Constraints and opportunities for organic crop production in areas of high agricultural productivity

Exploring the diversity of on-farm management practices in organic cereal production with a focus on crop sequence, yield variability and nutrient supply

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Abstract

Agricultural intensification has led to simplified production systems characterised by uniform arable landscapes and a low diversity of cropping systems across Europe. Organic farming has been put forward as one option for sustainable agriculture. However, studies assessing the diversity within organic cropping systems, and exploring processes that occur on farms as well as across different biophysical conditions are rare. The aim of my thesis was to examine the current diversity in organic farming practices, and to explore management alternatives to foster the increase in productivity of organic arable farming in highly productive areas. With the help of extensive national farmer reported data over a 10-year period, and on-farm data from 67 fields in south and southwestern Sweden, I identified large variations in both crop sequences and cereal yield in organic agriculture. The revealed disparities create an opportunity to make organic arable farming more profitable through adaptations in management practices, such as timely nutrient supply, and the implementation of precision agricultural methods to quantify within-field variation in organic cropping systems. I tested the application of biogas digestate as fertiliser to growing wheat, following perennial grass-legume ley, and found it to be a promising nitrogen management strategy to increase grain yield and protein content. My research findings contribute to the understanding of how organic crop production and productivity can be improved by integrating knowledge of site-specific biophysical processes with agronomic and ecological aspects of the cropping system.

Keywords: biogas digestate, cereals, crop sequence, management practices, nitrogen strategy, on-farm trial, organic farming, preceding crop, protein content.

Dedication

To my friends Sarah and Sebastian

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This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:
Papers I-IV are reproduced with the permission of the publishers.

I. Reumaux, R., Chopin, P., Bergkvist, G., Watson, C.A. & Öborn, I. (2023). Land Parcel Identification System (LPIS) data allows identification of crop sequence patterns and diversity in organic and conventional farming systems. European Journal of Agronomy, 149, 126916.

II. Reumaux, R., Karlsson, M., Carrié, R., Öborn, I., Watson, C.A., Bergkvist, G., Dahlin, S., Ekroos, J., Wetterlind, J., Smith, H. Determinants of yield variation of organic cereals in productive agricultural areas of Sweden (manuscript)

III. Morandin Figueiredo, B., Reumaux, R., Engström, L., Delin, S., Öborn, I., Söderström, M., Wetterlind, J. (2023) Optimising the nitrogen use efficiency of organic spring wheat: managing within-field variation in nitrogen requirements (submitted manuscript)

IV. Reumaux, R., Wetterlind, J., Dahlin, S., Bergkvist, G., Watson, C.A., Öborn, I. Improving the bread making quality of winter wheat on organic farms using biogas digestate as a nitrogen fertiliser. (manuscript)

The contribution of Rafaelle Reumaux to the papers included in this thesis was as follows:

I. Main author. RR and co-authors conceptualised the study based on existing data from PC. RR carried out descriptive analysis with guidance of PC. RR wrote the manuscript together with the co-authors.

II. Main author together with MK. RR designed and planned on-farm observation study together with co-authors. RR conducted the fieldwork in Västra Götaland and MK mirrored the sampling in Skåne and Halland. RR and MK carried out data analyses, interpretations and led the writing with guidance of RC, JE, HS and IO. All co-authors commented on the final version of the manuscript.

III. Second author. RR conceptualised the on-farm experimental trial together with JW and IO. RR participated in collecting data. RR interpreted the results together with BMF and JW. All co-authors commented on the final version of the manuscript.

IV. Main author. RR designed and planned on-farm experimental trials together with co-authors. RR conducted the fieldwork and carried out data analyses with guidance from JW. RR wrote the manuscript together with the co-authors.

1. Introduction

Agriculture has a significant impact on the environment and plays a crucial role in achieving sustainability, as reflected in the United Nations Agenda 2030 and the Sustainable Development Goals (SDGs) (specifically SDGs 2 and 12, (Griggs et al. 2013; Lee et al. 2016). The industrialisation of the food and agricultural sector has resulted in environmental degradation and destruction (Campbell et al. 2003; Willett et al. 2019). However, agriculture is an essential sector in meeting future challenges, such as an increasing world population, food security, resource scarcity and the need to mitigate climate change by reducing greenhouse gas emissions. Agricultural landscapes are important habitats for biodiversity and play a significant role in biodiversity conservation (Guerrero et al. 2012).

In recent decades, agricultural intensification has led to a simplified production system with lower diversity of cropping systems, increased genetic uniformity, and increased uniformity of agricultural landscapes. This has resulted in larger fields with fewer crop species in rotation (Barbieri et al. 2017; Stein & Steinmann 2018). Unfortunately, a great deal of environmental pressure from agricultural expansion and intensification has not shown any clear improvement in trends, according to the European Environment Agency (2021). The depletion of critical ecosystem conditions suggests that more sustainable forms of agriculture are needed to face upcoming challenges. Several stakeholders from academic, political, and social spheres have recognised the need for a transition towards sustainability in its three dimensions – economic, social and environmental sustainability (Martin et al. 2018). Sustainability discussions play a central role in global and regional initiatives, such as the Agenda 2030 (Lee et al. 2016) and The European Commission's Green Deal 2030 (European Commission 2021).

In agriculture, sustainability involves systems that are less dependent on anthropogenic input and fossil fuels, are resilient to global changes (Bommarco et al. 2013), and use practices that conserve biodiversity and ensure economic viability for farmers (Martin et al. 2018). Transition measures require significant changes in the entire agricultural sector, including agronomic practices such as reducing the use of fertilisers and pesticides (Tilman et al. 2002; Robertson & Vitousek 2009).

Over the past few years, studies forming the evidence base of ecological intensification in agriculture have increased. Ecological intensification has been suggested as an alternative approach to sustainable intensification, in which regulating and yield-supporting ecosystem services are provided through beneficial organisms replacing or reducing the need for anthropogenic inputs, such as pesticides (Bommarco et al. 2013). This alternative approach has demonstrated how management can enhance the delivery of a range of regulating and supporting ecosystem services, or even produce win-win situations for agricultural production and the environment. Organic farming has been suggested as one way to transition to more sustainable agricultural production, and its principles suggest an alignment with agroecology practices and nature-based solutions that are put forward in the current policies (Farm to Fork Strategy, European Commission 2020). Overall, organic farming has the potential to drive the transition to more sustainable agricultural practices, since pesticides and mineral fertilisers are not allowed (Eyhorn et al. 2019), and there is a crucial need for research to explore mechanisms for how this can be achieved.

To understand and facilitate the adoption of organic farming practices, constraints need to be investigated at several scales. This thesis focuses on crop production in arable systems at both regional and field scales. A key issue for the expansion of organic farming is the development of practices that allow farmers to produce yields with stable agronomic and economic benefits in the absence of chemical inputs. The marginal environmental benefits of organic farming may be greatest in structurally simple and intensively managed landscapes. However, there are relatively few organic farms in these areas, possibly due to the lack of subsidies compensating for the yield differential to conventional farms (Rundlöf & Smith 2006). Indeed, the geographical coverage of organic farmland is linked to subsidies from the EU Common Agricultural Policy (CAP).

These are mainly area-based and not production-based, which means subsidies are relatively more important on less productive land. For the EU to reach its goal for organic production, it is necessary to understand what factors beyond subsidy systems are constraining the expansion of organic farming, particularly in regions with low current uptake or intensively cropped regions with few ruminant animals.

In Sweden, organic farmland represents 20% of total agricultural land (Swedish Board of Agriculture 2023), which is high in comparison to many other European countries (European Environment Agency 2023). However, in recent years, there has been a decrease in organically farmed land, with 100,000 ha less in 2023 than 2022 (Swedish Association of Organic Farmers 2023). This trend was likely driven by reduced consumer demand, partly as a consequence of a general increase in food prices, which tends to make consumers choose cheaper or more local products (Lindström 2022).

This thesis focuses on the contemporary organic farming context, using Sweden as a case study, specifically looking at the arable production of cereals in highly productive areas, which has received little attention in previous agronomic studies.

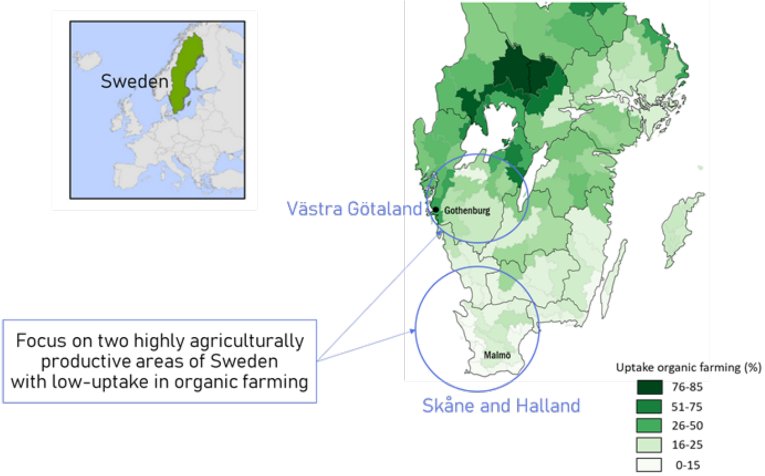


Figure 1. A map of the uptake in organic farming in the southern part of Sweden (the country is block-green coloured in map on the left), with a focus on the highly agriculturally productive agricultural areas studied in this thesis. The green colour increases in intensity with the proportion of organic farming, based on farm certification data reporting. The lightest green shade represents 0-15% of organic farmland relative to total arable land and the darkest green shade represents 76-85% of organic farmland. (Swedish Board of Agriculture, 2020)

1.1 Thesis aims and objectives

My work aims to examine the current diversity of organic farming practices in highly productive areas and explore management alternatives to increase the productivity of organic arable farming systems in these areas.

The specific objectives are to:

1. Evaluate and compare crop distribution, diversity and crop sequences, and to explore the pre-crops of spring barley and winter wheat on farmers' fields in different productivity zones in Sweden (Paper I);
2. Explore variation in the organic management of spring barley and winter wheat, and determine the agronomic, ecological and bio-physical limitations of organic crop yields, and the role of management practices in fields on different organic farms (Paper II);
3. Quantify at a high spatial resolution the within-field variation of spring wheat grain yield and protein content in response to soil N supply and different rates of biogas digestate on an organic farmer's field following a perennial grass-clover ley crop (Paper III);
4. Investigate how nitrogen management using ley pre-crop and the application of different rates of biogas digestate affects the grain yield and protein content of organic winter wheat on different organic farmers' fields (Paper IV).

1.2 Overview of articles

- Paper I identifies crop sequence patterns and diversity in organic and conventional farming systems using 10-years of farmers' reported data for crops grown in their fields (LPIS data).

- Paper II quantifies and explains the driving agronomic, ecological and biophysical factors behind the variation in agronomic performance of organic cereals.

- Paper III establishes an experimental approach based on precision agriculture methods using different biogas digestate application rates to understand variation in soil nitrogen supply and crop nitrogen requirement within an organic farmer's field.

- Paper IV assesses how nitrogen management through the application of biogas digestate can enhance the yield and bread-making quality of winter wheat using on-farm trials on ten organic farms with differing field properties (all having perennial ley as the pre-crop).

2. Background

2.1 Focus on cropping systems

In agriculture, crop production can be seen as an optimum combination of GxMxE (i.e. genetics - agronomic management – growing environment) (Rodriguez et al. 2018). The system managed at the field level is referred to as the cropping system, a set of management practices applied to a given area, including the crop sequence of species, or mixtures of species, and cultivars (Sebillotte 1990; Cochet 2012; Reckling et al. 2016). At the same level, animal production can be analysed using the concept of the livestock system, which integrates aspects of herd composition (e.g. genetic characteristics, demographic pyramid), feeding practices, forage calendar and herd management (e.g. herd movements, breeding, and care) (Edwards-Jones 2006). At the larger scale, the farming system is defined as a population of individual landowners with similar resource bases, enterprise patterns, household livelihoods and constraints, and for whom similar development strategies and interventions would be appropriate (Dixon 2001). Decisions related to the use and management of forest and agricultural lands are driven by farmer resources, personal characteristics and the structure of the social milieu (Edwards-Jones 2006). Food systems are generally conceived of as networks of actors and activities in interrelations with ecological, political, cultural, economic and environmental systems (Ericksen 2008). These activities include crop and livestock production, processing, distribution, consumption of goods as well as responsible supply of inputs and recycling of losses (International Panel of Experts on Sustainable Food Systems (IPES Food) 2015).

In this thesis, the focus is specifically on organic cropping systems in which on-farm management practices were investigated.

2.2 Ecological intensification

Ecosystem services play an important role in the transition to more sustainable agro-ecosystems, which have been increasingly acknowledged over recent decades (Millennium Ecosystem Assessment (Program) 2005). As a response to this, the concept of “ecological intensification” has been characterised as a way of actively managing farmland to increase the intensity of the ecological processes that support production, such as biotic pest regulation, nutrient cycling, and pollination (Doré et al. 2011; Bommarco et al. 2013; Tittonell 2014). Nonetheless, this approach is rarely adopted by farmers because they do not always see the immediate benefits (Kleijn et al. 2019). One of the main challenges for agro-ecosystems is to obtain high levels of food and feed production, while at the same time minimising environmental damage and positively contributing to ecosystem service delivery (Tilman et al. 2002). While several studies show the beneficial effects of ecological intensification management on biodiversity at multi-trophic levels (Shackelford et al. 2013; Bengtsson 2015; Birkhofer et al. 2018; Wan et al. 2019), few ecological studies focus on the delivery of provisioning ecosystem services, such as yield quantity and quality in arable farming systems (Pywell et al. 2015), which is the main focus within agronomy. The application of the concept of ecological intensification requires a good understanding of on-site biological and ecological processes and thus can provide better-suited solutions to specific pedo-climatic conditions. Though this approach may seem like a promising way of redesigning agro-ecosystems, there is a need for greater precision in defining the terms and respective practices used in ecological intensification (Wezel et al. 2015).

Several studies exist which evaluate the effects of farm management practices on regulating and maintaining ecosystem services (Bengtsson et al. 2005; Birkhofer et al. 2016). However, few of these studies have been able to capture the evaluation of corresponding provisioning ecosystem services, such as crop performance and yield provision (van den Belt & Blake 2014). A recent study by Nkurunziza et al. (2017) on organically and conventionally grown barley showed that there is a potential for the optimised use of management practices to increase nitrogen efficiency on farms. At the landscape level, studies of ecosystem services (Benoît et al. 2012) have a special focus on the existence of regulating services affecting pest and disease pressure (Bianchi et al. 2006; Tscharntke et al. 2011; Petit et al. 2016). In the case of organic farming, studies including the landscape perspective point to the ways the spatial aggregation of conditions beneficial for organic practices promote the conversion of farmers in the neighbourhood (Gabriel et al. 2009).

2.3 The development of research on organic farming over time

Research on organic food and agriculture has mainly focused on consumer perceptions of quality, particularly in comparison to conventional foods (Watson et al. 2008; Chopin et al. 2023). This emphasis on consumer health-consciousness may explain why organic systems often mimic conventional systems and prioritise meeting consumer demand for perceived higher quality products over improving environmental protection. While significant progress has been made in organic farming research, several knowledge gaps persist, such as the assessment of long-term effects of organic practices on the delivery of ecosystem services and resilience to climate change (Fan et al. 2018). Further research is needed to optimise the use of organic inputs, such as compost, green manures, and other manufactured products, that can be used as organic fertilisers, providing alternative nutrient sources to animal manure. This is essential to ensure adequate nutrient delivery in synchrony with the needs of the crops while minimising environmental impacts, such as nitrogen leaching (De Notaris et al. 2018) and emissions of nitrogenous gases (e.g. NH_3 and N_20). Weed management remains a significant challenge in organic farming (Melander et al. 2020). Thus, studies are needed to evaluate integrative and innovative weed management strategies, including cover cropping, mechanical weed control and allelopathic crops. With inevitable shifts in climate, research is necessary to assess the resilience of organic farming systems to climate change impacts, such as extreme weather events and fluctuating conditions (Marini et al. 2020a; Faye et al. 2023). Organic farming's economic viability is strongly dependent on access to markets for organically cultivated products, as well as on subsidies within CAP or similar systems (Offermann et al. 2009). More research is needed to address limiting factors, such as certification costs and requirements (Adamson et al. 2023), and issues with access to premium markets. Exploring scenarios (Öborn et al. 2013; Reinhardt 2023) can be a helpful tool to understand these opportunities for organic product commercialisation and consumer behaviour (Lindström 2022).

However, research on organic food and agriculture has so far mostly been mono-disciplinary (Chopin et al. 2023). This hampers the assessment of the overall effects of organic food and farming systems on the environment and their socioeconomic benefits.

Experiments that combine different disciplines and test multiple diversification practices could provide the necessary insights. For example, research on integrated crop-livestock organic production (Öborn et al. 2005). The research focus on crop diversification in organic farming differs from that in conventional farming; organic farming research places more emphasis on the use of service crops and less on rotation and cash crop mixtures (Chopin et al. 2023). Finally, farmer knowledge is an essential pillar of agricultural research (Kernecker et al. 2021; Lacoste et al. 2022; Klebl et al. 2023). Understanding farmers' perceptions and motivations is crucial for promoting the adoption and scalability of organic farming practices (Milestad & Darnhofer 2003; Chongtham et al. 2017). Studies to understand the levers and challenges in the conversion to organic farming need to be coupled to effective extension and education services (Martin et al. 2018) to support farmers in transition.

2.4 Targeted action at field level including farmer's participation and on-farm experiments

Organic farming typically presents lower yields compared to conventional farming (Seufert et al. 2012; Röös et al. 2018). In regions where organic farming uptake is low, such as in the plains of Sweden, obtaining a high yield of organic cash crops can present substantial opportunity costs for farmers contemplating converting to organic practices.

Research carried out in farmers' fields and at scales that are relevant to them is important since it allows a deeper understanding of the local context, including soil types, climate conditions, and the socio-economic factors that influence the productivity of organic farming systems. This is essential for developing locally adapted solutions (Watson et al. 2002). In comparison to controlled experimental settings, research conducted directly on farmers' fields allows the possibility to address constraints that might not occur in controlled environments (Hellin et al. 2008). This ensures findings that are directly applicable to farmers' needs and can be readily adopted in practice.

Enabling peer-to-peer learning is also a positive way of facilitating knowledge transfer (Nyberg et al. 2020), and more studies investigating neighbouring farm effects are needed (Gabriel et al. 2009). It is essential to facilitate the participation of multiple stakeholders who play important roles in the farming network alongside farmers.

For example, stakeholders from extension services are often involved in decision-making around the cropping system and its management. Through participatory experimental processes, this allows the harnessing of farmers' own knowledge, focuses the external perspective of other experts, and creates value for all actors in the farming system (Lamine & Bellon 2009; Lacoste et al. 2022). This approach contrasts with most agronomic research, which obtains results independently of specific on-farm conditions. In this context, it is important to acknowledge the heterogeneity of farming circumstances, practices and needs to facilitate local innovations. For example, finding suitable N management strategies is challenging, as there is a variation in N demand in organic farming systems (Arbenz et al. 2017). The in-field variability of crop N demand has mostly been addressed in conventional agriculture with the help of methods from precision agriculture using, for example, variable N-rate fertilisation (Argento et al. 2020). In this context, few studies have been undertaken to assess in-field variation in yield quantity and quality, and the potential for variable N-fertilisation in organic systems.

Finally, on-farm research can offer empirical evidence about the long-term sustainability of farm structure, activities and dynamics (Cialdella et al. 2009). Since farmers interactively adjust both their objectives and situations, studies have shown the ability of farming systems to adapt to ongoing change and cope with unpredictability (Darnhofer et al. 2010).

3. Material and methods

Pursuing this thesis in crop production ecology, with the aim of investigating on-farm processes and how organic management practices affected crop productivity, made it necessary to adopt a multi-method approach (Figure 2). The main methods are described in this section and include the use of observation data at regional and field levels, as well as experimental data at field and plot levels. More detail is given in Papers I to IV.

