livestock integration beyond the farm level: a review. *Agron. Sustain. Dev.* 36.
- Martin, G., Durand, J.-L., Duru, M., Gastal, F., Julier, B., Litrico, I., Louarn, G., Médiéne, S., Moreau, D., Valentin-Morison, M., Novak, S., Parnaudeau, V., Paschalidou, F., Vertès, F., Voisin, A.-S., Cellier, P., Jeuffroy, M.-H., 2020. Role of ley pastures in tomorrow's cropping systems. *A review. Agron. Sustain. Dev.* 40, 17.
- Melander, B., Rasmussen, I.A., Olesen, J.E., 2016. Incompatibility between fertility building measures and the management of perennial weeds in organic cropping systems. *Agric. Ecosyst. Environ.* 220, 184–192.
- Melander, B., Rasmussen, I.A., Olesen, J.E., 2020. Legacy effects of leguminous green manure crops on the weed seed bank in organic crop rotations. *Agric. Ecosyst. Environ.* 302, 107078.
- Mérel, P., Qin, Z., Sexton, R.J., 2023. Policy-induced expansion of organic farmland: implications for food prices and welfare. *Eur. Rev. Agric.* 50, 1583–1631.
- Messéan, A., Viguier, L., Paresys, L., Aubertot, J.-N., Canali, S., Iannetta, P., Justes, E., Karley, A., Keillor, B., Kemper, L., Muel, F., Stilmant, D., Watson, C., Willer, H., Zornoza, R., 2021. Enabling crop diversification to support transitions towards more sustainable European agrifood systems. *Front. Agric. Sci. Eng.* 8, 474–480.
- Meynard, J.M., Charrier, F., Fares, M., Le Bail, M., Magrini, M.B., Charlier, A., Messéan, A., 2018. Socio-technical lock-in hinders crop diversification in France. *Agron. Sustain. Dev.* 38.
- Michalke, A., Köhler, S., Messmann, L., Thorenz, A., Tuma, A., Gaugler, T., 2023. True cost accounting of organic and conventional food production. *J. Clean. Prod.* 408, 137134.
- Micke, B., Adler, S., Forkman, J., Parsons, D., 2023. Production and nutrient composition of forage legume fractions produced by juicing and leaf stripping. *Acta Agric. Scand. Sect. B Soil Plant Sci.* 73, 199–212.
- Milardo, R., 2025. The role of knowledge and innovation in organic farming systems: a systematic literature review. *Sustainability* 17, 6563.
- Milestad, R., Rööös, E., Stenius, T., Wivstad, M., 2020. Tensions in future development of organic production—views of stakeholders on Organic 3.0. *Org. Agric.* 10, 509–519.
- Mitrović, B., Zorić, M., Terzić, S., Živanov, D., Čanak, P., Milošević, B., Karagić, D., 2023. Evidence of scientific research on organic plant breeding: a bibliometric study. *Plant Breed.* 142, 407–417.
- Möhrling, N., Müller, A., Schaub, S., 2024. Farmers' adoption of organic agriculture—a systematic global literature review. *Eur. Rev. Agric.* 51, 1012–1044.

- Möller, K., Habermeyer, J., Zinkernagel, V., Reents, H.-J., 2006. Impact and interaction of nitrogen and *Phytophthora infestans* as yield-limiting and yield-reducing factors in organic potato (*Solanum tuberosum* L.) crops. *Potato Res.* 49, 281–301.
- Möller, K., Stinner, W., Deuker, A., Leithold, G., 2008. Effects of different manuring systems with and without biogas digestion on nitrogen cycle and crop yield in mixed organic dairy farming systems. *Nutr. Cycl. Agroecosyst.* 82, 209–232.
- Møller, H.B., Sørensen, P., Olesen, J.E., Petersen, S.O., Nyord, T., Sommer, S.G., 2022. Agricultural biogas production - climate and environmental impacts. *Sustainability* 14, 1849.
- Moojen, F.G., Grillot, M., Carvalho, P.C.D., Ryschawy, J., 2023. Farm advisors play a key role in integrating crop-livestock at the farm level: perceptions and experiences in Brazil and France. *J. Agric. Educ. Ext.* 30, 683–707.