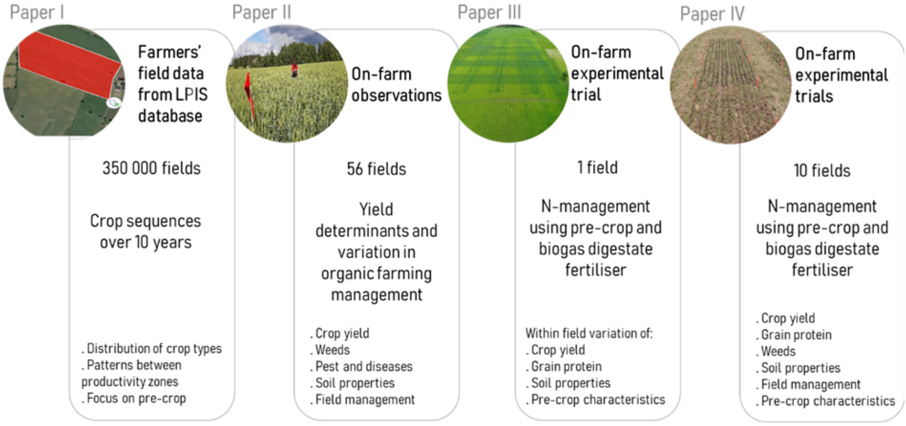


Figure 2. Synthesis of methods, framework and data used in papers I-IV.

3.1 Agricultural productivity zones in Sweden (study areas)

Paper I is a study based on large-scale data for different productivity zones in Sweden. The country has around 3 million hectares (ha) of agricultural land (7% of its territory), comprising 2.6 million ha of arable land and 0.45 million ha of permanent grassland (Swedish Board of Agriculture 2018). The main arable crops are grass or grass-legume leys (45%, including a small area of annual crops used to produce forage), and cereals (40%), particularly wheat and barley (Table 1). The Swedish landscape has been shaped by several glaciations that have formed soils of diverging traits and fertility. To account for this, Sweden can be subdivided into five productivity zones, each differing in growing conditions and, thus, land use, including crop growing and animal rearing (Swedish Board of Agriculture 2018; Piikki K., Söderström M. 2019).

Crop distribution and sequence diversity were analysed for each of the five productivity zones (Figure 3). These zones aggregate areas with combinations of climate, topography and soil type that give similar agronomic productivity potential; Zone 1 (11% of total arable area) is “the most productive”, Zone 2 (11%) has “high productivity”, Zone 3 (38%) has “medium productivity”, Zone 4 (21%) has “low productivity”, and Zone 5 (20%) is “the least productive” (Swedish Board of Agriculture 2023). In Paper I, zones 1, 3 and 5 were compared to reflect the main productivity gradient and contrasting patterns of crop sequences throughout the country.

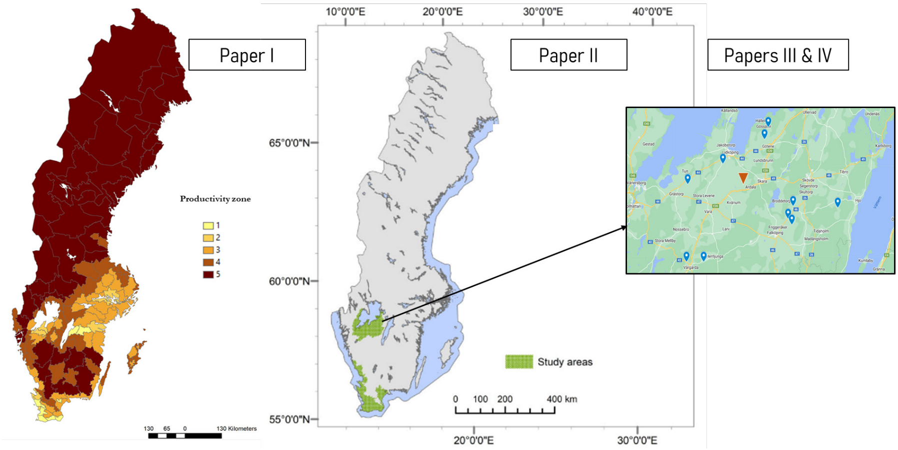


Figure 3. Maps showing the areas of study for papers I-IV. Paper I investigated five productivity zones across Sweden; Paper II focused on two areas dominated by arable farming in productive zones 1 to 3 located in the Skåne-Halland and Västra Götaland Counties; and Paper III and Paper IV were based on on-farm studies located in Västra Götaland. Paper III was an experiment on a single organic farmer’s field (labelled in orange), and Paper IV looked at 10 fields from different organic farms (labelled in blue).

Table 1. The distribution of crop types in the five productivity zones in the study period 2004-2015 (based on LPIS data), given as a percentage (rounded to the nearest whole number) relative to average area of those crops cultivated within each zone, averaged over the 10-year period, excluding fields with leys or pastures during the whole 10-year period (Swedish Board of Agriculture 2020).

Crop type	**Crop species**	**Productivity zone (%)**				
		1	**2**	**3**	**4**	**5**
Winter cereals		39	36	20	9	1
	Winter wheat	*34*	*32*	*16*	*5*	*1*
	Others[1]	*5*	*4*	*4*	*4*	*1*
Spring cereals		20	18	23	18	16
	Spring barley	*18*	*15*	*19*	*16*	*15*
	Spring wheat	*2*	*3*	*4*	*3*	*1*
Oats		3	12	12	13	7
Grain legumes		4	7	7	7	3
Mixture cereal and grain legumes		0	1	2	3	4
Oilseed rape		11	8	5	2	0
Roots and tubers		8	2	2	0	1
	Potato	*1*	*1*	*1*	*0*	*1*
	Sugar beet	*8*	*1*	*1*	*0*	*0*
Young ley (1-2 years)		5	6	12	19	24
Old ley and pastures (3 years or older)		4	6	13	26	43
Other crops		4	4	3	2	1
Fallow		3	6	7	6	3

[1] *"Others" include winter barley, triticale and rye.*

3.2 Analysis of crop sequence patterns in different productivity zones (Paper I)

Crop sequences in Sweden over the selected 10-year period (2005-2014) were identified using the Land Parcel Identification System (LPIS) database managed by the Swedish Board of Agriculture, which enables farmers to receive subsidies from the EU Common Agriculture Policy (CAP). The LPIS provided information on the crops that are cultivated on farmers' parcels, also known as "blocks". Each block is identified by an ID code (Milenov & Kay 2006). In the structure of the LPIS data, one block can contain several fields. Based on their ID, blocks were linked across years and then fields were linked within the blocks. Farm subsidy information was used to identify whether each block was declared as being under organic management or not in each year (Swedish Board of Agriculture 2018). We followed a total of 200,501 ha of organically managed fields over the 10-year period and 1,113,355 ha of conventionally managed fields (i.e., 15% of the included fields were organically managed). Fields registered as repeated grassland for the whole period were regarded as permanent grassland and were excluded from the analysis.

Using the LPIS dataset, crops with similar botanical and agronomic characteristics were consistently grouped. Crop sequences were further characterised based on: i) crop distribution, taken as relative cultivated area (ha) of the crop in each productivity zone averaged during the 10-year period; ii) crop type diversity, calculated as the number of different crop types grown on the same field during the 10-year period; and iii) crop share in the sequence, calculated as the number of times a specific crop type was grown in the 10-year period. In the crop share, only fields where the specific crops were grown at least once during the period were included, thus not given as average for all fields in the zone. The crop type diversity was obtained by counting the number of different individual crop types from the crop grouping and calculating them for each crop sequence occurring over the 10-year period. As an additional indicator of diversity, the exponential Shannon diversity index was calculated using crop types instead of species, with community replaced by years of the crop sequence.

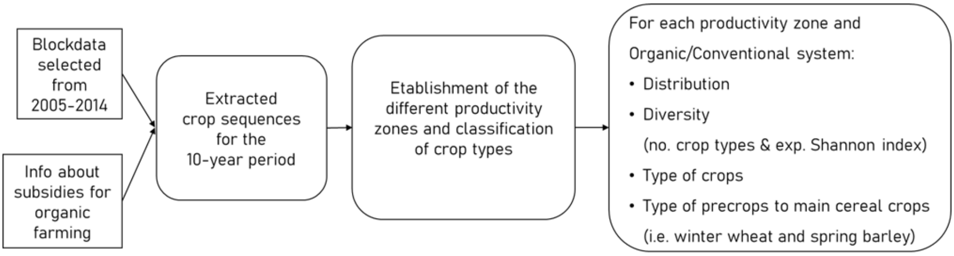


Figure 4. Steps used to complete the analysis of the blockdata in Paper I.

3.3 On-farm experiments

Identifying crop sequence patterns and diversity in different productivity zones, as done in Paper I, represents only one aspect of cropping systems. To gain a better understanding of yield limiting factors in fields on farms, we conducted studies on several organic farms in two areas of south-west and southern Sweden (Figure 3). We carried out both observational and experimental studies with a focus on the cultivation of major cereal crops (i.e. spring barley, winter wheat and spring wheat).

Figure 5. An organic winter wheat field on a farm in Västra Götaland in July 2020.

Figure 6. Soil sampling of topsoil in an organic spring barley field on a farm in Västra Götaland in August 2020.

3.3.1 Experimental set-up of the observation study on-farms to identify and quantify determinants of yields of organic cereals (Paper II)

In Paper II, the study areas included productivity zones 1 to 3, located in Västra Götaland, Skåne and Halland Counties. A total of 56 organic farms were included in the study, with a pre-requisite of being larger than 10 ha, managed organically for at least four years, and growing either winter wheat, spring barley or both in 2020.

On each farm, one field per crop that represented typical conditions and management practices on the farm, according to the farmer, was selected if available. In each field, our observation plots (2 by 2 meters) were established and visited three times during spring and summer 2020, from tillering to grain maturity. The grain yield of the observation fields was determined and reported by the individual farmers. Information on indicators of crop performance was collected, including development stage, nitrogen status in leaves using SPAD chlorophyll meter (Follett et al. 1992), weed abundance as estimated by ground weed coverage, aphid abundance and proportion of leaves with symptoms of disease.

In each observation plot, topsoil (0-20 cm) was sampled shortly before harvest of the cereal crop. Air-dried and sieved soil samples were analysed for pH (1:2.5, H2O; Brady & Weil 2017), plant-available potassium and phosphorus (ammonium acetate-lactate extracted; Egnér et al., 1960) and loss on ignition as an indicator of soil organic matter content (Howard & Howard 1990). During the winter following harvest, farmers were interviewed by phone to gather detailed information on the main field operations during the growing season of winter wheat (2019-2020) and spring barley (2020). Information was obtained about farm characteristics, time since transition to organic farming practices, and crop management of the focal fields (soil tillage, preceding crop, sowing dates, weed control methods, and type and amounts of fertilisers used). From the information obtained, we also estimated nitrogen inputs for manure-based fertilisers, using standard values from agricultural statistics, and for non-manure fertiliser products, using information from the manufacturer/provider. Weather data was obtained for 2019 and 2020, daily precipitation was summed over the growing season, and temperature was used to calculate cumulative growing degree days (GDD) with daily mean temperatures exceeding 4.5 degrees Celsius. Information on the soil clay content of the fields was extracted using a digital soil map of arable land in Sweden

(50 by 50 meters; Piikki K., Söderström M. 2019) by averaging across all raster cells within the fields. Finally, to consider the landscape context, we used the National Land Cover Database (Swedish Environmental Protection Agency 2018) and calculated the proportion of arable land within 1 km of each field's centre.

3.3.2 Analysis of data from observation study on-farms to identify and quantify determinants of yields in organic cereals (Paper II)

Firstly, a principal component analysis (PCA) was used to explore and describe the overall variation in organic crop and soil management practices, and our two contextual variables (time since transition to organic farming and proportion of arable land in the surrounding landscape). Then, to interpret the obtained results, each PCA axis was compared to the original variables and to the farmers' fields.

Thereafter, generalised linear models were used to explore the variation within management practices (Figure 7, Aim 1), and to identify and rank the limiting factors to yield of organic winter wheat and spring barley (Aim 2). A stepwise approach was applied to identify and rank the agronomic limitations, referred to as "mediators", on the yield (Aim 2.1). The mediators were grouped as "endogenous mediators", which were those that could be influenced through short-term management, and "exogenous mediators", which were those that could not be influenced through short-term management. The second step was to identify and rank the management and spatio-temporal variables, referred to as "factors", and their influence on the previously established mediators to yield (Aim 2.2).

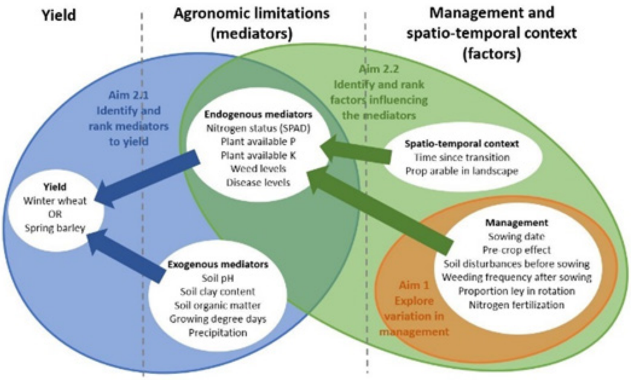


Figure 7. Conceptual framework showing the stepwise approach used in Paper II.

3.3.3 Experimental set-up of the within-field variability of yield in response to biogas digestate fertiliser (Paper III)

In spring 2022, a chessboard fertilisation trial (Kindred et al. 2015)was established in a spring wheat field in Västra Götaland, in southwestern Sweden (N 58.367, E 13.291). The field was located on a mixed crop-livestock farm that had been managed with organic farming practices for 20 years. The preceding crop was a 5-year grass-clover ley. The experiment was established in the subsequent spring wheat crop on an area of 2.46 ha of the field (Figure 8). In the experimental design, the spring wheat crop was fertilised with biogas digestate in a perpendicular direction to create a grid resembling a chessboard with 96 blocks (Figure 9). Each block was comprised of four treatments/plots, giving a total number of 384 plots. Each plot was 8 by 8 meters. For practical reasons, it was not possible to randomise the treatments within the blocks.

The N-rates applied with the biogas digestate treatments were 0, 50, 100 and 150 kg N ha^{-1}, calculated based on the NH_4+-N content in the biogas digestate. The biogas was digestate organically certified (KRAV) and was sourced from a nearby biogas treatment plant using residues of mostly plant-based by-products from local food industries; this was delivered by a local producer (Gasum AB, Lidköping). The dry matter content was 7.3% and the total N content was 0.6% (with 57% of that as NH_4+-N), and the total C:N ratio was 5.5. The application was carried out with a 5 m3 large Olby Slurry tanker with an 8 m wide ramp equipped with 24 trailing hoses. Application was performed at the continuous tillering stage BBCH 25 of the spring wheat crop.

Figure 8. Drone image of the chessboard trial after fertilisation of the spring wheat crop with biogas digestate at the elongation stage of the wheat (BBCH 37-45).

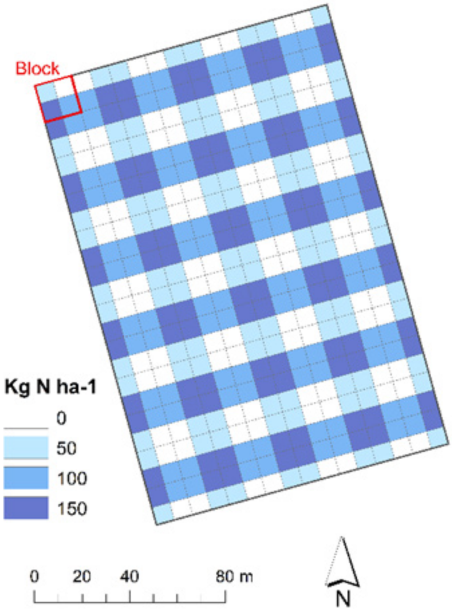


Figure 9. The chessboard field trial design. The biogas digestate slurry was applied over two consecutive days. On the first day, fertilisation took place in the north-south direction of the field trial in bands at a rate of 50 kg N ha^{-1}. The next day, slurry was applied at a rate of 100 kg N ha^{-1} in bands perpendicular to the former bands, creating plots with rates of 0, 50, 100 and 150 kg N ha^{-1}

The variation in biomass in the preceding grass-clover ley within the field trial area was characterised by calculating the normalised difference vegetation index (NDVI) with a pixel resolution of 3 by 3 meters from PlanetScope (Planet Labs PBC 2022) satellite images from early June 2021. Detailed mapping of the soil clay content was done using proximal soil sensing (gamma) (van Egmond et al. 2010). Soil samples were collected at nine locations (0-20 cm depth) across the field and analysed for pH, plant available P and K, and soil organic matter (SOM). The NDVI of the spring wheat in the 2022 season was calculated based on satellite data, similarly to NDVI in the ley pre-crop. The spring wheat was harvested using a combination on a 2 by 6 meters area in the center of the 8 by 8 meter plots. The grain samples were later used to determine the protein content in the harvest grain (InfratecTM - NIR Grain Analyser, Foss, Hilleröd, Denmark 2022).

3.3.4 Analysis of within-field variability of yield in response to biogas digestate fertiliser (Paper III)

The soil nitrogen supply (SNS) to the harvested crop was calculated by multiplying the grain nitrogen content (protein/5.7) with the grain yield from unfertilised control plots (N0) (Equation 1).

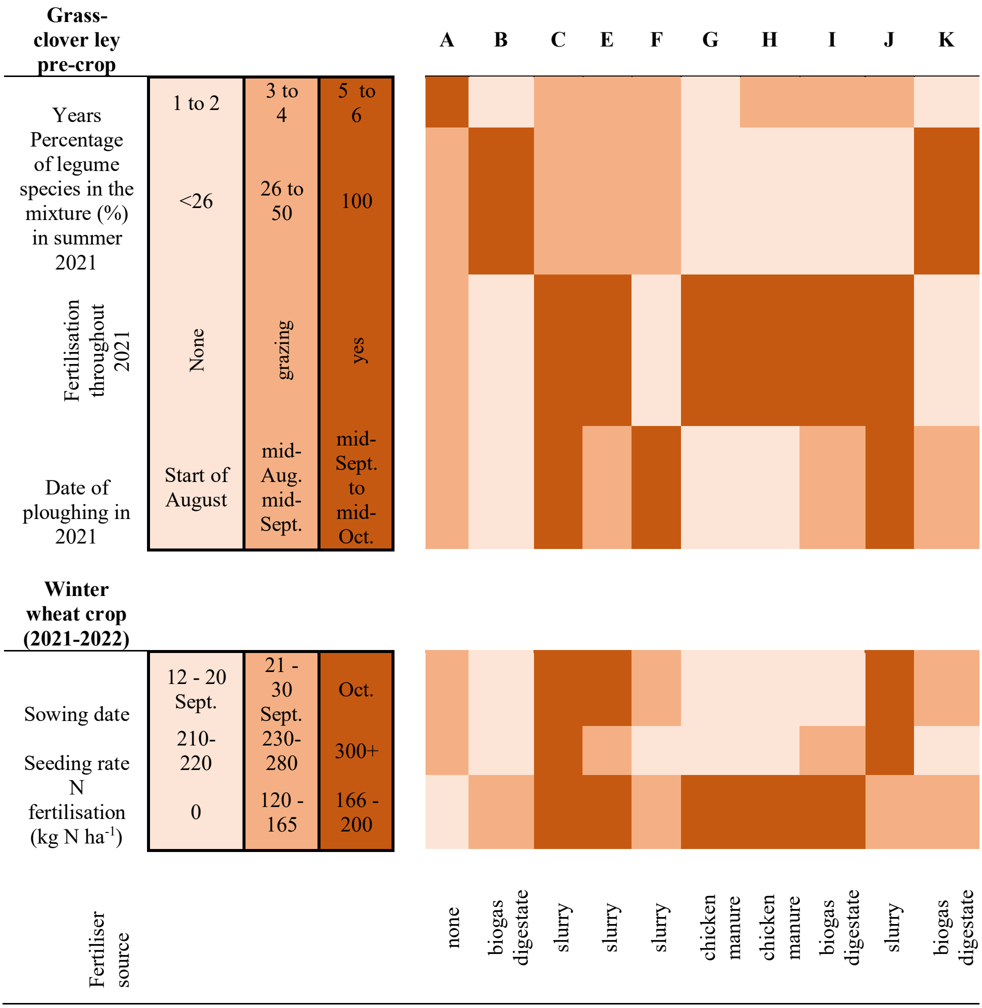
$$SNS = (protein/5.7) * yield \qquad (Eq. 1)$$

This value was then interpolated for the rest of the field using ordinary kriging. Unfertilised yield and protein maps were created, based on interpolation of the harvested yield and grain protein values from the control plots. The calculated ley and spring wheat NDVI, and measured soil properties were fitted to the unfertilised yield map to determine within-field variability in SNS. For each block, consisting of four plots representing each N-rate treatment, biological optimum nitrogen rate models were developed using quadratic regression of yield by N rate.

3.3.5 Experimental set-up of on-farm trials of winter wheat grain yield and protein content in response to biogas digestate fertiliser application (Paper IV)

In the spring of 2021, 10 fields were selected on different farms in the study region of Västra Götaland (Figure 3). With the help of information from the farmer, we identified fields with grass-clover ley (Figure 10) in 2021, where they planned to establish winter wheat in autumn 2021 to be harvested in summer 2022. The fields were managed by the farmer according to their own management practices (Table 2). One experimental area (20 by 20 m) was established in each field and was kept unfertilised by the farmer. Four replicates of each treatment were located within the unfertilised experimental area on each field in a randomised block design, amounting to 16 plots in total (Figure 11 shows the experimental design for one of the fields). Each plot measured 1 m by 1.5 m and included six rows of wheat with a 12.5 cm row spacing as the sampling area, and one crop row of buffer zone on each side of the sampling area. Nitrogen application treatments were applied in spring 2022 and were comprised of three incremental biogas digestate rates (N1-N3), as well as a non-fertilised control (N0) (Figure 12). This aimed to allow the separation of any effect of the preceding crop and the field properties on winter wheat yield and quality. The biogas digestate was applied as split doses on two occasions, half at the growth stage of two tillers detectable BBCH 22 and half at the beginning of stem elongation BBCH 30 (Lancashire et al., 1991). There was no weed control in the experimental plots. The four treatments were: no fertilisation (N0), 60 kg N ha^{-1} (N1), 120 kg N ha^{-1} (N2) and 180 kg N ha^{-1} (N3), calculated based on the available N (i.e. NH_4-N) in the biogas digestate. The biogas digestate was the same as used in the experimental trial in Paper III

Table 2. A visualisation of the variance in organic farm management practices between 10 selected fields (A-K) for the grass-clover ley pre-crop and the winter wheat crop. The trial at farm D is missing due to technical issues.



Grass-clover ley pre-crop				A	B	C	E	F	G	H	I	J	K
Years	░ 1 to 2	▒ 3 to 4	▓ 5 to 6	▓	░	▒	▒	▒	░	▒	▒	▒	░
Percentage of legume species in the mixture (%) in summer 2021	░ <26	▒ 26 to 50	▓ 100	▒	▓	▒	▒	▒	░	░	░	░	▓
Fertilisation throughout 2021	░ None	▒ grazing	▓ yes	▒	░	▓	▓	░	▓	▓	▓	▓	░
Date of ploughing in 2021	░ Start of August	▒ mid-Aug. mid-Sept.	▓ mid-Sept. to mid-Oct.	▒	░	▓	▒	▓	░	░	▒	▓	▒
Winter wheat crop (2021-2022)													
Sowing date	░ 12 - 20 Sept.	▒ 21 - 30 Sept.	▓ Oct.	▒	░	▓	▓	▒	░	░	░	▓	▒
Seeding rate	░ 210-220	▒ 230-280	▓ 300+	▒	░	▓	▒	░	░	░	▒	▓	░
N fertilisation (kg N ha^{-1})	░ 0	▒ 120 - 165	▓ 166 - 200	░	▒	▓	▓	▒	▓	▓	▓	▒	▒
Fertiliser source				none	biogas digestate	slurry	slurry	slurry	chicken manure	chicken manure	biogas digestate	slurry	biogas digestate

Figure 10. Photo of a three-year grass-clover ley pre-crop with varying coverage of white and red clover at one farm field during the summer of 2021.

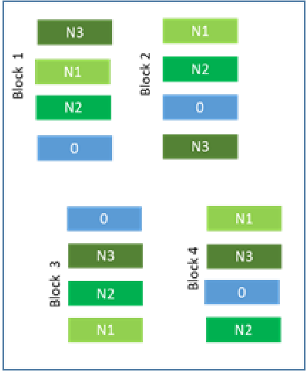


Figure 11. Experimental design on one field with the three experimental treatments of N-fertilisation with biogas digestate and one unfertilised treatment, placed in a randomised block design with four blocks.

Figure 12. Fertilisation of the on-farm plots and a zoom in on N3 treatment during the first application of biogas digestate (90 kg N ha^{-1}).

3.3.6 Analysis of on-farm trials of winter wheat grain yield and protein content in response to biogas digestate fertiliser application (Paper IV)

A mixed-effects linear model was used to address the effect of incremental N fertilisation across all fields, taking the field properties and historical management into account (represented by the SNS variable, N0 plots). The effects of N treatments N1, N2, N3 and SNS (N0) on yield and protein content were investigated. To assess the relationship across all fields, the variable "field" was used as a random factor with "block" nested in it. The data was the values per treatment, with four replicates (four blocks) per field.

Nitrogen response curves were calculated for each of the ten fields using quadratic regression of the winter wheat yield response to the applied biogas digestate. The optimum N-fertilisation was calculated as the curve maximum. In this case, the optimum N-fertilisation rate is defined as the fertiliser rate that gives the maximum yield within the range of the N rates investigated (N1 to N3).

The apparent fertiliser N-use efficiency relates to the grain N-yield in relation to the N fertilisation applied, and was calculated using the following equation (Sieling & Kage 2010) (Equation 2):

(N-yield in the fertilised treatment – SNS)/ fertilised N rate (Eq. 2)

4. Results

4.1 Crop sequence patterns and diversity in farming systems across Sweden (Paper I)

In this thesis, I first demonstrated the application of a method to assess crop patterns and sequences directly on farmer fields using agricultural statistics data. The arable land was grouped in five productivity zones and the results can be seen as representative of Swedish cropping systems. The analysis of LPIS data enabled the assessment of 349,891 fields, of which 200,501 ha were organically managed and tracked over a 10-year period. The patterns on farmers' fields revealed information about crop species distribution, diversity, and the order of the crops in the sequence over a 10-year period. The descriptive statistics on crop distribution showed clear differences between the productivity zones, with a dominance of small-grain cereals (62%) in high productivity zones versus ley crops (67% in the least productive zone). The crop diversity, i.e., the number of crop types and exponential Shannon index, was highest in the most productive zone (1) compared to the least productive zone (5). The average number of different crop types in conventional crop sequences ranged from 4.5 in Zone 1 to 3.4 in Zone 5, while in organic crop sequences it ranged from 4.9 to 3.4. The differences between organic and conventional crop sequences were significant in all productivity zones for crop type diversity (Figure 2a from Paper I, Reumaux et al. 2023). However, this was not observed for the exponential Shannon index, with all differences being significant except in the case of the low productivity zone. The results highlight that the pre-crops for spring barley were similar in both conventional and organic sequences, with pre-crop types such as oilseeds, cereals, oats, roots and tubers. However, for the cultivation of winter wheat, organic farmers used a more diverse choice of pre-crops, with a dominance of fertility building crops such as leys and grain legume pre-crops (Figure 13).

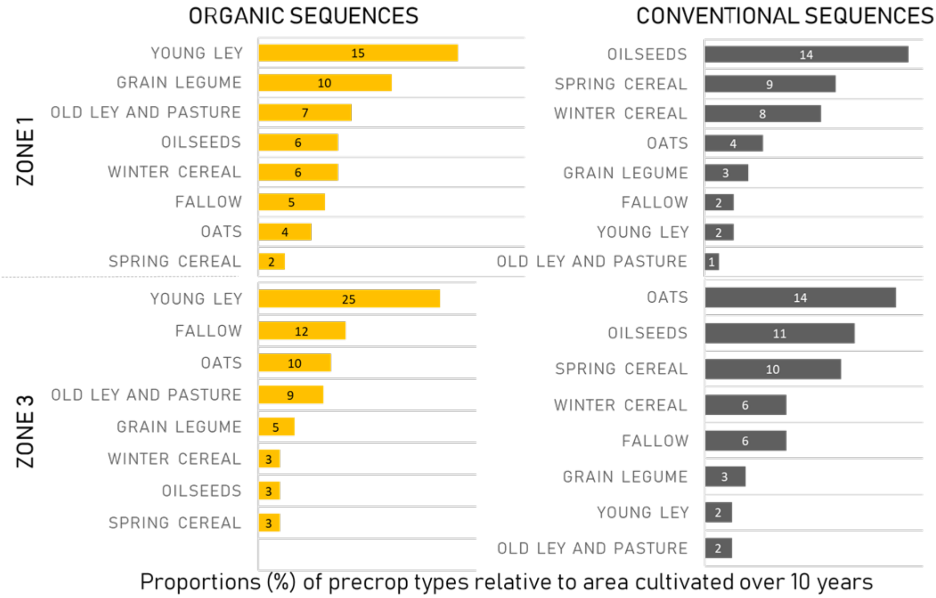


Figure 13. Pre-crop proportions for organic and conventional winter wheat in productivity zones 1 and 3.

4.2 Determinants for yield in organic cereals depending on farmer management and local field conditions (Paper II)

Based on on-farm observations, Paper II describes a detailed assessment of variability in management and mediators that determine yield in organic cereal production in two productive agricultural areas in Sweden (zone 1-3) dominated by arable farming (Figure 3). The recorded yields of both winter wheat and spring barley varied considerably between farms, with a three- to four-fold difference between the lowest and highest values, accompanied by considerable variation in management of both spring barley and winter wheat fields. In terms of management practices, the amount of N added as organic fertiliser ranged from 0 to 88 kg N ha^{-1} (mean ± sd, 37 ± 25 kg N ha^{-1}) for spring barley and from 0 to 160 kg N ha^{-1} (79 ± 41 kg N ha^{-1}) for winter wheat. A wide range of fertiliser types was used, of both manure and non-manure origin, including cattle and pig manure, by-products from the food industry, and biogas digestate. The most common pre-crops for spring barley were cereal crops and ley (mostly mixed grass-clover leys) and, to a minor extent, grain legumes. The most common pre-crops for winter wheat were ley (mostly mixed grass-clover leys), grain legumes and cereal crops, with sugar beet, potato, oilseed rape and maize being less frequent. Half of the spring barley fields had a preceding cereal crop, but only 31% of winter wheat fields had this. When a fixed rotation was applied, the crop rotation ranged in length from two (barley-ley) to eight years.

With the PCA analysis, it was possible to distinguish the most important factors describing the variation in management and landscape context of the studied spring and winter wheat fields. For both crops, the total years in the crop rotation, the number of years of ley in the rotation, and the frequency of weeding after sowing were important factors. However, the variation in the winter wheat fields was also related to other factors, such as the intended use of the harvested grain and the time since transition to organic practices. In the case of spring barley, the variation was related to the sowing date as well as the use of undersowing.

With the help of the two-step analysis, the yields of the two cereals were, as expected, influenced by both exogenous mediators, such as soil parameters and weather, and endogenous mediators, such as nutrients and pests. As for nutrients, the results showed that N status in the leaves (measured by SPAD) and plant available K were relevant for the grain yield of both crops (Figures 14). In addition, available P had a positive effect and weed pressure had a negative effect on spring barley yields (Figure 14). Nitrogen management was a mediator related to the yield levels of both spring barley and winter wheat (Figures 15 and 16). This result was supported by evidence from farmers' interviews about challenges in organic farming management, which was followed up for the following seasons in Papers III and IV.

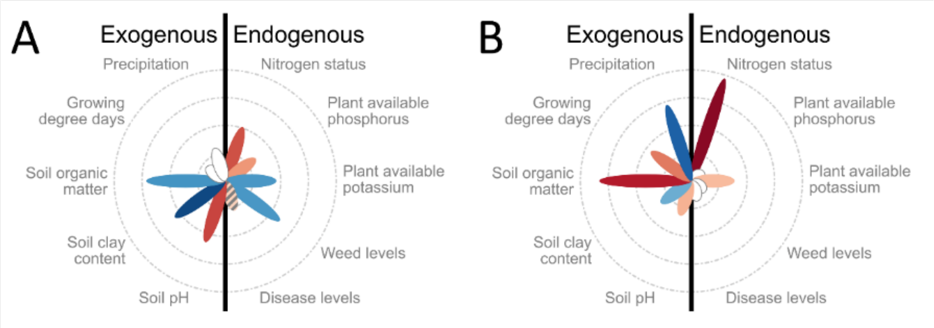


Figure 14. The importance of yield mediators (exogenous and endogenous) in (A) spring barley and (B) winter wheat. Petal length indicates the relative importance of the mediator relative to others (sum of weights), where concentric circles represent relative importance of 0.25, 0.5, 0.75 and 1, respectively. White petals show variables that were not included in any of the best competing models. For those that were, effects are negative (blue) or positive (red), with differences in relative slope indicated by intensity of colour. Grey hatching of a petal indicates an effect where the standard error of the slope was larger than the slope.

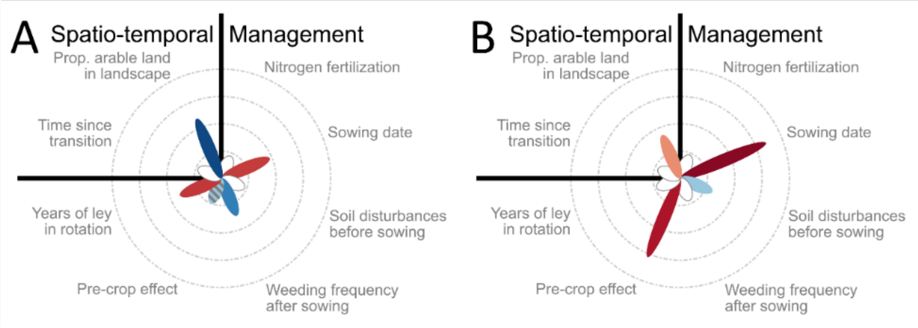


Figure 15. The importance of spring barley management and spatio-temporal context on (A) weed levels, (B) nitrogen status. For an explanation of symbols and colours, see Figure 14.

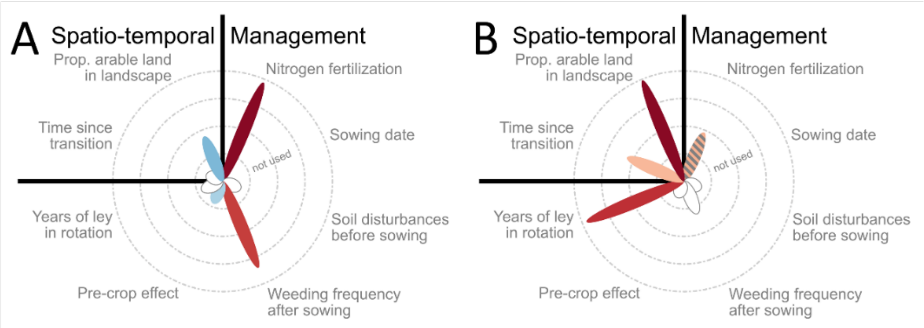


Figure 16. The importance of winter wheat management and spatio-temporal context on (A) nitrogen status and (B) plant-available potassium. For an explanation of symbols and colours, see Figure 14.

4.3 Use of precision agriculture methods to quantify within-field variation in soil nitrogen supply and response to fertilisation with biogas digestate to organic wheat (Paper III)

As a follow-up to the on-farm observation study (Paper II), I conducted two on-farm experimental studies focusing on the response of organic spring wheat and winter wheat to an alternative source of N, namely biogas digestate (Papers III and IV). In the first study on in-field variation in spring wheat, we used a precision farming method to demonstrate that fertilisation based on a chessboard pattern was an effective method to quantify variations in both SNS and the crop response to different rates of N-fertilisation with biogas digestate, with a high spatial resolution. The results showed that on the studied field, in-field variation was mainly driven by clay content and, to a lesser extent, by the variation in the biomass of the preceding grass-clover ley crop. Biogas digestate application had a positive effect on spring wheat grain yield and protein content in all areas of the field (Figure 17). The SNS varied between 32 and 120 kg ha^{-1} and had a positive relationship to the final wheat grain yield and protein content. The highest biogas digestate rate applied (corresponding to 150 kg N ha^{-1}) proved to be too low to reach an optimum N fertilisation rate in large parts of the field, whereas no fertiliser was needed in the areas with the highest SNS. This shows the potential for improved resource use efficiency by allocating the inputs to areas where it is most needed. Our findings confirm that biogas digestate fertilisation can be applied at a variable rate to manage in-field nitrogen requirements in an organic cultivation context.

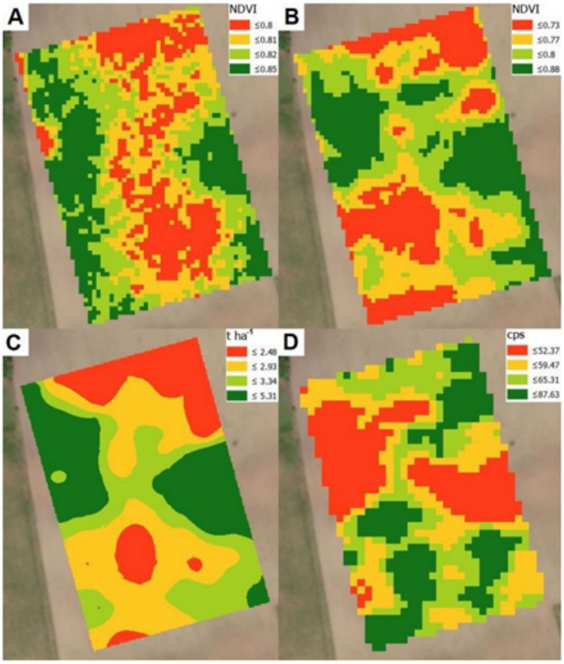


Figure 17. Maps showing in-field variation patterns of NDVI from the grass-clover ley pre-crop in the 2021 season (A), NDVI from the spring wheat in the 2022 season (B), unfertilised grain yield extrapolated from N0, non-fertilised control plots, in t ha^{-1} (C), and Thorium gamma radioactivity used as an indicator of clay content (D).

4.4 Improving the yield and quality of winter wheat for bread-making on different organic farms (Paper IV)

To complement the previous study (Paper III), I carried out additional on-farm experiments, looking at organic winter wheat yield response to biogas digestate fertilisation. The study included 10 organic fields on different farms with the aim of assessing the response of winter wheat to different biogas digestate application rates (3 incremental rates of split doses, 4 replicates per field), and the between-farm variability in that response. All fields had perennial grass-clover ley as a pre-crop. The findings showed that the biogas digestate fertilisation treatments had a significant effect and increased the grain yield and protein content across all fields on the different farms (Table 2). Used as a proxy to understand the soil's capacity to supply N, the calculated SNS from the unfertilised treatment plot (N0) significantly increased the grain yield level across all fields but did not affect the protein content. The results also showed that there was no significant interaction between SNS and the response to the biogas digestate fertilisation, i.e. the SNS did not affect the response to the biogas digestate treatments in terms of grain yield and protein content.

I further investigated each field individually with the help of N-response curves for both grain yield and protein content. The curves presented clear differences in response to N fertilisation between the fields of the different farms. The SNS varied largely between the fields (49 – 130 kg ha^{-1}) and was attributed to variables reflecting both long-term management, such as soil organic carbon, and shorter term effects, such as clover percentage in the ley the year before (Figure 18). Additionally, soil mineral N in the autumn, when the wheat was sown, was an important variable that may be related to both short-term and long-term management. Finally, I found that the overall variation in the field properties and historical management, which was assessed in the unfertilised plots (N0), was mainly related to soil properties such as clay content and soil organic carbon, as well as weed biomass. It was less related to pre-crop characteristics and chlorophyll in the winter wheat leaves (SPAD measurements as a proxy for N uptake).