- Moschitz, H., Müller, A., Kretschmar, U., Haller, L., de Porras, M., Pfeifer, C., Oehen, B., Willer, H., Stolz, H., 2021. How can the EU Farm to Fork strategy deliver on its organic promises? Some critical reflections. *EuroChoices* 20, 30–36.
- Moss, S., 2019. Integrated weed management (IWM): why are farmers reluctant to adopt non-chemical alternatives to herbicides? *Pest Manag. Sci.* 75, 1205–1211.
- Nesme, T., Senthilkumar, K., Mollier, A., Pellerin, S., 2015. Effects of crop and livestock segregation on phosphorus resource use: a systematic, regional analysis. *Eur. J. Agron.* 71, 88–95.
- Niggli, U., 2015. Sustainability of organic food production: challenges and innovations. *Proc. Nutr. Soc.* 74, 83–88.
- Nordin, M., 2021. Is a Shortage of Manure a Constraint to Organic Farming? Working Paper. Agrifood Economic Centre, Lund University, Lund.
- Nthinyurwa, P.D., de Vries, W.T., 2021. Farmland fragmentation concourse: analysis of scenarios and research gaps. *Land Use Policy* 100, 104936.
- Nuijten, E., Messmer, M.M., Lammerts van Bueren, E.T., 2017. Concepts and strategies of organic plant breeding in light of novel breeding techniques. *Sustainability* 9, 18.
- Odlare, M., Pell, M., Svensson, K., 2004. The fertilizing effect of compost and biogas residues from source separated household waste. *J. Agric. Sci.* 142, 461–467.
- OECD, 2022. Making Agri-Environmental Payments More Cost Effective. OECD Publishing, Paris.
- Ortman, T., Sandström, E., Bengtsson, J., Watson, C.A., Bergkvist, G., 2023. Farmers' motivations for landrace cereal cultivation in Sweden. *Biol. Agric. Hort.* 39, 247–268.
- Padel, S., Lampkin, N., 2007. The development of governmental support for organic farming in Europe. In: Lockretz, W. (Ed.), *Organic Farming: An International History*. CABI International, pp. 93–122.
- Pandey, S., Johnson, A.C., Xie, G., Gurr, G.M., 2022. Pesticide regime can negate the positive influence of native vegetation donor habitat on natural enemy abundance in adjacent crop fields. *Front. Ecol. Evol.* 10.
- Pantelopoulos, A., Aronsson, H., 2021. Two-stage separation and acidification of pig slurry – Nutrient separation efficiency and agronomical implications. *J. Environ. Manag.* 280, 111653.
- Pe'er, G., Dicks, L.V., Visconti, P., Arlettaz, R., Baldi, A., Benton, T.G., Collins, S., Dieterich, M., Gregory, R.D., Hartig, F., Henle, K., Hobson, P.R., Kleijn, D., Neumann, R.K., Robijns, T., Schmidt, J., Schwartz, A., Sutherland, W.J., Turbé, A., Wulf, F., Scott, A.V., 2014. EU agricultural reform fails on biodiversity. *Science* 344, 1090–1092.
- Pe'er, G., Finn, J.A., Díaz, M., Birkenstock, M., Lakner, S., Röder, N., Kazakova, Y., Šumrada, T., Bezák, P., Concepción, E.D., Dänhardt, J., Morales, M.B., Rac, I., Špulerová, J., Schindler, S., Stavrinides, M., Targetti, S., Viaggi, D., Vogiatzakis, I.N., Guymard, H., 2022. How can the European Common Agricultural Policy help halt biodiversity loss? Recommendations by over 300 experts. *Conserv. Lett.* 15, e12901.
- Petit, S., Muneret, L., Carbone, B., Hannachi, M., Ricci, B., Rusch, A., Lavigne, C., 2020. Landscape-scale expansion of agroecology to enhance natural pest control: a systematic review. *Adv. Ecol. Res.* 63, 1–48.
- Peyraud, J.L., Taboada, M., Delaby, L., 2014. Integrated crop and livestock systems in Western Europe and South America: a review. *Eur. J. Agron.* 57, 31–42.