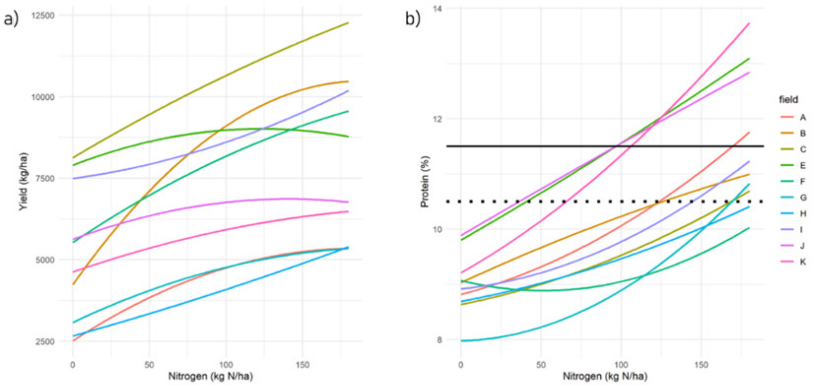


Figure 18. Winter wheat a) grain yield (kg ha^{-1}), and b) protein content (%) in response to nitrogen fertilisation with biogas digestate (kg N ha^{-1}). Curves were fitted using a polynomial model, and the optimum N-fertilisation for grain yield was calculated as the N-fertilisation rate at which the yield achieved a maximum value within the N ranges investigated (N0 to N3). Colour indicates the ten fields (A-K) where the on-farm trials were carried out. The red dotted line marks the threshold for protein content of 10.5%, which is the minimum requirement for organic winter wheat grain to be sold for baking purposes, and the black line marks the threshold of maximum price premium.

The nitrogen management practices that the farmers applied differed from field to field, with variations in choice of N source and N amount. As a result, the winter wheat yield between farms varied, with a six-fold increase from 2 to 12 tons ha^{-1}, as did the protein content, from 8 to 14% (Figure 19). Only two farms (J and K) were able to achieve a high yield and a high protein content (>10.5%). Farms such as B and C, however, reached high yields, of up to 8 to 12 tons ha^{-1}, but low protein contents, of 8.4 and 9.7%, respectively. The results from the farmer practice plots did not reflect those obtained when applying similar amounts of N in the form of biogas digestate. For example, in the case of farm B using biogas digestate from a different biogas plant, the farmer applied more N than in the highest biogas digestate N-treatment (N3) but obtained yields that were on average 1 ton ha^{-1} lower than in N3. The timing of application was different, as most farmers applied fertiliser in the autumn when sowing the winter wheat crop and in the early spring while the crop was at tillering stage (BBCH 25), while in the on-farm experiments, split top-dressing with biogas digestate was applied at later development stages.

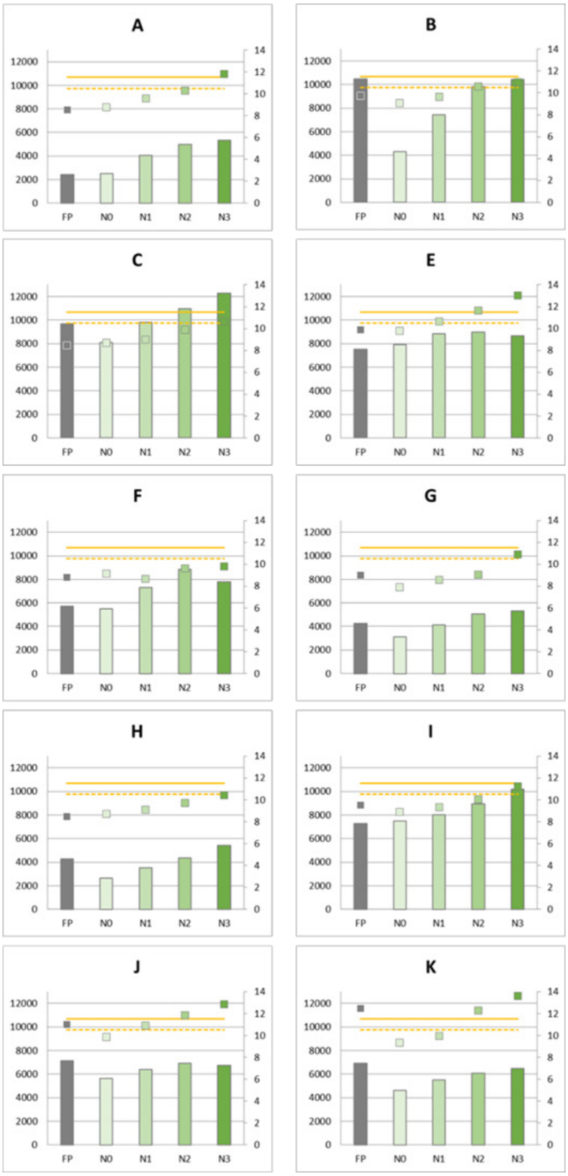


Figure 19. Organic winter wheat grain yield in kg ha-1 (bars; left y-axis) and protein content in % (squares; right y-axis) in each farmers' field (panels from A to K) for the farmer practices (FP) and applied biogas digestate fertilisation treatments (N0, N1, N2 and N3). The dotted line corresponds to the 10.5% protein content, which is the minimum requirement for organic winter wheat grain to be sold for baking purposes. The full line marks the threshold of maximum price premium at 11.5% protein content.

5. Discussion

5.1 Constraints and opportunities of organic arable production

Crops and livestock have historically been coupled in organic production (Watson et al. 2002). However, in highly productive areas dominated by crop production, organic arable farming systems have more commonly been characterised by a decoupling of crop and livestock components. This has led to the contemporary specialisation of farming systems with more intensive management. As a result, large agricultural areas in Europe are lacking grazing livestock (e.g. eastern and southeastern Denmark, eastern Germany, and East Anglia in the UK) (Haynes & Williams 1999). Mechanisation, high agricultural inputs, and large farm size tend to be associated with specialisation, whereas smaller farms, with the potential for diversification and innovation, more often demonstrate multifunctionality. Frei et al. (2018)noted that areas with high multifunctionality exhibit diverse combinations of ecosystem services, while other areas are characterised by intensive agricultural practices focused solely on maximising crop production, often at the expense of other services. In Chopin et al.'s (2023) analysis of the literature on organic food and agriculture, most research on diversification practices focused on only one practice, with 80% of papers following this approach. Instead of redesigning systems to increase diversity, organic agriculture research tended to rely on substituting inputs from the conventional agriculture paradigm (Duru et al. 2015). In Sweden, land use is driven by a strong climatic gradient, together with differences in geology and soil parent material, and organic farming uptake is lower in the most productive regions as compared to the mixed farming found in more diverse landscapes (Paper I, Reumaux et al., 2023). Therefore, it is essential to focus on high agricultural productivity regions to identify levers for organic cropping systems (Figure 1). This highlights the importance of integrating agronomic and ecological processes to foster sustainable farming systems that balance productivity with the consideration of environmental impact (Weiner et al. 2010; Bommarco et al. 2013).

5.2 A reality-check for the heterogeneity within organic arable systems (in Sweden)

In this thesis, special attention was given to processes occurring on farms and methodological considerations for capturing multiple indicators of productivity. The results focused on the productivity of the most commonly grown cereal crops, wheat and barley, and specific nutrient resources that were readily available in organic management. Interdisciplinary efforts were needed to quantify and understand the links between the ecological and agronomic aspects of organic cropping systems.

By collecting and working with on-farm field data, I was able to capture snapshots of current management practices in several productivity zones. The LPIS data helped to identify a large variation between zones, showing that the differences were at least partly correlated to the climate gradient existing in Sweden. Geographic crop distribution and crop productivity worldwide is governed largely by environmental conditions (Hatfield et al. 2011). In my study (Paper I), zones of low productivity were situated in the central and northern part of the country, where growing conditions are less favourable for annual crops such as oilseed rape, sugar beet, potatoes, and grain legumes. However, these zones, where mixed farming is common, were dominated by ley crops with the potential for nutrient cycling and diversification, as grass-clover mixtures are often high in species richness and the legumes contribute to biological nitrogen fixation (Micke 2023; Nilsson et al. 2023). Farmers can capitalise on diverse ley crops for multiple purposes, including food, feed, fuel, fiber, and ecosystem services, enhancing economic resilience and sustainability on their farm (Tidåker et al. 2014; Micke 2023).

In areas of high agricultural productivity, there was a dominance of cash crops, mainly cereals such as winter wheat. In Paper I, it was possible to follow the same fields over 10 years in areas corresponding to 40% of the total arable land in Sweden. Alternative methods using LPIS data have previously been studied to assess crop sequences in the United Kingdom (Castellazzi et al. 2010) and Finland (Peltonen-Sainio et al. 2017). In this case, LPIS data gave us information on organic and conventional farm field management, where each field was traced over a 10-year period. The results from the crop diversity analysis showed that, across all productivity zones, there was a slightly higher diversity of crop types in organic, as compared to conventional, production systems.

This difference in crop types was mainly explained by the use of non-cereal crops, such as grain legumes, oilseeds, root and tuber crops, and encourages the diversification of crop sequences. By focusing on the position of crops in crop sequences, pre-crops for crops of specific interest could be studied. I was able to identify patterns where organic cropping systems favoured ley pre-crops or oats for a winter wheat crop. The results resonate with recent research identifying the legacy effect of a previous crop on a subsequent crop in rotation as a valuable and often underutilised ecosystem service which can provide benefits in cereal cropping systems (Peltonen-Sainio et al. 2024). Indeed, the methodology using LPIS data can be useful for understanding the untapped potential in utilising crop diversity to maximise pre-crop effects. However, crop sequence patterns did not include information about the delivery of ecosystem services such as provision services (i.e. grain and biomass yield). Therefore, more information about the agronomic and ecological processes occurring at the farm and field level were necessary (Paper II) to complement the diverse picture of organic cropping systems given here (Paper I).

The results from the on-farm observations (Paper II) showed that by applying a set of different analysis methods, it was possible to uncover a large variation in organic farming practices as well as a large variation in yield between the different farms for both spring barley and winter wheat. These findings revealed the potential for organic yields to be raised and two dominating yield determining factors were nutrient and weed management. Indeed, results showed that farmers had different objectives, and for the same cereal crop the intensity of weed control, fertiliser type and amount of fertiliser applied as well as the planned use of the harvest products varied highly between farms. Identifying specific objectives and constraints relating to the practice of organic agriculture has until now been poorly understood and research and can help rethink the application and system's scalability (Lamine & Bellon 2009).

5.3 Improving the productivity of organic cereals crops by optimising nitrogen management on-farm

The supply of available N during the major phases of crop growth is critical to productivity and crop quality (Berry et al. 2003).

Variation of nutrient (in particular nitrogen) availability can occur within-field and my research shows that yield maps generated from the interpolation of unfertilised control plots are an effective way to determine the soil nitrogen supply during the cropping season. These maps were highly related to the variation of final grain yield and provided high resolution across the field thanks to the chessboard design (Paper III). Several studies have investigated the fertility-building potential of leys, often mixed grass-legume (clover and/or lucerne) leys in organically managed cropping system experiments with cereal crops (Reboud 2010; Watson et al. 2011). When including legume species in the rotation, it has been possible to reduce the overall nitrogen and energy inputs (Iannetta et al. 2016; Watson et al. 2017). Consequently, there has been an emerging interest in the re-introduction of legume crops in farming systems all over Europe (Reckling et al. 2020), although options including mixed ley pastures in the rotation are poorly investigated (Martin et al. 2020). In highly productive agricultural areas dominated by arable farming, such as the plains in Sweden, the expansion of organic farming has so far been constrained by a lack of livestock manure and other certified organic fertilisers (Lovén & Nordin 2020). Diversifying the crop rotation by including crop types other than cereals in stockless systems has been proven as a way to increase winter wheat productivity and has been proposed as an alternative to crop-livestock systems (St-Martin et al. 2017).

The growing awareness of the population around the consequences of their diet and lifestyle towards better health, as well as environmental and climate change aspects such as reducing GHG emissions, has led to a decrease in the consumption of animal-based food (Pollan 2010; Willett et al. 2019). As a result, in the future, there might be an increasing number of farms without livestock in regions with fertile arable land and a focus on arable farming (Röös et al. 2018; Barbieri et al. 2019). To increase arable systems´ efficiency in terms of nutrient management, alternatives to the import of conventionally produced manure to organic farms are required (Brozyna et al. 2013; Nowak et al. 2013; Lovén & Nordin 2020).

Stockless organic farming systems have been shown to be able to compete with existing conventional systems in regard to fertile soils (Welsh et al. 2002; Cormack et al. 2003). Organic farmers have less choice in accessing nitrogen inputs, so the use of nitrogen-fixing legumes is an alternative to conventional nitrogen fertilisers. The effect of mixed ley pre-crops on soil properties may be considered as short- or long-term effects, depending on the age of the ley and the legume proportion. While an old ley might have a lower clover content when incorporated in the soil, a young ley may be more legume rich, resulting in different N available to the subsequent crop (Torstensson 1998). However, in some cases, longer established leys showed an increase in total soil C and N (Müller-Stöver et al. 2012). Therefore, studies investigating the pre-crop effects of ley in different soil environments, as well as temperature conditions, are important. Frøseth et al. (2022) found that the initial net N mineralisation of clover leaves was lower in clay than in sandy soil and initial N immobilisation was higher at 8 and 15°C than at 0 or 4°C.

Studies have shown that the reallocation of nutrients from grass-clover to cash crops following anaerobic digestion can help solve issues with low nitrogen availability in organic farming (Brozyna et al. 2013), as well as producing biogas. When a high proportion of grass-legume mixtures is included in the crop rotation, several pathways have been developed to promote the use. In a mixed farming system, the fertility-building elements in the crop rotation (i.e. grass legume mixtures like grass-clover leys) are initially used for fodder, but examples in stockless systems mention selling the obtained biomass as green manure fertiliser, for biogas digestion, as feeds to mono-gastric animals, and even to be processed as a human protein source (Cormack et al. 2003; Watson et al. 2011; Tidåker et al. 2014; Micke 2023).

Research is scarce on alternative sources of nutrients, and there is a need to overcome restrictions for the recycling of biological materials in organic agriculture (Løes & Adler 2019). In addition, regulations differ between different countries, making it even more difficult to introduce and evaluate alternative organic fertilisers for certification. In Sweden, there is a positive attitude towards circular systems in society, which is in line with the principle of recycling within organic farming philosophy (Vogt et al. 2001). This may favour discussions around and the implementation of the recycling of plant nutrients (Milestad et al. 2020), although there are concerns about potential contaminants in the products (Marini et al. 2020b; Carter et al.

2024), including plastics, pharmaceutical residues and weeds seeds (Bünemann et al. 2024). A recent study sheds light on the positive connotations of the use of household waste compost, as well as digestates or sewage sludge (Bünemann et al. 2024). Other findings show that the repeated application of compost-based soil amendments can improve soil structure and water holding capacity, and reduce drought and fuel consumption associated with tillage practices (Peltre et al. 2015).

Among the options available to replace the use of conventional livestock manure in organic farming, the utilisation of the residue from the anaerobic digestion of organic waste as a crop fertiliser has been suggested. It can enhance soil fertility and crop yield, promoting closure of the global energy and nutrient cycles, although there is a lack of studies carried out during field conditions (Arthurson 2009). As many studies exist on the comparison of biogas digestate with other types of organic fertilisers (Ramezanian et al. 2015), few studies test the crop's response to biogas digestate from a common source in several on-farm conditions with varying biophysical characteristics. The nutrient availability in the digestate is also dependent on the quality of the substrate (Nyang'au et al. 2023), as well as on the digestion process. A recent study by Jared et al. (2022) discovered that extended two-step anaerobic digestion increases digestate NH_4+-N availability and decreases carbon mineralisation in the soil.

My findings show that the application of biogas digestate significantly improved the grain yield and protein content of organic winter wheat in several fields on different farms (Paper IV). It also shows potential for being used for variable N rate application to address in-field variation (Paper III). Other studies have also investigated the use of biogas-digestate and found that it has positive effects on nutrient availability to the crop (Herrmann et al. 2017; Sogn et al. 2018; Koch et al. 2019). A study by Autret et al. (2020) showed that organic arable systems do not systematically have lower N surplus and N losses than conventional ones. This suggests the possibility of increasing the N use efficiency of organic systems. Accordingly, a study by Nkurunziza et al. (2017) on organically and conventionally grown barley showed that there is a potential for the optimisation of management practices to increase N efficiency on farms in order to supply crops with N more quickly. In our study, farms differed in their soils' capacity to supply nitrogen (SNS), however the interaction between SNS and biogas digestate application was not decisive for crop productivity.

Additionally, when comparing yields from the experiments to those from the farmers, the variation observed might be due to several factors that need to be further investigated. For example, our experiment raises the importance of the timing of fertilisation, as the application of the biogas digestate was done in the growing crop in spring, during the sensitive window between tillering and stem elongation (BBCH 23 – 31). Sowing conditions and crop establishment also affect the mobilisation of nitrogen resources.

My results underline the potential for managing N more efficiently and call for more research investigating the application of biogas digestate in combination with other organic management practices. Therefore, more studies are needed to understand the effects of different types and amounts of alternative fertilisers on the delivery of ecosystem services other than yield provision, such as the maintenance and enhancement of soil fertility, and reduction of nitrogen leaching.

6. Conclusions and future directions

In this thesis, I used multiple descriptive and statistical methods to assess on-farm data and identify the diversity of on-farm management practices used in organic cereal production in Sweden.

I found that crop distribution at a national level was highly driven by the climatic gradient in the country. Crop sequences were more diverse in zones of high agricultural productivity than in those of low productivity. Especially in zones where the productivity was important, organic farmers prioritised the cultivation of winter wheat over spring barley with the use of more diverse pre-crop types, including nitrogen-fixing crops such as mixed grass-clover leys and grain legumes. The uncovered diversity of crop sequences was further linked to an array of crop productivity and management practices that were observed on several organic farms in two highly productive areas. The most important yield limiting factors for organic winter wheat and spring barley related to practices that farmers could control in the short- and long-term management of their fields were related to nitrogen management, leaf nitrogen status and weed levels, despite differing bio-physical conditions like soil characteristics.

In a detailed on-farm study, I observed variation in-field, which was successfully quantified through precision agriculture methods. The results showed that soil nitrogen supply and clay content were able to explain much of the variation seen in harvested grain yield and protein content data. To understand how these processes differ depending on the biophysical conditions, I investigated how nitrogen management focused on ley pre-crop and the application of biogas digestate affects the grain yield and protein content of organic winter wheat in fields on different organic farms. I found that biogas digestate fertilisation as split doses in late spring is a successful way to achieve both high grain yield and high protein content. However, achieving high yield is also significantly dependent on the capacity of the soils to deliver nitrogen.

Organic farmers employ a diversity of management practices that are reflected in the wide range of crop yields that were observed in areas of high agricultural productivity. In my thesis, I conducted comprehensive research and identified opportunities for increasing productivity by addressing agronomic, ecological and bio-physical factors.

From these results, I advocate that there is no "one-size fits all" solution and acknowledge the importance of context-dependent findings to help prioritise key management practices, including recommendations for more efficient resource use.

Organic farming is part of a broader context that includes the whole food system. Thus, it is important to address policy support and institutional frameworks that can both support current organic practices and facilitate the transition to organic agriculture in areas where there is a large economic gap between organic and conventional arable production. For example, there is a need to address constraints that can bridge subsidy discrepancies, which discourage farmers to convert, and identify opportunities to streamline regulations, enhance transparency and reduce administrative burdens for organic farmers and businesses. Several examples of knowledge exchange through conferences, workshops, and collaborative inter- and transdisciplinary research (Schillo & Robinson 2017) have been shown to help develop solutions that balance environmental, social and economic objectives. Environmental and agricultural policies play a decisive role in the adoption of practices and the expansion of organic farmland and crop diversification (Schaak et al. 2023). Organic regulations need to place more emphasis on environmental and climate best practices in order to ensure that organic agriculture can contribute to sustainability objectives (Seufert et al. 2017). Our present food system is highly dependent on external and excessive energy inputs, especially in the form of fossil fuels (Sherwood 2020). Therefore, when addressing the need for transformative change of the food system, it is important to tackle the issue of recycling nutrients in agriculture production (Helenius et al. 2020).