- Plantegenest, M., Le May, C., Fabre, F., 2007. Landscape epidemiology of plant diseases. *J. R. Soc. Interface* 4, 963–972.
- Ponizio, L.C., M'Gonigle, L.K., Mace, K.C., Palomino, J., de Valpine, P., Kremen, C., 2015. Diversification practices reduce organic to conventional yield gap. *Proc. R. Soc. Lond. B Biol. Sci.* 282.
- Ponizio, L.C., Gaiarsa, M.P., Kremen, C., 2017. Opportunistic attachment assembles plant–pollinator networks. *Ecol. Lett.* 20, 1261–1272.
- Porter, P., 2009. Crop Rotations in Organic Production Systems. In: Francis, C. (Ed.), *Organic Farming: The Ecological System*. American Society of Agronomy, Madison, USA, pp. 49–67.
- Potts, S.G., Imperatriz-Fonseca, V., Ngo, H.T., Aizen, M.A., Biesmeijer, J.C., Breeze, T.D., Dicks, L.V., Garibaldi, L.A., Hill, R., Settele, J., Vanbergen, A.J., 2016. Safeguarding pollinators and their values to human well-being. *Nature* 540, 220–229.
- Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. *Philos. T. R. Soc. B* 365, 2959–2971.
- Purnhagen, K.P., Clemens, S., Eriksson, D., Fresco, L.O., Tosun, J., Qaim, M., Visser, R.G. F., Weber, A.P.M., Wesseler, J.H.H., Zilberman, D., 2021. Europe's Farm to Fork Strategy and its commitment to biotechnology and organic farming: conflicting or complementary goals? *Trends Plant Sci.* 26, 600–606.
- Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Zander, P.M., Walker, R.L., Pristeri, A., Toncea, I., Bachinger, J., 2016. Trade-Offs between economic and environmental impacts of introducing legumes into cropping systems. *Front. Plant Sci.* 7.
- Reckling, M., Bergkvist, G., Watson, C.A., Stoddard, F.L., Bachinger, J., 2020. Re-designing organic grain legume cropping systems using systems agronomy. *Eur. J. Agron.* 112.
- Redlich, S., Martin, E.A., Steffan-Dewenter, I., 2018. Landscape-level crop diversity benefits biological pest control. *J. Appl. Ecol.* 55, 2419–2428.
- Reed, M.S., Moxey, A., Prager, K., Hanley, N., Skates, J., Bonn, A., Evans, C.D., Glenk, K., Thomson, K., 2014. Improving the link between payments and the provision of ecosystem services in agri-environment schemes. *Ecosyst. Serv.* 9, 44–53.
- Reimer, M., Möller, K., Hartmann, T.E., 2020. Meta-analysis of nutrient budgets in organic farms across Europe. *Org. Agric.* 10, 65–77.
- Reimer, M., Oelofse, M., Müller-Stöver, D., Möller, K., Bünemann, E.K., Bianchi, S., Vetemaa, A., Drexler, D., Trugly, B., Raskin, B., Blogg, H., Rasmussen, A., Verrastro, V., Magid, J., 2023. Sustainable growth of organic farming in the EU requires a rethink of nutrient supply. *Nutr. Cycl.* 129, 299–315.
- Reumaux, R., Chopin, P., Bergkvist, G., Watson, C.A., Öborn, I., 2023. Land Parcel Identification System (LPIIS) data allows identification of crop sequence patterns and diversity in organic and conventional farming systems. *Eur. J. Agron.* 149, 126916.
- Reumaux, R., Karlsson, M., Carrié, R., Öborn, I., Watson, C.A., Bergkvist, G., Dahlin, S.A., Ekroos, J., Wetterlind, J., Smith, H.G., 2026. Determinants of yield variation of organic cereals in productive agricultural areas. *Agric. Syst.* 234, 104689.
- Revoyron, E., Bail, M.L., Meynard, J.M., Gunnarsson, A., Seghetti, M., Colombo, L., 2022. Diversity and drivers of crop diversification pathways of European farms. *Agric. Syst.* 201.