The dependence of our agri-food systems on relatively few crops highlights a potential risk to food security and agricultural resilience (Tscharntke et al. 2012). This thesis highlights how less than five crop types are dominating agricultural production in Sweden. With the need to support healthier diets, address climate change and transition to more sustainable land use management, identifying economically viable alternatives that are suited to Nordic conditions and can enhance the diversity of cropping systems is important. In this context, the cultivation of novel crops and cultivars that do not need high nutrient inputs (e.g. different types of grain legumes, oil crops, and crops for fibre) may be beneficial to the expansion of organic agriculture systems.

Expanding crop diversity across a landscape (by growing novel crops and crop mixtures in some places) can help create agricultural matrices that provide habitats for species important to ecosystem health (Grass et al. 2021). However, the environmental impacts of introducing a novel crop should be considered comprehensively to achieve the most sustainable outcomes for both farmers and wildlife habitats (Haughton et al. 2009). Crop suitability is thus a complex concept, as is any attempt to capture in aggregate the climatic, economic, social, and cultural environment that may affect the limitations of growing a new crop in a specific area (Garland et al. 2021).

Other information

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Papers produced but not included in the thesis

Chopin, P., Menegat, A., Bergkvist, G., Dahlke, S., Jäck, O., Karlsson, I., Lana, M., Ortman, T., Reumaux, R., Öborn, I. & Watson, C.A. (2023). The reflection of principles and values in worldwide organic agricultural research viewed through a crop diversification lens. A bibliometric review. Agronomy for Sustainable Development, 43 (1), 23. https://doi.org/10.1007/s13593-023-00875-y

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Popular science summary

Organic farming has been put forward as one option for transitioning to more sustainable agriculture systems. In Sweden, the share of organic farmland is 20% of the total arable land and is often located in areas with less productive land. The overall aim of this research has been to build understanding of methods for improving the productivity of organic farming, especially in highly productive agricultural areas, using Sweden as an example.

Farmers have strategies for the order in which they grow crops to reduce the presence of weeds, pests and diseases, and to build soil fertility and optimise the use of nutrients, thereby obtaining higher and more stable yields. The crop sequences are especially important for organic farmers who do not use synthetic pesticides and fertilisers. The first study used Land Parcel Identification System data, which is based on what farmers report when they are applying for agricultural subsidies from the European Union. By studying the distribution of crop types, I found that small grain cereals like winter wheat are commonly cultivated, with a higher concentration (62%) in the south of Sweden. However, we see the opposite pattern for forage crops, which are more concentrated (67%) in the north of the country.

The diversity of crops was greater on organic farms, with nine percent higher crop diversity than conventional farms in areas of higher agricultural productivity. By investigating crop sequences across all agricultural areas, I found that organic farmers prioritise the cultivation of cash crops, such as winter wheat, over spring barley, using specific pre-crops which can help enhance the quality of the winter wheat. Indeed, the results also showed that the crops cultivated the year before organic winter wheat were more often ley or grain legumes, while for spring barley, another cereal was often the pre-crop.

Additionally, I carried out observation studies on winter wheat and spring barley fields on organic farms in 2020 and found that organic farming management practices are very diverse, making every farmer's management strategy unique. Indeed, fertiliser source and use, weed and pest control, and soil preparation differed greatly in the 57 farms that were studied. This wide range of management, together with a large variation of climatic and soil conditions, resulted in important differences in yields between different farms, with, for example, a winter wheat yield range of 2 to 7 tons ha-1. Weed levels were an important limitation to spring barley yields, while for winter wheat, nutrient management, such as nitrogen fertilisation, was critical for achieving high yield.

Organic winter wheat is characterised by variable grain yield and grain protein content, which is limiting if farmers want to sell the grain for bread making. To bridge the yield and quality gap, while minimising the potential environmental impact, nitrogen management needs to be improved. This is especially true in areas dominated by arable farming, where animal manure is scarce. Fertilisation of the crop with biogas digestate was studied as a complementary method to fertilisation with livestock manure. In 2022, by using precision agriculture methods, I was able to quantify the in-field variability on an organic farmer's field. My results confirm the importance of nitrogen availability in the soil and timely fertilisation for achieving a high yield, and the relevance of high spatial resolution data to tackle nutrient variability in organic farming practices. In the same year, I carried out repeated experiments on the fields of ten different organic farms, and found that fertilisation of the crop with biogas digestate in late spring is a viable way to achieve good grain yield and high protein quality in organic wheat crops.

By combining different methods, from national statistical data analysis to field observations, I obtained snapshots of the real-world effects and was able to track the progress of specific fields over a long time. With results from designed field experiments, I gained specific understanding of crop responses to nutrient management under several organic farming conditions. This thesis highlights the large variation in the productivity of organic farms in areas of high agricultural productivity. This underlines the potential for improving the productivity of organic cropping systems, especially by growing several crop types and, when focusing on cereal production, by tackling the varying nitrogen needs for each farm site.

Populärvetenskaplig sammanfattning

Begränsningar och möjligheter för ekologisk växtproduktion i produktiva jordbruksområden

Betydelsen av mångfalden av brukningsmetoder på ekologiska spannmålsgårdar med fokus på växtföljd, skördevariation och näringstillgång

Ekologiskt lantbruk har föreslagits som ett alternativ för att övergå till mer hållbara odlingssystem. I Sverige är andelen ekologisk jordbruksmark 20% procent av den totala åkermarken och är ofta belägen i områden med mindre produktiv mark. Syftet med denna forskning har varit att förstå hur man kan förbättra produktiviteten i ekologisk växtodling, särskilt i produktiva jordbruksområden i Sverige.

Lantbrukare har strategier för i vilken ordning de odlar grödor för att minska ogräs, skadegörare och sjukdomar samt för att bygga upp markens bördighet och optimera användningen av näringsämnen och därigenom t få högre och mer stabil avkastning. Bra växtföljder är särskilt viktigt för ekologiska lantbrukare som inte använder syntetiska bekämpningsmedel och gödselmedel. I min första delstudie använde jag data från Land Parcel Identification System (SAM-ansökan till Jordbruksverket), som baseras på vad lantbrukare rapporterat när de ansökt om stöd från Europeiska Unionen. Genom att studera arealfördelningen av grödor fann jag att spannmål, främst höstvete, är vanligt förekommande och att det har störst utbredning (62 %) i de mest produktiva områdena i södra och mellersta Sverige. Det motsatta mönstret observerades för fleråriga vallar (oftast gräs-klöver) som dominerar (67 %) i skogs- och mellanbygder och andra mindre bördiga områden. I de mest produktiva områdena (slättbygderna) var mångfalden av grödor större på ekologiska gårdar, med nio procent större diversitet av grödor, än på konventionella gårdar. Genom att undersöka växtföljder i alla jordbruksområden fann jag att ekologiska jordbrukare prioriterar odlingen av grödor med hög avkastning och som kan säljas till ett bra pris, t ex höstvete framför vårkorn. Till höstvete använder de ofta specifika förfrukter som kan bidra till att förbättra avkastningen och kvaliteten av höstvetet. Resultaten visade att de grödor som odlades året före ekologiskt höstvete ofta var vallväxter eller trindsäd, medan för vårkorn var förfrukten ofta en annan spannmålsgröda.

Under 2020, genomförde jag en observationsstudie av höstvete- och vårkornsfält på ekologiska gårdar i Skåne, Halland och Västra Götaland och fann att de ekologiska förvaltningar är mycket varierande, vilket gör varje lantbrukares brukningsmetoder unika. Typ av gödsel och mängden av gödselmedel, ogräs- och skadedjursbekämpning samt jordbearbetning skilde sig åt mellan de 57 gårdar som studerades. Den stora variationen i skötsel, tillsammans med en stor variation i klimat- och markförutsättningar, resulterade i viktiga skillnader i avkastning mellan olika gårdar, med en avkastning på höstvete från 2 till 7 ton ha-1. Ogräsnivåerna var en viktig begränsning för avkastningen av vårkorn, medan för höstvete var näringsförsörjningen, främst av kväve, avgörande för att uppnå hög avkastning.

Ekologiskt höstvete har ofta varierande avkastning och proteinhalt, och det sistnämnda är begränsande om jordbrukarna vill sälja spannmålen för brödtillverkning. För att överbrygga klyftan mellan avkastning och kvalitet och samtidigt minimera den potentiella miljöpåverkan behöver kväveförsörjningen förbättras, särskilt i områden som domineras av åkermark där det är brist på stallgödsel. I två delstudier studerade jag effekten av gödsling av ekologiskt vår- och höstvete biogasrötrester, som ett komplement till den traditionella gödslingen med stallgödsel. Under 2022 kunde jag med hjälp av precisionsodlingsmetoder kvantifiera variationen inom fältet på en ekologisk lantbrukares fält där olika givor av rötrester spreds i växande gröda under senvåren. Mina resultat bekräftar vikten av att ta hänsyn till kvävetillgången i jorden (från förfrukt och tidigare gödsling) och att gödsla i rätt tid för att uppnå en god avkastning med tillräckligt hög proteinhalt. Samma år genomförde jag fältförsök på tio ekologiska gårdar i Västra Götaland och fann att gödsling med biogasrötrester sent på våren är ett effektivt sätt att uppnå god spannmålsavkastning och hög proteinkvalitet i ekologiskt höstvete.

Genom att kombinera olika metoder från nationell statistisk dataanalys till fältobservationer fick jag möjlighet att både följa fält under en längre tid och mer i detalj under en odlingssäsong. Med resultaten från de designade fältförsöken fick jag specifik förståelse för grödornas reaktioner på både markens förmåga att leverera kväve och deras respons på olika gödslingsnivåer med rötrester som är rika på kväve. Eftersom försöken utfördes på flera gårdar fick jag resultat på effekterna av näringsförsörjningen (främst kväve) under olika biofysiska och ekologiska odlingsförhållanden. Denna avhandling pekar på att det finns en stor variation i produktiviteten hos ekologiska växtodlingsgårdar i slättbygder med hög jordbruksproduktivitet. Till exempel, tillräcklig näringsförsörjning vid rätt tidpunkt är en viktig faktor för både kärnskörd och proteinhalt i vete. Detta understryker potentialen för att öka produktionen och produktiviteten i ekologiska odlingssystem genom förbättrade brukningsmetoder.

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Land Parcel Identification System (LPIS) data allows identification of crop sequence patterns and diversity in organic and conventional farming systems.

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ABSTRACT

Farmers grow crops in specific sequences to lower disease pressure and boost crop productivity, particularly in organic farming where artificial pesticides and chemical fertilisers are prohibited. Knowledge about crop sequences used in organic and conventional farming will aid the development of future farming systems through optimising crop diversity and pre-crop effects for improved resource efficiency. This study aims to investigate crop diversity and patterns in organic and conventional crop sequences in Sweden. Large-scale LPIS field data managed by the European Union (EU) Integrated Administration and Control System (IACS) were used to monitor crop sequences on arable land in Sweden over 10 consecutive years (2005–2014). Individual fields (land parcels) could be followed on 40% of Sweden's total arable area (349,891 fields extracted) over the 10 years. The LPIS data was combined with information from a database on which fields were farmed organically. Crop distribution, diversity of crop sequences and pre-crops to the main cereal crops (winter wheat, spring barley) were analysed in organic and conventional farming systems in the five agricultural productivity zones of Sweden. The results showed that in the most productive zone in southernmost Sweden, small-grain cereals (particularly winter wheat) were the most common crops (62%), followed by oilseeds (11%), ley and forage crops (9%) and sugar beet (8%), when excluding permanent grassland. In the least productive zone (at higher altitudes and/or latitudes), ley and forage crops dominated (67%), followed by spring cereals (barley, oats) (23%). Crop diversity was higher in the two more productive zones (mean 4.6 crop types) than in two less productive zones (3.4) and organic farms showed 9% higher crop diversity than conventional farms in the most productive zones. Overall, in all zones, the pre-crop to winter wheat was generally a different crop type (3 out of 5 times) e.g., young ley (1–2 years) or grain legume, while the pre-crop to spring barley was most often (4 out of 5 times) another cereal. For both these crops, pre-crop type was more diverse in organic than conventional systems. These findings demonstrate that LPIS data can offer valuable insights into agronomic trends and on-farm practices regarding crop choice and that analysis of field-level LPIS data on crop sequences at large scale can reveal information about organic and conventional cropping in different productivity zones across countries. This information can be used to understand the practical limitations in the use of crop diversity to maximise pre-crop effects. This could in turn support advisory service and policy makers to facilitate more sustainable, productive and resource efficient crop production.

1. Introduction

Crop rotation, defined as "the sequence of crops grown in succession on a particular field" (Wibberley, 1996), is one of the oldest and most fundamental agronomic practices (Lawes and Gilbert, 1895). A varied crop rotation provides benefits in traditional farming (Bennett et al.,

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2012), where it has been used for thousands of years (Hasanuzzaman, 2019). The development of efficient biocides and wider availability of mineral fertilisers during the 20th century enabled use of simpler rotations, resulting in environmental problems associated with overuse of these inputs and emerging resistance to biocides. Organic cropping involving diverse crop rotations has increased in recent decades, aiming to improve the sustainability of systems by combining different species in space and time (Bachinger and Zander, 2007; Zegada-Lizarazu and Monti, 2011; Tamburini et al., 2020). Diverse cropping systems can improve resource use efficiency (Wezel et al., 2014), e.g., legumes add nitrogen to the system, perennial crops improve soil structure and fertility, and plant species diversity helps regulate weed, pest and disease pressure (Reckling et al., 2016). Moreover, since temporal aspects of management differ between crop types, the workload can be more efficiently spread over the year rather than concentrated to an intense period. Changes in crop sequences may include an array of different options to increase crop genetic diversity (Zhao et al., 2022), such as introduction of different species (e.g., legumes in wheat-based rotations) and introduction of service crops for specific functions (Lagerquist et al., 2022).

Preceding crops (pre-crops) can have a direct effect on nutrient availability to the following crop and also provide yield benefits by improving crop health (Angus et al., 2015). The pre-crop effect varies depending on environmental conditions (Khakbazan et al., 2018) but tends to be similar in absolute terms regardless of yield level (Angus et al., 2015). Thus, in relative terms, the effect is especially significant when yield is low. Winter wheat growing after a non-related crop, such as oilseed rape or a grain legume, typically yields about one ton more per hectare than when grown after wheat, barley or rye, to which wheat is closely related (Angus et al., 2015). In addition, nutrient inputs can be reduced with an optimal choice of pre-crop (Engström and Lindén, 2009). This means that the pre-crop choice has an important economic impact for arable farms (Khakbazan et al., 2018). The pre-crop effect on spring barley is typically about half that of winter wheat, mainly because the longer time between harvest and sowing allows pathogen pressure to decline, however with the spring sown barley some residual nitrogen might have been lost during the winter (O'Donovan et al., 2014). Resource use efficiency can be improved by sowing a crop with lower requirements after a nutrient- or water-demanding crop (Altieri and Nicholls, 2003). Therefore, it is important to maximise the pre-crop effect, especially before e.g., an organic cereal cash crop with specific quality requirements for human consumption (Angus et al., 2015; Ingver et al., 2019). The major annual crops in Sweden are winter wheat *(Triticum aestivum L.)* and spring barley *(Hordeum vulgare L.)*. Winter wheat is high-yielding and generally requires more nutrients and control of pests and diseases than spring barley. In spite of being demanding, many organic farmers still consider winter wheat to be the most valuable crop (Chongtham et al., 2017; Rempelos et al., 2020) and therefore place it in a favourable position in the crop sequence (Chongtham et al., 2017). Spring barley is less demanding although it is a popular crop choice due to its high adaptability to different environmental conditions and multiple uses (Fox et al., 2009).

Data on crop sequences are commonly collected on limited spatial scale, e.g., in farm surveys, experimental plots (Lorenz et al., 2013) and small zones e.g. regions (Castellazzi et al., 2007). A recent review revealed high availability of crop sequence data from organic experiments, but lack of knowledge on whether and how crop rotations differ between organic and conventional farms in practice (Barbieri et al., 2017). This is important knowledge considering that optimizing crop rotations towards higher diversity could lead to more sustainable and efficient food production (Barbieri et al., 2019). By identifying crop sequences in regions, it is possible to understand economic constraints and drivers of diversity of management practices in organic and conventional farming systems (Steinmann and Dobers, 2013). By using a regional approach, for example at the watershed scale, it is possible to encompass the variation in local conditions and how it affects cropping systems (Rizzo et al., 2019). Further knowledge of the productivity of the region can help distinguish zones where different proportions of crop types occur. Together with knowledge about management, such as crop choice, these zones can be used to study the influence of environmental conditions on farming practices. For instance, in zones of lower productivity, because of soil and climate conditions, a higher proportion of perennial crops such as leys and pastures can be expected. Increased knowledge about crop sequences can also improve understanding of how farmers are adapting to climate change (Bohan et al., 2021). Evaluating the crop types (and species) grown in crop sequences and their position and function in the sequence (Peltonen-Sainio et al., 2017) can provide information on the technical orientation of the farming system. The proportion of each crop in the sequence and number of break years before it returns can be used as indicators of sequence diversity (Leteinturier et al., 2006).

Different approaches can be used to evaluate crop sequences. For example, the CropRota model (Schönhart et al., 2011) assesses crop sequences based on frequency of return of crops (Castellazzi et al., 2010). An alternative is to use expert knowledge to describe existing crop sequence patterns and monitor changes in crop frequency over time which has also been used to identify landscape heterogeneity, as a proxy for diversity (Peltonen-Sainio et al., 2017). The Land Parcel Identification System (LPIS), a geographic information system used in the European Union (EU) Integrated Administration and Control System (IACS) to allow authorities to geolocate, display and spatially integrate data on farm subsidies, can be used to track changes over very large areas (Bailly et al., 2018). LPIS data can also be used to assess crop diversity (Schaak et al., 2023) since it shows the crop species or crop types farmers grow on their fields. Nonetheless, each parcel (block) can combine several undetermined fields, so to avoid uncertainty, a specific method for estimating real sequences of crops at field scale is necessary (Levavasseur et al., 2016). The Swedish Board of Agriculture has detailed information about subsidies paid to Swedish farmers, which allows organically certified fields to be distinguished. Sweden is an ideal case study for this type of analysis as it has a relatively large proportion (20%) of organic agricultural land compared to other European countries and large proportion of it is arable fields (3rd highest share of organic land in EU27 (Eurostat, 2020a)).

The aim of this study was to evaluate and compare crop distribution, diversity and crop sequences in organic and conventional agriculture in different productivity zones of Sweden using LPIS data. Such knowledge is vital in the work to understand and optimise pre-crop effects to obtain more sustainable and resource-efficient crop sequences with potential for higher yields and crop quality. Specific objectives were to (i) determine the distribution of arable crops at national scale in Sweden and in different productivity zones using LPIS data; (ii) evaluate crop type diversity over a 10-year period (2005–2014); and (iii) compare common pre-crops to the two main cereal crops in Sweden (winter wheat and spring barley) and their role in organic and conventional cropping systems.

2. Materials and methods

2.1. Study area

Sweden has in total around 3 million hectares (ha) of agricultural land (7% of its territory), comprising 2.6 million ha arable and 0.45 million ha permanent grassland (Swedish Board of Agriculture, 2018). The main arable crops are ley and forage (45%), and cereals (40%), particularly wheat and barley (Table 1).

The Swedish landscape has been shaped by several glaciations that have formed soils of diverging traits and fertility. To account for this, Sweden has been subdivided into five productivity zones differing in growing conditions and thus, land use, including crops grown and animals reared (Swedish Board of Agriculture, 2018; Piikki and Söderström, 2019). Crop distribution and sequence diversity were

Table 1
Use of arable land in Sweden in 2020 (Swedish Board of Agriculture, 2020b) compared to crop sequences from period 2004–2015 from LPIS data analysis. Total area (ha) and percentage of crops are given in the table.

Crop type	Crop species	Statistics Sweden ha	Statistics Sweden percentage	Aggregated LPIS data ha	Aggregated data percentage
Cereals		1007,600	40	406,761	47
	Wheat	*(452,700)*	*(18)*	*(148,630)*	*(17)*
	Barley	*(299,800)*	*(12)*	*(144,457)*	*(17)*
	Oats	*(184,700)*	*(7)*	*(87,578)*	*(10)*
	Others	*(70,500)*	*(3)*	*(26,095)*	*(3)*
Grain legumes		47,900	2	14,579	2
Ley and forage[a]		1138,800	45	295,778	34
Potato		24,200	1	6519	1
Sugar beet		29,800	1	9509	1
Oilseeds[b]		99,300	4	38,696	4
Other crops		55,300	2	23,611	3
Fallow		134,700	5	49,806	6
Unspecified		10,900	0	18,870	2
Total arable land		2548,600	100	864,128	100

[a] Ley and forage crops include perennial grass or grass/clover leys, mowed and grazed meadows and also a small proportion (<1%) of annual forage crops such as fodder maize or other crops harvested before maturity. Specifically in the crop sequence data, ley and forage include both young and old leys.

[b] Rape and turnip rape.

analysed for each of the five productivity zones (Fig. 1). These zones aggregate areas with similar combinations of climate, topography and soil type that give similar agronomic productivity potential, where: Zone 1 (11% of total arable area) is “most productive”, Zone 2 (11%) is “highly productive”, Zone 3 (38%) has “medium productivity”, Zone 4 (21%) has “low productivity” and Zone 5 (20%) is “least productive” (Swedish Board of Agriculture, 2022). Here, zones 1, 3 and 5 were compared in particular, to reflect the main productivity gradient and contrasting patterns of crop sequences throughout Sweden.

2.2. *Crop data source and analysis of crop sequences*

Crop sequences in Sweden over the selected 10-year period were identified using the LPIS database managed by the Swedish Board of Agriculture, which enables farmers to receive subsidies from the EU Common Agriculture Policy (CAP). The LPIS provides information on the crops that are cultivated on farmers’ parcels also known as “blocks”. Each block is identified by an ID code (Kay and Milenov 2008). In the structure of the LPIS data, one block can contain several fields. Based on their ID, blocks were linked across years. A block in year i was in 93% of the cases the same area as the one in year i + 1, during the period 2004–2015. Since our method is based on block area (Levavasseur et al., 2016), to ensure the tracking of the unique crop sequence in each field over several years, we discarded identically sized fields in each block. We checked that the discarding of fields did not favour any crop type by ensuring that the final area of crop types after filtering was the same as in the initial database for each year. After this filtering step, we linked

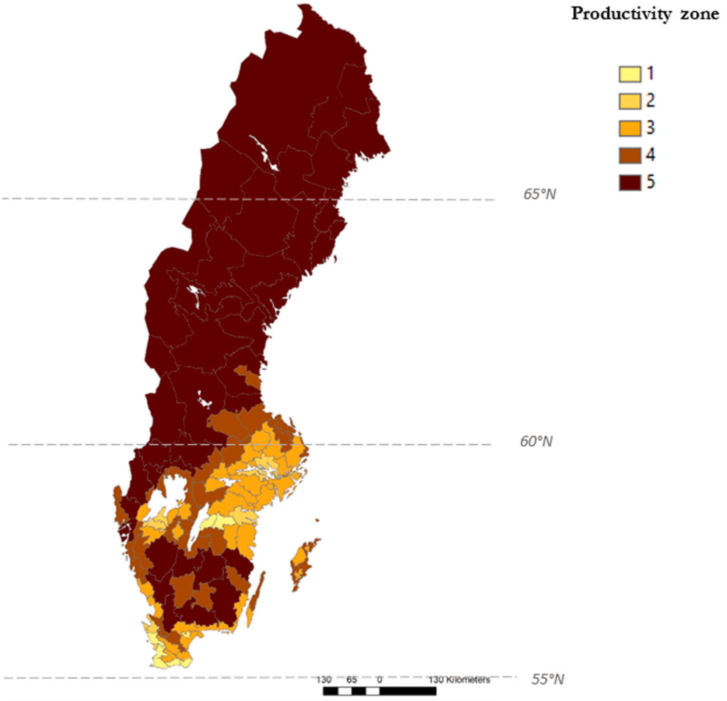


Fig. 1. Location of different productivity zones in Sweden (1 = most productive, 5 = least productive) used as a basis in this study. The number of hectares per productivity zone that is available from our LPIS database can be seen in Supplementary Material Table S2.
Source: (Swedish Board of Agriculture, 2022) (in color).

fields within the blocks considering the size of the field, using rules according to Levavasseur et al. (2016). Farm subsidy information was used to identify whether each block was declared as being under organic management or not in each year (Swedish Board of Agriculture, 2018). The sum of organically managed fields that could be followed over the 10-year period was 200,501 ha and the sum of conventionally managed fields was 1113,355 ha, i.e. 18% (See Supplementary Material (SM) Table S1). Fields registered as repeated grassland for the whole period were regarded as permanent grassland and were excluded from the analysis. This resulted in a total of 349,891 fields, representing 887, 777 ha or around 40% of Swedish arable land, which were monitored over the 10-year period.

2.3. Indicators of diversity in crop sequences

The LPIS data include 94 crop types which characterize single crop species (e.g., code 4 for winter wheat) and in some cases groupings of crop species (e.g., code 50 for 'Ley and cultivated grass on arable land') (See SM Table S2).

Crops with similar botanical and agronomic characteristics were consistently grouped in two different ways, thus avoiding minor crop types with small areas (<1%) to down-weight the variation in area of the fields analysed (Aramburu Merlos and Hijmans, 2020). Grouping in 19 crop types (G19) was done by selecting the main crop types cultivated on arable land in all productivity zones in Sweden. The G11 crop types were combined from the G19 based on their agronomic functions as preceding crop to spring barley and winter wheat that were our focus crops and on other ecological characteristics, such as susceptibility to diseases and time of sowing (Table 2). Oats (spring) were kept in a separate group from the other cereals, because it is not as closely related to other spring crops and is a better preceding crop to winter wheat and spring barley. The categories called 'leys' primarily consisted of mixtures of grass and herbaceous legumes and are mainly used as forage or for grazing. As most rotational leys in Sweden consist of mixtures of grass and clover, particularly red clover (sometimes also white clover), a distinction was made between young leys (1–2 years) and old leys (>2 years). Young leys contain higher proportions of red clover than old leys, as red clover tends to die during winter due to diseases. Young leys therefore generally have a larger residual nitrogen effect on the following crop, but less long-term effects than older leys (Watson et al., 2011). Non-cereal break crops used to diversify crop sequences in Sweden include grain legumes, oilseeds, and root and tuber crops.

Table 2

Crop types when 94 different crop codes from the LPIS database were merged into 19 (G19) and 11 (G11) groups, respectively based on crops function in cropping systems, listed in alphabetical order.

	G19 crop types (n = 19)		G11 crop types (n = 11)
1	Winter wheat	1	Winter cereals
2	Triticale		
3	Rye		
4	Winter barley		
5	Spring barley	2	Spring cereals
6	Spring wheat		
7	Oats	3	Oats
8	Beans	4	Grain legumes
9	Peas		
10	Mixture cereal and grain legumes	5	Mixture cereal and grain legumes
11	Spring oilseed rape[a]	6	Oilseed rape
12	Winter oilseed rape		
13	Potato	7	Roots and tubers
14	Sugar beet		
15	Young ley (1–2 years)	8	Young ley (1–2 years)
16	Old ley (3 years or older)	9	Old ley and pasture (3 years or older)
17	Pasture		
18	Others (woody species, perennials, minor vegetable crops)	10	Others (woody species, perennials, minor vegetable crops)
19	Fallow	11	Fallow

[a] Including a small proportion of turnip rape (Brassica rapa L.)

Crop sequences were characterised based on: i) crop distribution, taken as relative cultivated area (ha) of the crop in each productivity zone averaged during the 10-year period; ii) crop type diversity (calculated as number of different crop types grown on the same field subsequently during the 10-year period) and the exponential Shannon diversity index; iii) crop share in the sequence, calculated as number of times a specific crop type was grown in the 10-year period only including fields where the specific crop was actually grown at least once during the period, not as average for all fields in the zone. Thus, a minor crop can be grown with a high share if it returns frequently in field where it is grown.

The crop type diversity (n) was obtained by counting the number of different individual crop types (g) from grouping G19 and summing them for each crop sequence occurring over the 10-year period (Eq.1).

$$n = \Sigma g \tag{1}$$

The exponential Shannon diversity index was adapted by using crop types instead of species and community replaced by years of the crop sequence. Using the following formulae, the exponential Shannon diversity index (H') was used to calculate the diversity of crop types and their relative abundance in the crop sequence (Eq.2).

$$H' = \exp(-\Sigma pi * \ln(pi)) \tag{2}$$

where pi is the proportion of individual crop type count in the crop sequence belonging to the ith crop type, and the summation is taken over all crop types present in the crop sequence.

2.4. Statistical analyses

A randomisation test was used to estimate the significance in differences in average crop type diversity between organic and conventional farming systems in different productivity zones. Also known as a permutation test or re-sampling test, this statistical technique is used to test the significance of a hypothesis by randomly re-assigning observations to different groups and computing the test statistic of interest under the new grouping (Good, 2013). The randomization test does not make any assumptions about the distribution of the data, and it is commonly used in situations where traditional hypothesis tests are not applicable or when the data is not normally distributed which was the case of our data. The test involves randomly shuffling the fields with their associated crop sequence across the organic and conventional treatment groups. This enables the calculation of test statistics for each new allocation, and repeats the process many times (here 100,000 times) to obtain results. The p-value is then calculated as the proportion of simulated test statistics that are at least as extreme as the observed test statistic. If the p-value is less than the significance level (usually 0.05), then the null hypothesis (no difference in diversity) is rejected in favour of the alternative hypothesis (significant difference in terms of diversity). All analyses were performed using R Statistical Software (v4.1.2; R Core Team 2021). R-package "coin" was used for the randomisation test and package "stats" was used for the Exact Fisher's test. Additional R-packages used for data transformation and visualisation were the following: vegan, car, ggpubr, ggplot2.

3. Results

3.1. Distribution of crops in Sweden

Based on the 10-year LPIS-data of cultivated area in the different productivity zones, crop proportions were calculated for each zone (Table 3). Cereal crop proportion decreased with decreasing zone productivity, from 62% in Zone 1–24% in Zone 5. Winter wheat, the most widely grown cereal crop in Sweden, clearly drove these differences,

Table 3

Distribution of crop types in the five productivity zones in the study period 2004–2015 (based on LPIS data, G11), i.e., percentage (rounded to the nearest whole number) relative to average area of those crops cultivated within each zone averaged over the 10-year period, excluding fields with leys or pastures during the whole 10-year period.

		1	2	3	4	5
Winter cereals		39	36	20	9	1
	Winter wheat	*34*	*32*	*16*	*5*	*1*
	Others[a]	*5*	*4*	*4*	*4*	*1*
Spring cereals		20	18	23	18	16
	Spring barley	*18*	*15*	*19*	*16*	*15*
	Spring wheat	*2*	*3*	*4*	*3*	*1*
Oats		3	12	12	13	7
Grain legumes		4	7	7	7	3
Mixture cereal and grain legumes		0	1	2	3	4
Oilseed rape		11	8	5	2	0
Roots and tubers		8	2	2	0	1
	Potato	*1*	*1*	*1*	*0*	*1*
	Sugar beet	*8*	*1*	*1*	*0*	*0*
Young ley (1–2 years)		5	6	12	19	24
Old ley and pastures (3 years or older)		4	6	13	26	43
Other crops		4	4	3	2	1
Fallow		3	6	7	6	3

[a] "Others" include winter barley, triticale and rye.

while spring barley, the second most common cereal crop, was more evenly distributed among the five productivity zones. Spring oats were common and evenly spread across zones 2, 3 and 4, but not as common in zones 1 and 5. In contrast to cereals, the area of ley increased with decreasing zone productivity, from 9% in Zone 1–67% in Zone 5. These perennial crops are better adapted to the climatic conditions in the least productive Zone 5 compared to cereal crops. Additionally, even though ley crops in the study belong to single crop types (young leys and old leys), they can often contain several species of grass and forage legumes which may indicate a higher functional diversity.

3.2. Diversity of crop types in organic and conventional farming

3.2.1. Diversity of crop types in different productivity zones

The two indices for crop diversity i.e. the crop type diversity and exponential Shannon index, were aligned in the following results:

When grouping all fields in the different zones, the indices of crop diversity indicated that the diversity was highest (4.6 for number of crop types and 3.8 for exponential Shannon index) in Zone 1 and gradually decreased (4.5, 3.7, for crop types and Shannon) in Zone 2, Zone 3 (4.3, 3.6), Zone 4 (4.0, 3.2) and finally to 3.4 and 2.8, respectively, in Zone 5.

When distinguishing between organic and conventional farms, the results showed a similar pattern of increasing crop diversity in higher productivity zones in both systems and crop diversity indices. For example, in the case of the crop type diversity, the average number of crop types in conventional crop sequences ranged from 4.5 in Zone 1–3.4 in Zone 5, while in organic crop sequences it ranged from 4.9 to 3.4 (Fig. 2). The differences between organic and conventional crop sequences were significant in all productivity zones for the crop type diversity (Table S3 in SM). However, this was not observed for the exponential Shannon index with all differences being significant except in the case of the low productivity zone (Table S3 in SM). For both crop type diversity and exponential Shannon index, the differences were larger in the higher productivity zones than in the least productive zone.

3.2.2. Structure of crop sequences containing the main cereal crops in organic and conventional systems

In conventional systems, winter wheat and spring barley were sometimes grown in very simple sequences with one or two break crops for ten years (Fig. 3). In other cases, farmers used up to 7 or 8 different crops in ten years. Winter wheat was grown very frequently on conventional farms (up to 9 years out of 10 in zones 1–4). There were, however, very few organic fields with winter wheat more than five times during the ten years and the majority of fields had winter wheat two times or less (average of 2.5 years out of 10 in Zone 1) (Fig. 3). Spring barley was more commonly cultivated in the medium and less productive zones. The patterns for spring barley in organic systems look similar to conventional systems, with many fields with more than five crops of

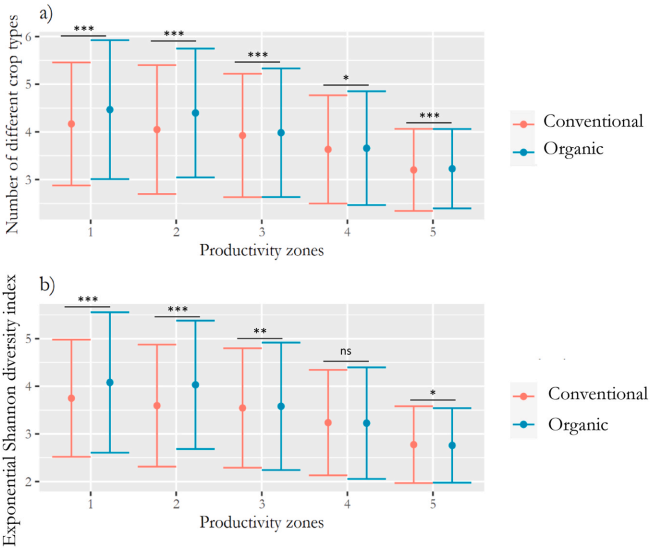
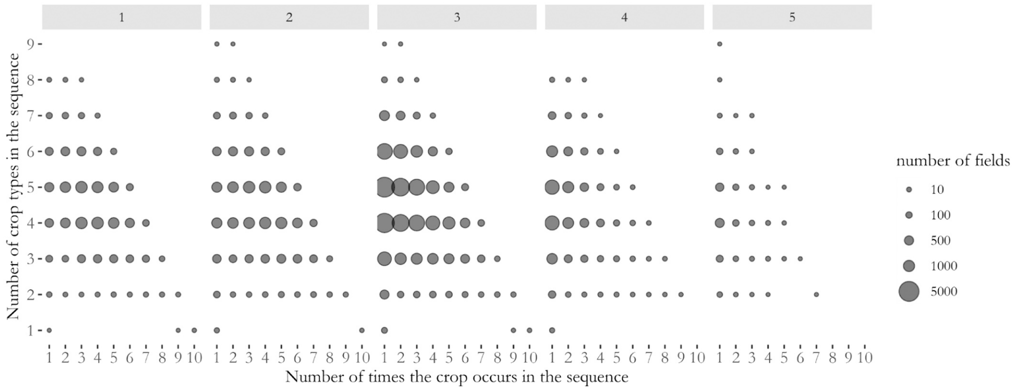


Fig. 2. Average crop diversity (G19 grouping, see Table 1) in conventional and organic farming systems in productivity zone 1–5 (most to least productive). Two diversity indexes are used, values shown are average a) crop type diversity, and b) exponential Shannon diversity index. Error bars represent standard deviation. Based on randomisation test * **P < 0.001; * *P < 0.01; *P < 0.05, ns = non-significant. Data include 349,891 fields representing 887,777 ha, number of observations in each zone and production system can be found in Table S3 in Supplementary Material. **(in color)**.

a) Conventional winter wheat sequences



b) Organic winter wheat sequences

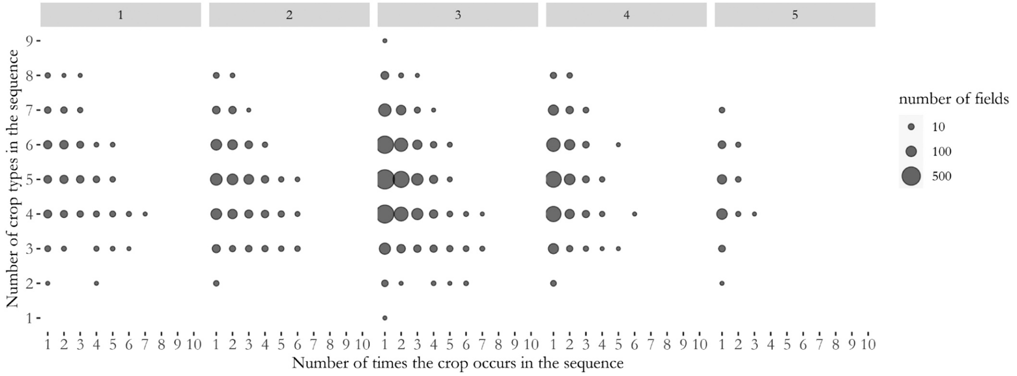


Fig. 3. Crop type diversity (y-axis) and intensity of winter wheat (a, b) or spring barley (c, d) production (x-axis) in (a, c) conventional and (b, d) organic systems in productivity zones 1–5. The intensity is shown as the number of times the winter wheat or spring barley crop occurs in the 10-year period (2005–2014). Panels correspond to the different productivity zones. Bubble size reflects the number of fields with y count of crop types and x count of the cereal crop (winter wheat or spring barley) occurring in the crop sequence.

spring barley during the ten years, particularly in zones 3–5.