- Röös, E., Mie, A., Wivstad, M., Salomon, E., Johansson, B., Gunnarsson, S., Wallenbeck, A., Hoffmann, R., Nilsson, U., Sundberg, C., Watson, C.A., 2018. Risks and opportunities of increasing yields in organic farming. A review. *Agron. Sustain. Dev.* 38, 14.
- Roschewitz, I., Gabriel, D., Tschamtker, T., Thies, C., 2005. The effects of landscape complexity on arable weed species diversity in organic and conventional farming. *J. Appl. Ecol.* 42, 873–882.
- Rundlöf, M., Smith, H.G., 2006. The effect of organic farming on butterfly diversity depends on landscape context. *J. Appl. Ecol.* 43, 1121–1127.
- Rusch, A., Bommarco, R., Ekbom, B., 2017. Conservation biological control in agricultural landscapes. *Adv. Bot. Res.* 81, 333–360.
- Sahm, H., Sanders, J., Nieberg, H., Behrens, G., Kuhnert, H., Strohm, R., Hamm, U., 2013. Reversion from organic to conventional agriculture: a review. *Renew. Agric. Food Syst.* 28, 263–275.
- Salembier, C., Segrestin, B., Weil, B., Jeuffroy, M.-H., Cadoux, S., Cros, C., Favrelière, E., Fontaine, L., Gimaret, M., Noilhan, C., Petit, A., Petit, M.-S., Porhriel, J.-Y., Sicard, H., Reau, R., Ronceux, A., Meynard, J.-M., 2021. A theoretical framework for tracking farmers' innovations to support farming system design. *Agron. Sustain. Dev.* 41, 61.
- Salliou, N., Vialatte, A., Monteil, C., Barnaud, C., 2019. First use of participatory Bayesian modeling to study habitat management at multiple scales for biological pest control. *Agron. Sustain. Dev.* 39.
- Sanders, J., Stolze, M., Padel, S., 2011. Use and Efficiency of Public Support Measures Addressing Organic Farming. Institute of Farm Economics, Braunschweig, Germany.
- Sandström, E., Ortman, T., Watson, C.A., Bengtsson, J., Gustafsson, C., Bergkvist, G., 2024. Saving, sharing and shaping landrace seeds in commons: unravelling seed commoning norms for furthering agrobiodiversity. *Agric. Hum. Values* 41, 1825–1840.
- Sandström, E., Boere, E., Krisztin, T., Verburg, P.H., 2025. Enabling and constraining factors for organic agriculture in Europe: a spatial analysis. *Environ. Res.: Food Syst.* 2, 035006.
- Sapbamrer, R., Thammachai, A., 2021. A systematic review of factors influencing farmers' adoption of organic farming. *Sustainability* 13, 3842.
- SBA, 2025. **Ekologisk växtodling 2024 (Organic plant production 2024)**. Swedish Board of Agriculture. <https://jordbruksverket.se/om-jordbruksverket/jordbruksverket-s-officiella-statistik/jordbruksverkets-statistikrapporter/statistik/2025-05-15-ekologisk-vaxtodling-2024#:~:text=Den%20omst%C3%A4llda%20arealens%20andel%20av,2024%2C%20till%2029%203000%20hektar>.
- Schaak, H., Bommarco, R., Hansson, H., Kuns, B., Nilsson, P., 2023. Long-term trends in functional crop diversity across Swedish farms. *Agric. Ecosyst. Environ.* 343.
- Schmidtnr, E., Lippert, C., Engler, B., Haring, A.M., Aurbacher, J., Dabbert, S., 2012. Spatial distribution of organic farming in Germany: does neighbourhood matter? *Eur. Rev. Agric.* 39, 661–683.
- Scott, D., Freckleton, R.P., 2022. Crop diversification and parasitic weed abundance: a global meta-analysis. *Sci. Rep.* 12, 19413.
- Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. *Nature* 485, 229–232.
- Seufert, V., Ramankutty, N., Mayerhofer, T., 2017. What is this thing called organic?—How organic farming is codified in regulations. *Food Policy* 68, 10–20.