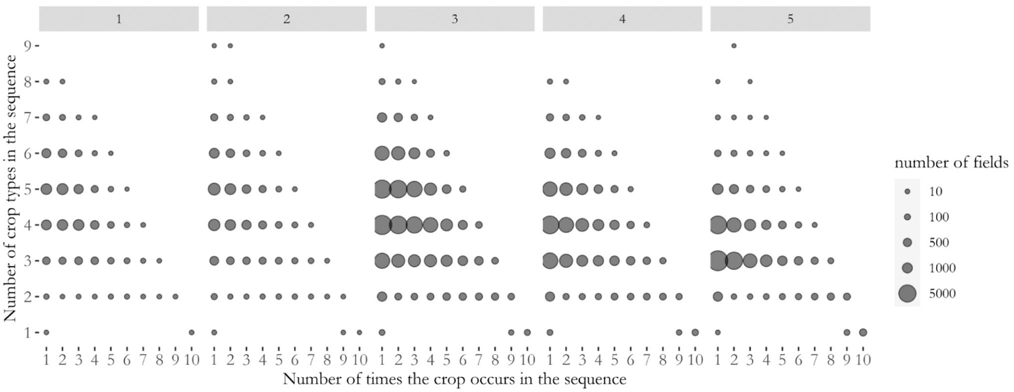
3.2.3. Crop sequence attributes in organic and conventional crop sequences

The diversity of crops in organic and conventional sequences was further analysed by assessing how often the main crop types were grown *in crop sequences where they occurred* (Fig. 4). This revealed that although cereals occurred more frequently in conventional cropping sequences than organic sequences, they had different patterns across productivity zones. Winter cereals returned more frequently across both organic and conventional cropping systems in the higher productivity zones (1, 3), whereas spring cereals returned less frequently in the lower productivity zones (4, 5) in conventional sequences. Oats returned more frequently in Zone 3 than in Zones 1 and 5. As for the shares of non-cereal crop types, grain legumes were more often cultivated in organic sequences, with similar frequencies across the productivity zones. Oilseed rape and roots and tuber crops returned more frequently during the 10-years in conventional sequences. Ley dominated sequences were more common in organic cropping systems, being up to four times more common than in conventional ones. On organic farms, young leys were cultivated at similar frequencies across all productivity zones, whereas on conventional farms young leys occurred more frequently in Zones 3–5. Old leys and pastures were less frequent in Zones 1 and 3, in both organic and conventional sequences, whereas in Zone 5 it occurred on average over five times in a 10-year sequence (Fig. 4).

3.3. Preceding crops to winter wheat and spring barley

There were clear differences in pre-crops to winter wheat and spring barley between organic and conventional farms and between productivity zones (Table S4 in SM). Fig. 5 shows the pre-crop types that were used ranked according to the importance of their proportions in organic and conventional in the Zones 1, 3 and 5.

In winter wheat cultivation, winter and spring cereals were common pre-crops in conventional farming in all zones (up to 32% for winter cereals in Zone 1% and 23% for spring cereals in Zone 5) (Fig. 5). Winter cereals were only common pre-crops in organic farming in Zone 1


c) Conventional spring barley sequences

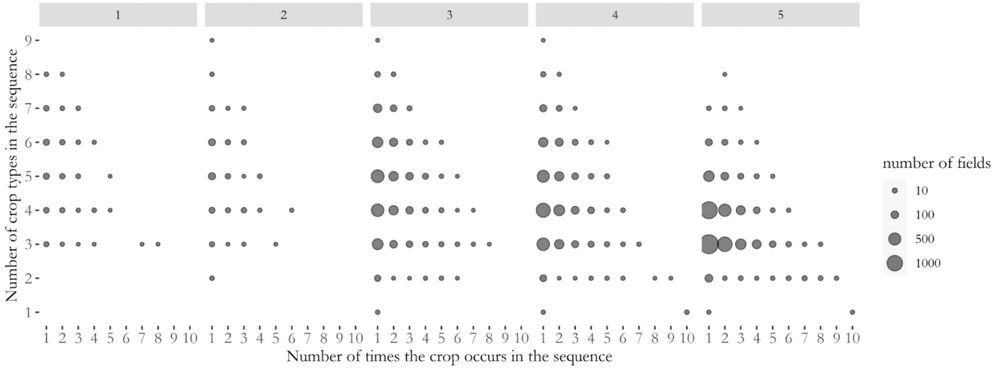

d) Organic spring barley sequences

Fig. 3. (*continued*).

(25%). Oilseed crops preceded winter wheat two and a half times more often in conventional than in organic sequences (28% and 11%, respectively, in Zone 1). In contrast, leguminous crops or crop mixtures with legumes as pre-crops were seven to ten times more common in organic than conventional cropping systems. In organic production, grain legumes represented a stable proportion of 9% of pre-crops in all zones. Young leys were also a frequent pre-crop in organic winter wheat with as much as 25% in Zone 3% and 15% in Zones 1 and 5.

In spring barley cultivation, winter and spring cereals were frequent pre-crops in both organic and conventional sequences in Zones 1 and 3 (Fig. 5d, e). Root and tuber crops were common pre-crops to spring barley in conventional fields in Zone 1 (32%), whereas organic fields in Zone 1 had a more diverse set of pre-crops including grain legumes (12%), leys (14%) and oats (6%). The proportion of young and old leys as pre-crop to spring barley was higher in organic farming across all zones (up to 24% in organic vs. 5% in conventional in Zone 3%, and 54% in organic vs. 32% in conventional in Zone 5). Higher diversity of pre-crops in organic compared to conventional sequences was observed in all zones, expect Zone 5, where main pre-crops were spring cereals, spring oats and leys in both systems (Fig. 5f).

In both winter wheat and spring barley cultivation, pre-crop diversity was higher in organic farming than in conventional (10 and 7 crop types, respectively) (Fig. 5). In organic production, the percentages of young leys as pre-crops was relatively uniform across zones for both winter wheat and spring barley (19% and 7%, respectively). Grain legumes showed a different pattern and were only a frequent pre-crop for cereals in Zone 1 (19%) (Table S4 in SM).

Compared to spring barley, winter wheat cultivation had a more diverse set of pre-crops in conventional systems in all zones. Grain legumes and young leys were always more frequent pre-crops to organic winter wheat than to spring barley (Table S4 in SM). This was the case in both organic and conventional sequences, except for conventional sequences in Zone 5 where young leys were about as common as pre-crops to both spring barley and winter wheat. In contrast, old leys and pasture were more frequent pre-crops in organic winter wheat than in organic spring barley. In conventional sequences, old leys and pasture occurred with the same percentage as pre-crop to winter wheat and spring barley.

4. Discussion

4.1. *Distribution of crop type and crop sequence diversity vary with productivity*

The distribution of crops was closely aligned with the productivity

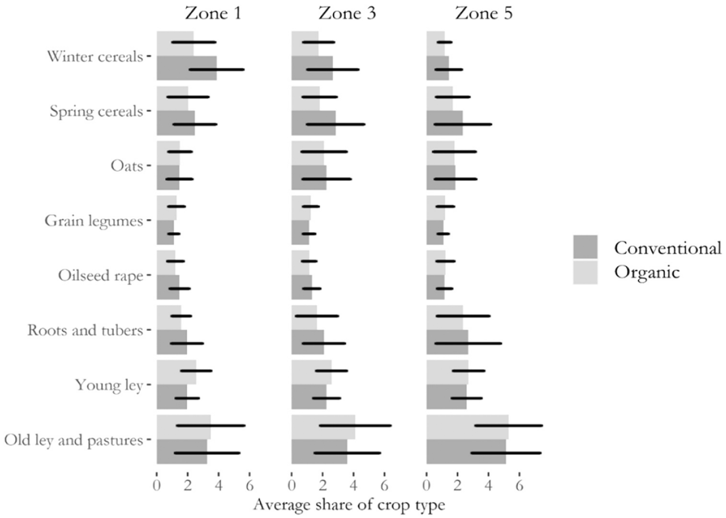


Fig. 4. Average number of times winter and spring cereals, spring oats, grain legumes, oilseed rape, roots and tubers, young ley, old ley and pastures are grown in sequences in which they actually occurred in conventional and organic sequences in the high (1), medium (3) and low (5) productivity zones during the 10-year period. The columns represent the different productivity zones. Values shown are mean number of crop types in sequences with these crop types, error bars represent standard deviation for the 10-year period. **(in color).**

gradient from Zones 1–5 (Fig. 1). Cereals were the main crops in the more productive mainly arable zones located in southernmost Sweden. This area is dominated by fertile clayey soils (boulder clay) suitable for cultivation of cereals, oilseed, sugar beet and vegetables (Fogelfors, 2015).

The medium productivity zone around the large lakes on the plains of central Sweden, is also dominated by arable farming but with greater occurrence of mixed farming and spring cereals than in the more productive zones in the south. Its soils contain 25–50% clay (mainly post-glacial sediment), suitable for annual crops such as cereals and oilseeds (Fogelfors, 2015). The less productive zones are situated at higher altitudes in southern Sweden and at higher latitudes where the growing season is shorter, winters are more severe, and soils are coarse textured dominated by silt and sand. On these less fertile soils and where the climate is less favourable for more demanding crops, leys and forage crops perform better than annual crops such as winter wheat and oilseed rape. The distribution share of leys and forage crops is high under these conditions, since agriculture focuses on mixed farming and livestock production.

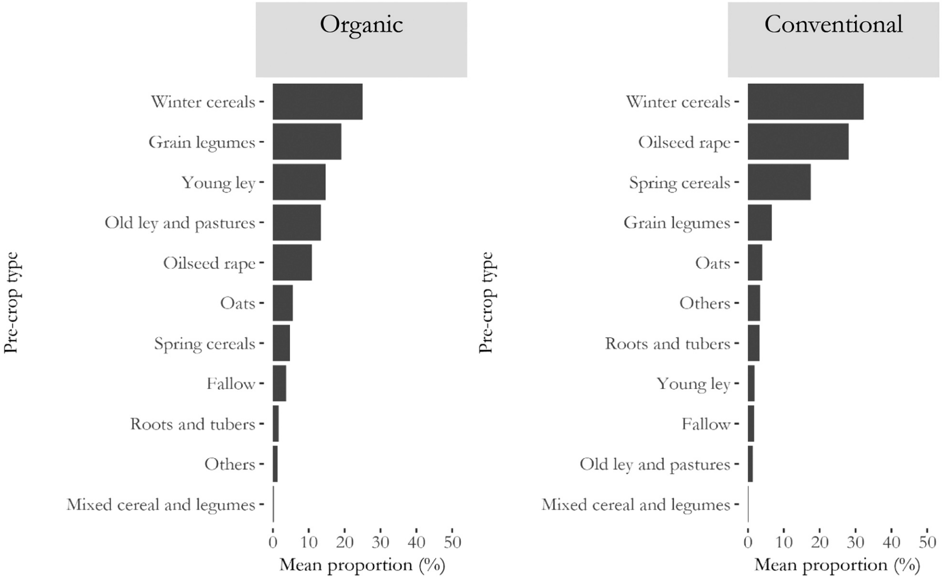
The diversity of crop types was lower in the less productive zones and this both in average number of crop types and in relative proportion of crop type species in the sequences. The leys dominating in these zones are most often a mixture of perennial grass and legume species (clovers) grown over several years. This, in combination with the lack of viable options of annual crops explains the lower diversity of crop types. However, the biodiversity per se is generally higher in the landscape in these zones due to multi-species leys and relatively large areas of semi-natural grassland (Öckinger and Smith, 2007). Development of new markets or quality assurance schemes for annual species or varieties suitable for low productivity conditions (e.g., heritage cultivars of rye, wheat and peas) could promote crop diversification in these zones (Ortman et al., 2022). Our findings highlight Sweden's unique climatic range (from cold temperate to subarctic, SMHI, 2023) and growing conditions with a relatively limited choice of crop types in comparison to more southern countries in Europe. Crop type distribution in Sweden contrasts with patterns in Germany for example, where winter wheat cultivation was more frequent in the northern regions, while maize was more frequently cultivated in the southern regions (Jänicke et al., 2022).

4.2. Crop sequence diversity and shares of crop types vary between organic and conventional systems

The number of crop types used during the ten years was on average 4.5% higher in organic than in conventional farming. However, the difference was smaller than expected, in spite of much emphasis on crop rotation design in organic farming to manage weeds, pests and diseases (Chongtham et al., 2017; Barbieri et al., 2017; Seufert et al., 2019). Northern growing conditions are generally considered to be less favourable areas in the European Union (EU) with regional cropland areas typically ranging from 0% to 25% of total land area (Rounsevell et al., 2005). These conditions are not suitable for cold sensitive crops that require long growing seasons. The inherent limited choice of crop types in under Swedish conditions may be one explanation for the relatively small differences in crop diversity between organic and conventional crop sequences that was found. The differences in crop diversity were significant between organic and conventional fields in all productive zones, except for in Zone 4 when assessing the exponential Shannon index. Since this result relates to crop diversity in relation to the number of crop types grown during the length of the 10 year crop sequence, it can be explained by an even distribution of cereal crop types and old leys and a lack of focus on specialized crops in the sequences of this low productivity zone. Crop sequence diversity is influenced by soil and environmental conditions, and also by socio-economic and external factors, such as infrastructure, market prices and access to processing industries. For example, the only processing factories for sugar beet and potatoes for industrial uses (sugar and starch) are situated in the most productive regions in southernmost Sweden and no price premium for organic produce was available during the investigated period (Björklund and Renström, 2010). As seen in our results, conventional sequences proved to be more specialized than organic sequences, focusing on annual species that respond well to external inputs, such as winter wheat responding to mineral fertilization and winter oilseed rape productivity depending on use of insecticides (Fig. 4). Crops dependent on high inputs occurred less frequently in the organic sequences (Thorup-Kristensen et al., 2012).

Many factors influence the design of crop sequences in organic farming including susceptibility to diseases and pests as well as the

a) Winter wheat Zone 1



b) Winter wheat Zone 3

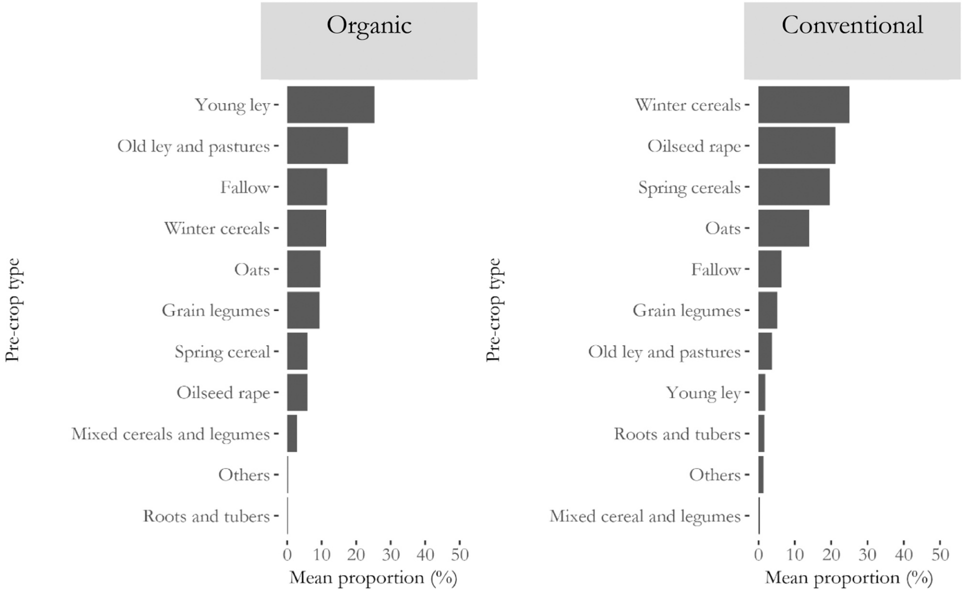
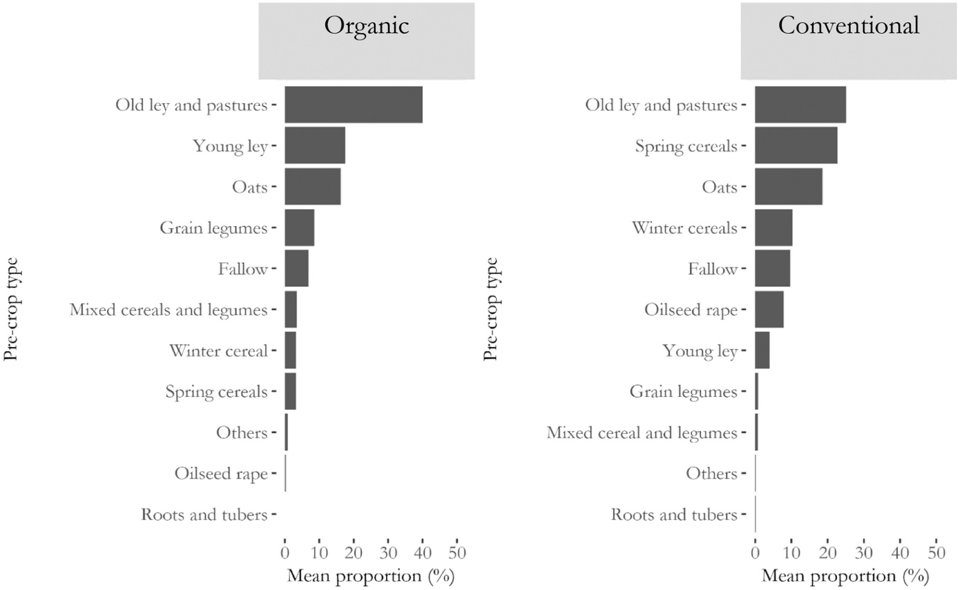


Fig. 5. Average proportions during 9 years of the most important pre-crops to winter wheat (a, b, c) and spring barley (d, e, f) in organic (left) and conventional (right) production in high (Zone 1), medium (Zone 3) and least productive zone (Zone 5).

c) Winter wheat Zone 5



d) Spring barley Zone 1

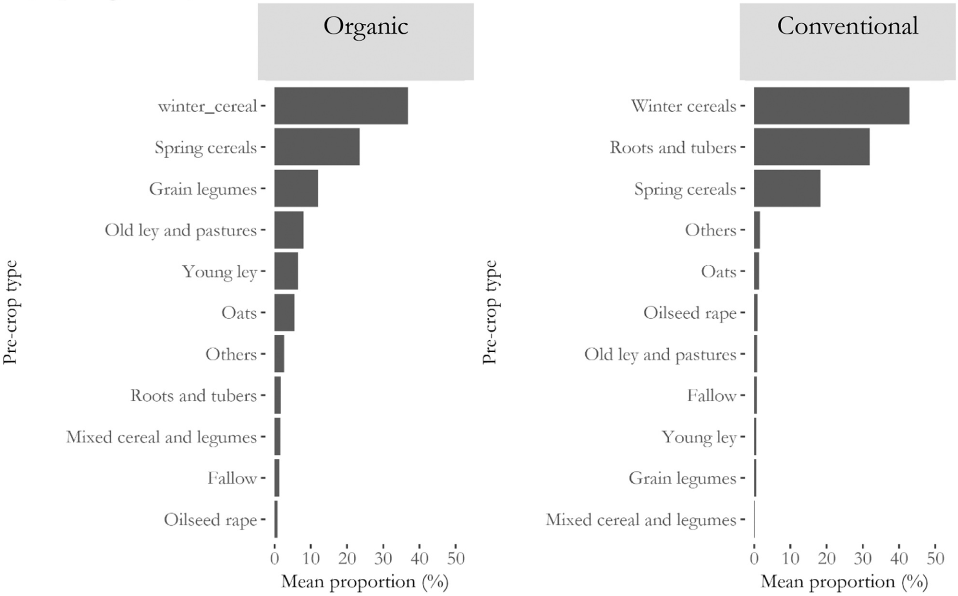
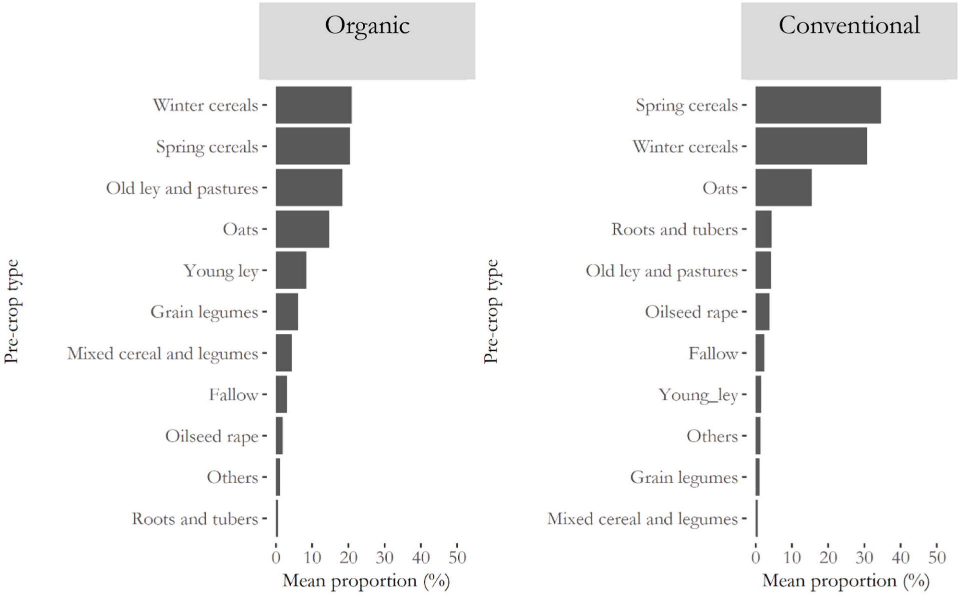