- Sidemo Holm, W., Brady, M.V., Carrié, R., Ekroos, J., Smith, H.G., 2024. Cost-effective spatial allocation of organic farming for biodiversity conservation. *Biol. Conserv.* 294, 110624.
- Sidemo-Holm, W., Smith, H.G., Brady, M.V., 2018. Improving agricultural pollution abatement through result-based payment schemes. *Land Use Policy* 77, 209–219.
- Sidemo-Holm, W., Carrié, R., Ekroos, J., Lindström, S.A.M., Smith, H.G., 2021. Reduced crop diversity increases floral resources to pollinators without affecting crop yield in organic and conventional fields. *J. Appl. Ecol.* 58, 1421–1430.
- Simin, M.T., Janković, D., 2014. Applicability of diffusion of innovation theory in organic agriculture. *Econ. Agric.* 61, 517–529.
- Simon, S., Rusch, A., Wyss, E., Sarthou, J.-P., 2014. Conservation biocontrol: principles and implementation in organic farming. In: Bellon, S., Penvern, S. (Eds.), *Organic Farming, Prototype for Sustainable Agricultures: Prototype for Sustainable Agricultures*. Springer, Netherlands, Dordrecht, pp. 83–105.
- Smith, H.G., Birkhofer, K., Clough, Y., Ekroos, J., Olsson, O., Rundlöf, M., 2014. Beyond dispersal: the role of animal movement in modern agricultural landscapes. In: Hansson, L.-A., Åkesson, S. (Eds.), *Animal Movement across Scales*. Oxford Univ. Press, Oxford, pp. 51–70.

- Smith, H.G., Dänhardt, J., Blombäck, K., Caplat, P., Collentine, D., Grenerstam, E., Hanson, H., Höjgård, S., Jansson, T., Johnsson, H., Jönsson, A.M., Lantz, M., Lindström, Å., Nilsson, L., Nordin, M., Olsson, O., Stewart, R., Stjernman, M., Öckinger, E., 2016. Slututvärdering av det svenska landsbygdsprogrammet 2007–2013. Delrapport II: Utvärdering av Åtgärder för Bättre Miljö. Swedish Board of Agriculture, Jönköping.
- Smith, O.M., Cohen, A.L., Rieser, C.J., Davis, A.G., Taylor, J.M., Adesanya, A.W., Jones, M.S., Meier, A.R., Reganold, J.P., Orpet, R.J., 2019. Organic farming provides reliable environmental benefits but increases variability in crop yields: a global meta-analysis. *Front. Sustain. Food Syst.* 3, 82.
- Smith, O.M., Cohen, A.L., Reganold, J.P., Jones, M.S., Orpet, R.J., Taylor, J.M., Thurman, J.H., Cornell, K.A., Olsson, R.L., Ge, Y., Kennedy, C.M., Crowder, D.W., 2020. Landscape context affects the sustainability of organic farming systems. *Proc. Natl. Acad. Sci. USA* 117, 2870–2878.
- Speiser, B., Wyss, E., Maurer, V., 2006. Biological control in organic production: first choice or last option? In: Eilenberg, J., Hokkanen, H.M.T. (Eds.), *An ecological and societal approach to biological control*. Springer, Dordrecht, The Netherlands, pp. 27–46.
- Stoate, C., Boatman, N.D., Borralho, R.J., Carvalho, C.R., de Snoo, G.R., Eden, P., 2001. Ecological impacts of arable intensification in Europe. *J. Environ. Manag.* 63, 337–365.
- Stoate, C., Báldi, A., Beja, P., Boatman, N.D., Herzog, I., van Doorn, A., de Snoo, G.R., Rakosy, L., Ramwell, C., 2009. Ecological impacts of early 21st century agricultural change in Europe – A review. *J. Environ. Manag.* 91, 22–46.
- Stolze, M., Lampkin, N., 2009. Policy for organic farming: rationale and concepts. *Food Policy* 34, 237–244.
- Sūmane, S., Kunda, I., Knickel, K., Strauss, A., Tisenkopfs, T., Rios, I.D.I., Rivera, M., Chebach, T., Ashkenazy, A., 2018. Local and farmers' knowledge matters! How integrating informal and formal knowledge enhances sustainable and resilient agriculture. *J. Rural. Stud.* 59, 232–241.