Fig. 5. (*continued*).

e) Spring barley Zone 3



f) Spring barley Zone 5

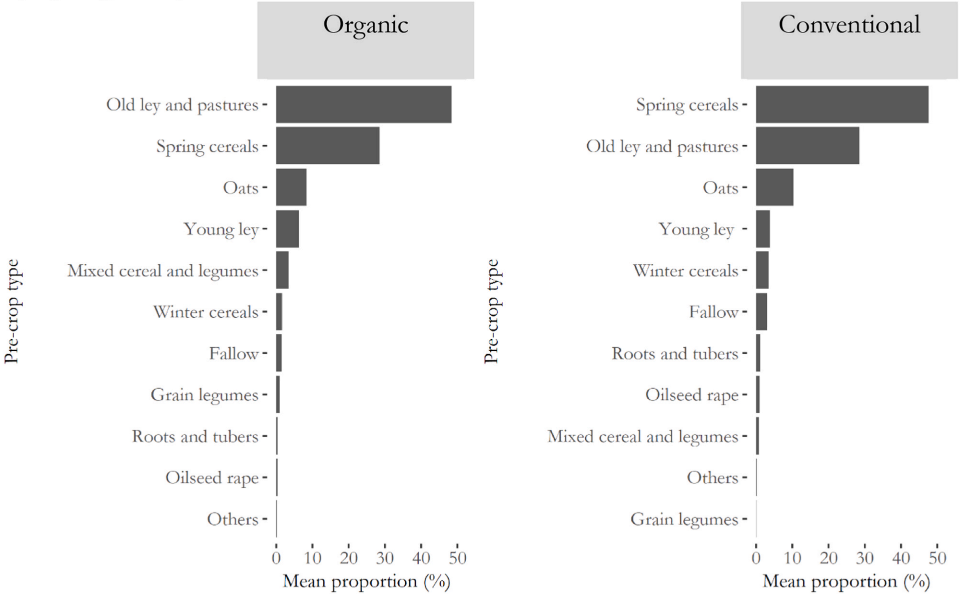


Fig. 5. (*continued*).

access to organically certified nutrient sources (Chongtham et al., 2017). Due to shortage of locally available animal manure, nitrogen deficiency is a common problem in organic cropping systems (Olesen et al., 2009; Lovén and Nordin, 2020), which was reflected in a higher proportion of young leys (often being legume-grass species mixtures), particularly in the more productive zones (Table 3). Organic crop rotations are generally characterised by a fertility building phase and a cash crop or income-generating phase (Öborn et al., 2005; Watson et al., 2011; Bohan et al., 2021). This is in accordance with earlier studies on land-use on organic and conventional farms (Bengtsson et al., 2005; Norton et al., 2009). As seen in our results, the share of old leys was consistently higher in organic compared to conventional sequences in all productivity zones (Fig. 4). The old leys were also more frequent in the less productive zones, representing in some cases 50% of the crop sequence in Zone 5. However, it is difficult to maintain productive leys with a high red clover content for longer than 2–3 years, due to winter kill and clover root rot (Wallenhammar et al., 2000). Increasing the proportion of legume species in the ley mixture can increase yield stability compared with fertilised pure grassland (Frankow-Lindberg et al., 2009), due to niche complementarity (Nyfeler et al., 2009), but will require that the leys are re-established after 2–3 years or that other legumes, such as white clover and lucerne, are used in the mixture. Our results suggest that ley is not always a major component in organic crop sequences, these sequences are often intensified with frequent cereal crops and similar patterns to conventional crop sequences, especially in high productivity zones dominated by arable farming (Figs. 4 and 5). Perennial grasses and legume species or mixtures can also be incorporated into cropping systems as cover crops with known positive properties affecting soil organic carbon (Beillouin et al., 2023) as well as the subsequent crop such as increasing its yield (Bergkvist, 2015, Zhao et al., 2022) and reducing nutrient leaching (Hauggaard Nielsen et al., 2012, Plaza-Bonilla et al., 2016).

4.3. Pre-crops to winter wheat and spring barley differ between organic and conventional systems and productivity zones

In highly productive zones, winter wheat was frequently included in sequences with other cereal crops, with little inclusion of break crops, particularly in conventional systems. Break crops were more frequent in organic systems. Wheat after a break crop can yield significantly more than growing wheat after wheat or another cereal crop, with oats as an intermediate (Angus et al., 2015). The pre-crops to winter wheat were less diverse in the less productive zones where leys dominated. Ruminants are common in the least productive zones, which makes leys important crops. Under-sowing of grass/clover is generally done in spring cereals, frequently spring barley, and leys are generally terminated in the summer to be able to control couch grass efficiently before the next crop. Winter wheat is good at taking advantage of pre-crop effects (Angus et al., 2015) and can be sown timely to avoid a long period of bare soil after the ley.

In organic farming where mineral nitrogen cannot easily be added to winter crops in the spring, it is of particular importance to grow a pre-crop to the winter wheat that leaves some nitrogen in the soil as well as nitrogen rich plant residues. For example, young leys or legumes as pre-crops can contribute to achieving sufficiently high protein concentrations in the wheat grains to be accepted for milling (bread making quality) (Casagrande et al., 2009). Additionally, the inclusion of specific crops such as legume crops are subject to subsidies under the current CAP (Balázs et al., 2021). Ley crops can also be an effective way to increase soil organic carbon benefiting the soil health (Börjesson et al., 2018). Young leys were on average 9 times more frequent as pre-crops in organic than in conventional sequences, with up to 12.5 times more important in Zone 3, where winter wheat is widely cultivated. Oilseed and oats crops were also frequently used as pre-crops, especially in conventional sequences. The potential of oilseeds to break cereal disease and weed cycles in the field adds to the economic benefits of cultivating them with another profitable crop such as winter wheat (Sieling and Christen, 2015).

Spring barley is a fast-maturing cereal crop that does well at high latitudes with short growing seasons. The pre-crop to barley varied significantly more in organic than in conventional sequences except in Zone 5, where the diversity of pre-crops was similar. Even if several management factors are important for spring barley yields and quality (Nkurunziza et al., 2017), our results indicate that pre-crops to spring barley are not carefully selected. Instead, they seem to be a consequence of other priorities, such as the need for a suitable crop for under-sowing of grass and clover in less productive zones and the difficulties associated with autumn-sown crops after late harvested sugar beets in the most productive region.

4.4. Future research uses for LPIS data

The cropping plan on a farm emerges from a dynamic decision-making process (Dury et al., 2013) and the initial plan can change over time (Chongtham et al., 2017). Although it is difficult to predict changes in crop sequences at farm level, LPIS data provide information about crop diversity at large temporal and spatial scales for multiple uses. However, crop distribution and sequence patterns are not the only variables reflecting farming systems and productivity. Our study highlights the importance of the position of crop types in the sequence. A typological approach could be further applied to distinguish more or less diverse crop sequence types (Peltonen-Sainio et al., 2017; Stein and Steinmann, 2018).

In order to better understand variations between productivity zones and farming systems, in future studies LPIS data could be combined with data on livestock production (type and number of animals, reflecting manure availability), crop yields, soil cultivation methods and intensities, type of fertiliser and pesticide use (Chellemi et al., 2013; Nowak et al., 2013; Büchi et al., 2019; Chahal et al., 2021; Karlsson et al., 2022). In organic production, crop choice in the sequence addresses the nitrogen availability in the system which is an especially critical factor for organic farming uptake (Barbieri et al., 2021). Yield quantity and quality, generating the farm income, are critical factors in crop sequence design and need to be the starting point in assessments of crop production at different scales (Watson et al., 2011; Seufert et al., 2012).

Paired with weather data, LPIS data can also reveal farmers' incentives and practical strategies for adapting to climate change (Bane et al., 2021). Geographical areas or specific landscapes with the greatest opportunity for ecosystem service delivery can be identified based on their current cropping patterns (Bohan et al., 2021). All the more, a recent study by Schaak et al. (2023) assesses changes in crop diversity at farm-level in relation to the CAP reforms. Modelling of future scenario perspectives (Lychuk et al., 2021) can help identify the best-suited organic and conventional crop management regime to adapt to climate change in different target zones. Jänicke et al. (2022) confirm that the complexity and heterogeneity of crop sequences can reveal important patterns in regional land use and should be taken into account when developing agricultural policies and strategies.

Nonetheless, access to LPIS data can be restricted with data not always available in the same time and space resolution as in our study. The upcoming use of remote sensing data has proven to accurately detect crop types (Griffiths et al., 2019) and changes in crop sequences (Blickensdörfer et al., 2022) at field level over time.

5. Conclusions

Land Parcel Identification System (LPIS) data were useful to evaluate and compare crop distribution, diversity and crop sequences in organic and conventional agriculture in different productivity zones of Sweden. For a 10-year period the crops grown on specific land parcels (field or part of a field) could be followed for 40% of the arable land of the country.

Farming systems in Sweden were dominated by small-grain cereals in the high productivity zones and ley crops in the less productive zones. Farmers relied on an average of 4.2 crop types over the 10-year study period, with higher diversity (4.6) in the most productive areas and lower diversity (3.4) in less productive zones. Organic farms used a slightly higher number of crop types, including nitrogen-fixing crops such as grass/clover leys and grain legumes than conventional farms where cereals, particularly winter wheat, dominated. Spring barley was rather well distributed among productivity zones and grown similarly in both organic and conventional sequences. Pre-crops to winter wheat were usually of a different crop type, particularly leguminous crops in organic sequences, while spring barley was more often grown after another cereal crop.

The diversity and patterns of crop sequences found in the present study provide information on how crop sequences are used by farmers to optimise their production. This is information that cannot easily come out of national agricultural statistics. Farmers' motives are not investigated in the present study, but they are probably diverse. Choice of crop sequence is a flexible decision as reflected in a variation in number of crop types in the sequences and the years between the same crops among farms driven by farmers' knowledge and experience, taking numerous bio-physical and socio-economic conditions into account. By combining data from LPIS with other databases, it is possible to answer a number of questions that relate to land-use and cropping patterns at field, farm and landscape scales.

CRediT authorship contribution statement

Rafaelle Reumaux: Conceptualization, Methodology, Sofware, Validation, Vizualization, Investigation, Writing – original draft, Writing – review & editing, Formal analysis, Resources, Investigation, **Pierre Chopin:** Data Curation, Conceptualization, Software, Formal analysis, Validation, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing, **Göran Bergkvist:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Resources, Supervision, **Christine A. Watson:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Resources, Supervision, **Ingrid Öborn:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Resources, Supervision, Funding acquisition, Project administration.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126916.

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Supplementary Material, Paper I

Table S1 Number of hectares from our database of organic and conventional fields in the whole of Sweden and number of hectares in the original LPIS data (2014). The total number of hectares in our database corresponds to the sum of the organic and conventional fields. This corresponds to 631,835 fields representing in total 1,313,857 ha. For our final dataset, for the analysis of crop sequences, we removed fields registered as grassland (71869 fields, 149,816 ha) and fields that were strictly considered as grassland on non-arable land (210,075 fields, 276,263 ha, which have not been ploughed during the 10 year period). As a result we obtained 349,891 fields representing 887,777 ha for the whole Sweden.

	Our database					**All LPIS block data (2014)**
				In total hectares		
	Organic (ha)	**Conventional (ha)**	**Total hectares**	**Percentage of organic fields**	**Percentage of conventional fields**	**Total hectares**
Whole of Sweden	200,501	1,113,355	1,313,857	15	85	3,230,153
Productivity zone 1	7,128	92,594	99,722	7	93	304,706
Productivity zone 2	11,91	109,21	121,12	10	90	292,379
Productivity zone 3	68,589	431,999	500,588	14	86	1,195,712
Productivity zone 4	55,395	246,856	302,251	18	82	735,416
Productivity zone 5	57,478	232,694	290,172	20	80	701,923

Table S2. Details of crop types and their codes in groupings G94, G28 and G19. Crops were grouped depending on "agronomic family type" (see Table 1 in main file)

Code	Code name	Group G94	Group G19
-1	Missing data	OTHE	OTHE
1	Winter barley	WBAR	WBAR
2	Spring barley	SBAR	SBAR
3	Oats	OATS	OATS
4	Winter wheat	WWHE	WWHE
5	Spring wheat	SWHE	SWHE
6	Mix of forage legumes or clover	OALE	OTHE
7	Winter triticale	STRI	TRIT
8	Rye	RYEE	RYEE
9	Maize	MAIZ	OTHE
10	Buckwheat	SARA	OTHE
11	Cereal experiments	CERE	OTHE
12	Mix of cereals	MIXC	MIXT
13	Mix of cereals (>50%) and legumes	MIXL	MIXT
14	Canaryseed	KANA	OTHE
15	Millet	HIRS	OTHE
16	Cereal grains used for animal feed	ENSI	OTHE
17	Biodiversity conservation plot	ENV	OTHE
18	Pasture	PAS1	PAST
19	No crop	OTHE	OTHE
20	Winter oilseed rape	WOSR	WOSR
21	Spring oilseed	SRAP	SRAP

22	Winter turnip rape	WNAV	WOSR
23	Spring turnip	SNAV	SRAP
24	Sunflower	SUNF	OTHE
25	Oilseed experiments	OILR	WOSR
26	Oilseed rape with high erucic acid content	OILM	WOSR
27	White mustard	MOUT	OTHE
28	Oil radish	RADI	OTHE
29	Spring triticale	WTRI	TRIT
30	Peas (not for freezing)	PEAF	PEAS
31	Peas for freezing and other types of preservation	PEAC	PEAS
32	Faba bean	BEAN	BEAN
33	Narrowleaf lupin	LUPI	OTHE
34	Mixed protein crops (pulses/cereal)	MILE	MIXT
35	Common bean	BBEA	BEAN
36	Vetch	VESC	OTHE
37	Chickpea	CHIC	OTHE
38	Soybean (for oil)	SOJH	OTHE
39	Soybean (for animal feed)	SOJA	OTHE
40	Linseed (for oil)	LINO	OTHE
41	Common linseed	LINV	OTHE
42	Hemp	HEMP	OTHE
43	Other beans	OBEA	BEAN
44	Potato	POTA	POTA
45	Potato (table)	POTF	POTA
46	Potato (industrial)	POTS	POTA
47	Sugar beet	SBEE	SBEE
48	Fodder beet	FBEE	OTHE
49	Ley and cultivated grass on arable land with a ley crop not approved for agri-environmental payments	LEY1	LEYS
50	Ley and cultivated grass on arable land	LEY2	LEYS
51	Ley and cultivated grass on arable land not approved for agri-environmental payments	LEY3	LEYS
52	Pasture (non-arable land)	PAS2	PAST

53	Meadow (non-arable land)	LEY4	LEYS
54	Forest grazing	PAS3	PAST
55	Mountain pasture not entitled to farm and compensation payments	PAS4	PAST
56	Strand grazing on islands	PAS5	PAST
57	Ley on arable land (contract with forage drying facility)	LEY5	LEYS
58	Grass seeds for ley (annual)	LEY6	LEYS
59	Grass seeds for ley (perennial)	LEY7	LEYS
60	Fallow	FALL	FALL
61	Mountain pasture entitled to farm and compensation payments	PAS6	PAST
62	Clover seed	PAS7	OTHE
63	Reed canarygrass (energy production)	FROS	LEYS
64	Reed canarygrass (for other uses)	FROT	LEYS
65	Willow	SALI	OTHE
66	Adjusted protected areas (buffer zones)	BAND	OTHE
67	Poplar	POPP	OTHE
68	Hybrid aspen	PEUP	OTHE
69	Biodiverse fallow	MANG	FALL
70	Strawberry	JORD	OTHE
71	Other berry production	BERR	OTHE
72	Fruit production	FRUI	OTHE
73	No crop	OTHE	OTHE
74	Vegetable	VEGE	OTHE
75	No crop	OTHE	OTHE
76	No crop	OTHE	OTHE
77	Buffer zone	BANT	OTHE
78	Nursery with production of permanent crops	TREE	OTHE
79	Aromatic plants and vegetable seeds	LEG2	OTHE
80	Green fodder	GREF	LEYS
81	Green manure	GRE2	LEYS
82	Wetlands	POND	OTHE

83	Christmas tree production	JULT	OTHE
84	Tree plantation on arable land	SKOG	OTHE
85	Horticulture (not including vegetables, fruits or berries)	GARD	OTHE
86	Crop not eligible for single payment scheme (only certified organic/ recycling agriculture)	MEK1	OTHE
87	Other crop eligible for single payment scheme (only certified organic/recycling agriculture)	MEK2	OTHE
88	Other land use on arable land	OTHE	OTHE
89	Mosaic pasture	PAS8	PAST
90	Land poor in grass species	PAS9	PAST
91	Non-approved crop arable land	OTHE	OTHE
92	Non-approved pasture	PA10	PAST
93	Non-approved crop on non-arable land	OTHE	OTHE
94	No crop	OTHE	OTHE
95	Pasture and meadow under restoration	PA11	PAST
96	Mosaic pasture and other land poor in grass species	PA12	PAST
97	Pasture non-eligible for compensation	PA13	PAST

Table S3. Summary of statistics for the randomisation test on crop type diversity and exponential Shannon indices between organic and conventional sequences in productivity zones 1 to 5.

	Difference between organic and conventional crop sequences			
	Crop type diversity means		**Exponential Shannon index**	
Productivity zone	**Z**	**p-value**	**Z**	**p-value**
1	-6.473	< 0.001***	-7.4724	< 0.001***
2	-10.67	< 0.001***	-14.038	< 0.001***
3	-4.5801	< 0.001***	-2.8785	0.0037**
4	-2.1987	0.02884*	0.90379	0.3669
5	-3.331	< 0.001***	2.2426	0.02578*

Table S4. Average percentages during the 9 years of the different pre-crop types to winter wheat and spring barley in organic and conventional farming systems in the different productivity zones.

			Average proportion of preceding crop type (%)										
Focus crop	**Production**	**Productivity zone**	**Fallow**	**Grain legumes**	**Mixed cereal and legumes**	**Oats**	**Oilseed rape**	**Old ley and pastures**	**Others**	**Roots and tubers**	**Spring cereals**	**Winter cereals**	**Young leys**
Winter wheat	**Conventional**	**1**	2	7	0	4	28	1	3	3	18	32	2
		2	5	5	0	17	20	2	4	1	14	32	1
		3	6	5	0	14	21	4	1	2	20	25	2
		4	9	4	1	17	13	11	1	1	21	22	2
		5	10	1	1	19	8	25	0	0	23	10	4
	Organic	**1**	4	19	0	6	11	13	1	2	5	25	15
		2	12	16	1	11	8	12	0	0	5	10	26
		3	12	9	3	10	6	18	0	0	6	11	25
		4	7	10	4	10	7	26	0	0	9	8	19
		5	7	9	3	16	0	40	1	0	3	3	18
Spring barley	**Conventional**	**1**	1	1	0	1	1	1	2	32	18	43	1
		2	2	2	1	10	4	1	2	4	29	46	1
		3	2	1	1	16	4	4	1	4	35	31	1
		4	3	1	1	20	4	11	1	1	40	17	2
		5	3	0	1	10	1	29	0	1	48	3	4
	Organic	**1**	1	12	2	6	1	8	3	2	23	37	6
		2	4	10	2	16	3	5	1	0	20	31	6
		3	3	6	4	15	2	18	1	1	21	21	8
		4	3	4	5	17	2	25	1	0	25	11	8
		5	2	1	3	8	0	48	0	0	28	2	6