- Sutherland, L.-A., Gabriel, D., Hathaway-Jenkins, L., Pascual, U., Schmutz, U., Rigby, D., Godwin, R., Sait, S.M., Sakrabani, R., Kunin, W.E., Benton, T.G., Stagl, S., 2012. The 'Neighbourhood Effect': a multidisciplinary assessment of the case for farmer co-ordination in agri-environmental programmes. *Land Use Policy* 29, 502–512.
- Terres, J.-M., Scacchiafichi, L.N., Wania, A., Ambar, M., Anguiano, E., Buckwell, A., Coppola, A., Gocht, A., Källström, H.N., Pointereau, P., Strijker, D., Visek, L., Vranken, L., Zobena, A., 2015. Farmland abandonment in Europe: identification of drivers and indicators, and development of a composite indicator of risk. *Land Use Policy* 49, 20–34.
- Tidåker, P., Sundberg, C., Öborn, I., Kätterer, T., Bergkvist, G., 2014. Rotational grass/clover for biogas integrated with grain production—a life cycle perspective. *Agric. Syst.* 129, 133–141.
- Török, P., Dengler, J., 2018. Palaeoartctic grasslands in transition: overarching patterns and future prospects. In: Squires, V.R., Dengler, J., Feng, H., Hua, L. (Eds.), *Grasslands of the World: Diversity, Management and Conservation*. CRC Press, Boca Raton, US, pp. 15–26.
- Tscharntke, T., Tylianakis, J.M., Rand, T.A., Didham, R.K., Fahrig, L., Batary, P., Bengtsson, J., Clough, Y., Crist, T.O., Dormann, C.F., Ewers, R.M., Frund, J., Holt, R. D., Holzschuh, A., Klein, A.M., Kleijn, D., Kremen, C., Landis, D.A., Laurance, W., Lindenmayer, D., Scherber, C., Sodhi, N., Steffan-Dewenter, I., Thies, C., van der Putten, W.H., Westphal, C., 2012. Landscape moderation of biodiversity patterns and processes – eight hypotheses. *Biol. Rev. Camb. Philos. Soc.* 87, 661–685.
- Tscharntke, T., Grass, I., Wanger, T.C., Westphal, C., Batary, P., 2021. Beyond organic farming – harnessing biodiversity-friendly landscapes. *Trends Ecol. Evol.* 36, 919–930.
- Ustaoglu, E., Collier, M.J., 2018. Farmland abandonment in Europe: an overview of drivers, consequences, and assessment of the sustainability implications. *Environ. Rev.* 26, 396–416.
- van Bruggen, A.H.C., Finckh, M.R., 2016. Plant diseases and management approaches in organic farming systems. *Annu. Rev. Phytopathol.* 54, 25–54.
- van Ittersum, M.K., Silva, J.V., Bommarco, R., Hijbeek, R., Lundin, O., Nandillon, R., Bergkvist, G., Menegat, A., Öborn, I., Söderholm-Emas, A., Stoddard, F.L., Vico, G., Vonk, W.J., Watson, C.A., MacLaren, C., 2025. Narrowing the ecological yield gap to sustain crop yields with less inputs. *Glob. Food Sec.* 45, 100857.
- van Loon, M.P., Alimgham, S., Pronk, A., Fodor, N., Ion, V., Kryvoshein, O., Kryvobok, O., Marrou, H., Mihail, R., Minguez, M.I., Pulina, A., Reckling, M., Rittler, L., Roggero, P.P., Stoddard, F.L., Topp, C.F.E., van der Wel, J., Watson, C., van Ittersum, M.K., 2023. Grain legume production in Europe for food, feed and meat-substitution. *Glob. Food Sec.* 39, 100723.
- van Vliet, J., de Groot, H.L.F., Rietveld, P., Verburg, P.H., 2015. Manifestations and underlying drivers of agricultural land use change in Europe. *Landsc. Urban Plan.* 133, 24–36.
- Vermunt, D.A., Wojtynia, N., Hekkert, M.P., Van Dijk, J., Verburg, R., Verweij, P.A., Wassen, M., Runhaar, H., 2022. Five mechanisms blocking the transition towards 'nature-inclusive' agriculture: a systemic analysis of Dutch dairy farming. *Agric. Syst.* 195, 103280.
- Vikki, K., Tampio, E., Winquist, E., Saarinen, M., Luostarinen, S., 2025. Valorising digestate as bio-based fertiliser next to biogas: environmental life cycle costing of three farm-scale anaerobic co-digestion scenarios. *Bioresour. Technol.* 440, 133401.
- Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of Earth's ecosystems. *Science* 277, 494–499.
- Wanasundara, J.P.D., Schmitt, C., Lamsal, B.P., 2024. Chapter 19 - Challenges of plant protein processing and protein ingredient functionality assessment. In: Wanasundara, J.P.D., Schmitt, C., Lamsal, B.P. (Eds.), *Functionality of Plant Proteins*. Academic Press, pp. 505–520.
- Watson, C.A., Atkinson, D., Gosling, P., Jackson, L.R., Ryans, F.W., 2002a. Managing soil fertility in organic farming systems. *Soil Use Manag.* 18, 239–247.
- Watson, C.A., Bengtsson, H., Ebbesvik, M., Loes, A.-K., Myrbeck, A., Salomon, E., Schroder, J., Stockdale, E.A., 2002b. A review of farm-scale nutrient budgets for organic farms as a tool for management of soil fertility. *Soil Use Manag.* 18, 264–273.
- Wätzold, F., Drechsler, M., Johst, K., Mewes, M., Sturm, A., 2016. A novel, spatiotemporally explicit ecological-economic modeling procedure for the design of cost-effective agri-environment schemes to conserve biodiversity. *Am. J. Agric. Econ.* 98, 489–512.
- Weisberger, D., Nichols, V., Liebman, M., 2019. Does diversifying crop rotations suppress weeds? A meta-analysis. *PLoS One* 14, e0219847.
- Weituschat, C.S., Pascucci, S., Matera, V.C., Blasi, E., 2023. Understanding the role of value chain formation in the scaling of crop diversification. *Agron. Sustain. Dev.* 43, 25.
- Wesseler, J., 2022. The EU's farm-to-fork strategy: an assessment from the perspective of agricultural economics. *Appl. Econ. Perspect. Policy* 44, 1826–1843.
- Whitton, C., Bogueva, D., Marinova, D., Phillips, C.J.C., 2021. Are we approaching peak meat consumption? Analysis of meat consumption from 2000 to 2019 in 35 countries and its relationship to gross domestic product. *Animals* 11, 3466.
- Willer, H., Moeskops, B., Busacca, E., Brisset, L., Gernets, M., Schmidt, S., 2021. Organic in Europe: recent developments. In: Willer, H., Trávníček, J., Meier, C., Schlatter, B. (Eds.), *The World of Organic Agriculture*. FiBL and IFOAM, Frick, Switzerland, pp. 219–228.
- Willer, H., Schlatter, B., Trávníček, J., Schaacks, D., 2024. Organic farming and market development in Europe and the European Union. In: Willer, H., Trávníček, J., Schlatter, S. (Eds.), *The World of Organic Agriculture. Statistics and Emerging Trends 2024*. FiBL, Frick, and IFOAM, Bonn, Germany.
- Wiréhn, L., 2018. Nordic agriculture under climate change: a systematic review of challenges, opportunities and adaptation strategies for crop production. *Land Use Policy* 77, 63–74.
- Wuest, S.E., Peter, R., Niklaus, P.A., 2021. Ecological and evolutionary approaches to improving crop variety mixtures. *Nat. Ecol. Evol.* 5, 1068–1077.
- Xu, B., Gui, D., Pu, Q., Sha, Z., 2025. The fate of nitrogen derived from green manure and its influence on crop N agronomic performance. *Eur. J. Agron.* 168, 127646.
- Zehnder, G., Gurr, G.M., Kuhne, S., Wade, M.R., Wratten, S.D., Wyss, E., 2007. Arthropod pest management in organic crops. *Annu. Rev. Entomol.* 52, 57–80.