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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

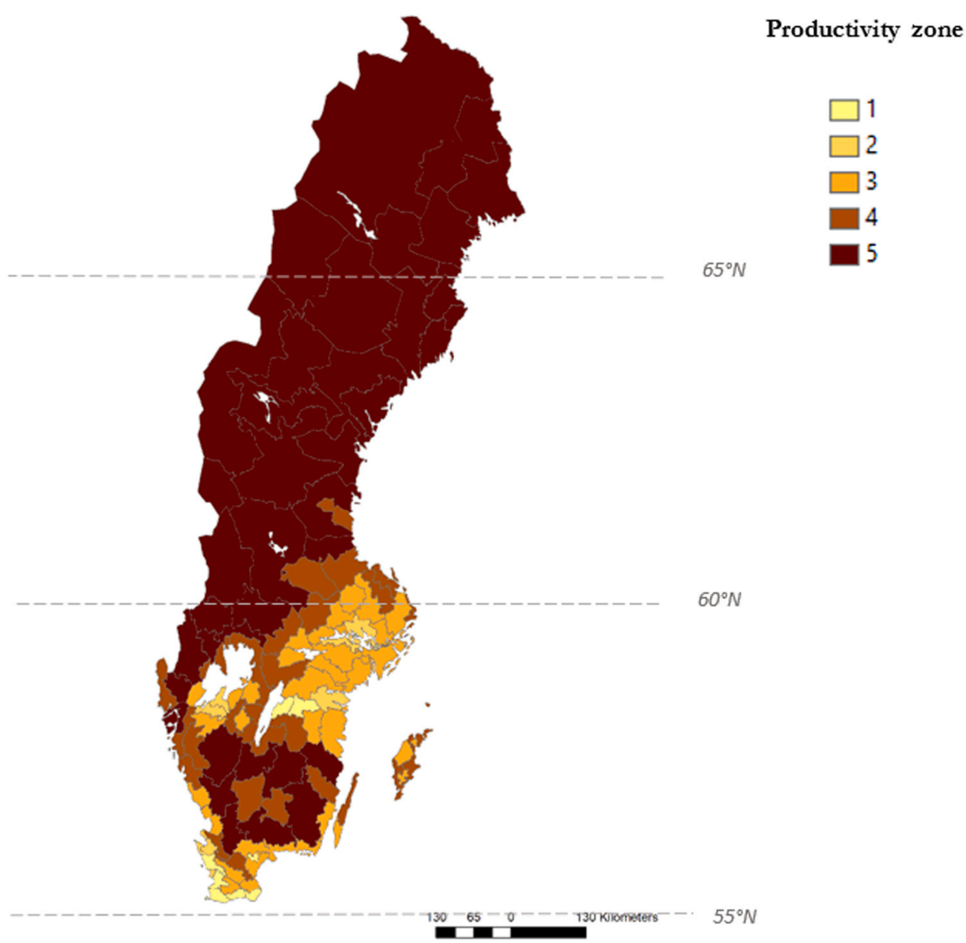


Fig. 1. Location of different productivity zones in Sweden (1 = most productive, 5 = least productive) used as a basis in this study. The number of hectares per productivity zone that is available from our LPIS database can be seen in Supplementary Material Table S2.
Source: (Swedish Board of Agriculture,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

$$n = \Sigma g \quad (1)$$

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).

$$H' = \exp(-\Sigma pi * \ln(pi)) \quad (2)$$

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

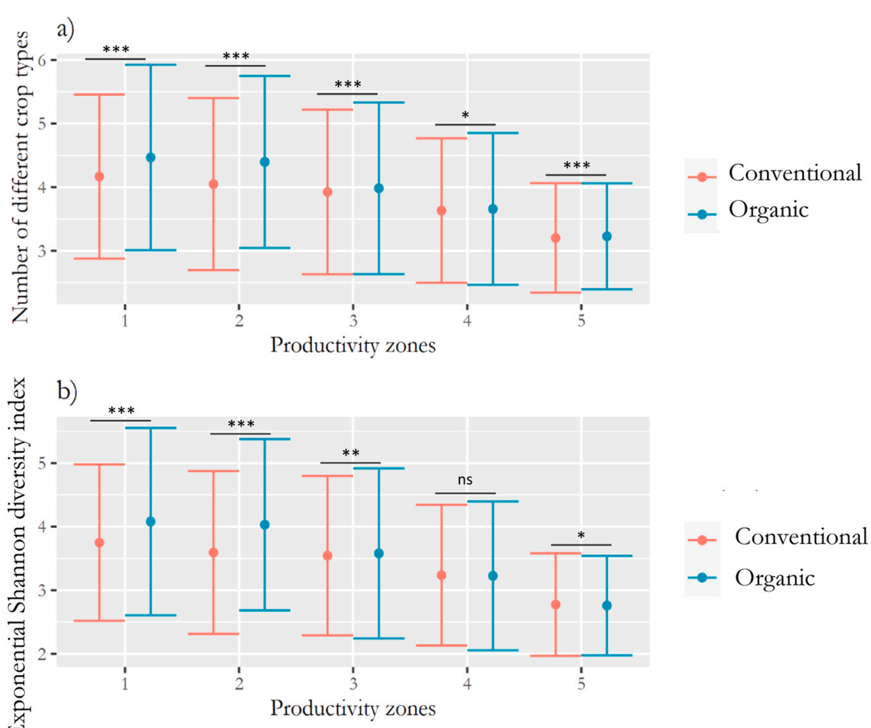


Fig. 2. Average crop diversity (G19 grouping, see Table 1) in conventional and organic farming systems in productivity zone 1–5 (most to least productive). Two diversity indexes are used, values shown are average a) crop type diversity, and b) exponential Shannon diversity index. Error bars represent 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)**.

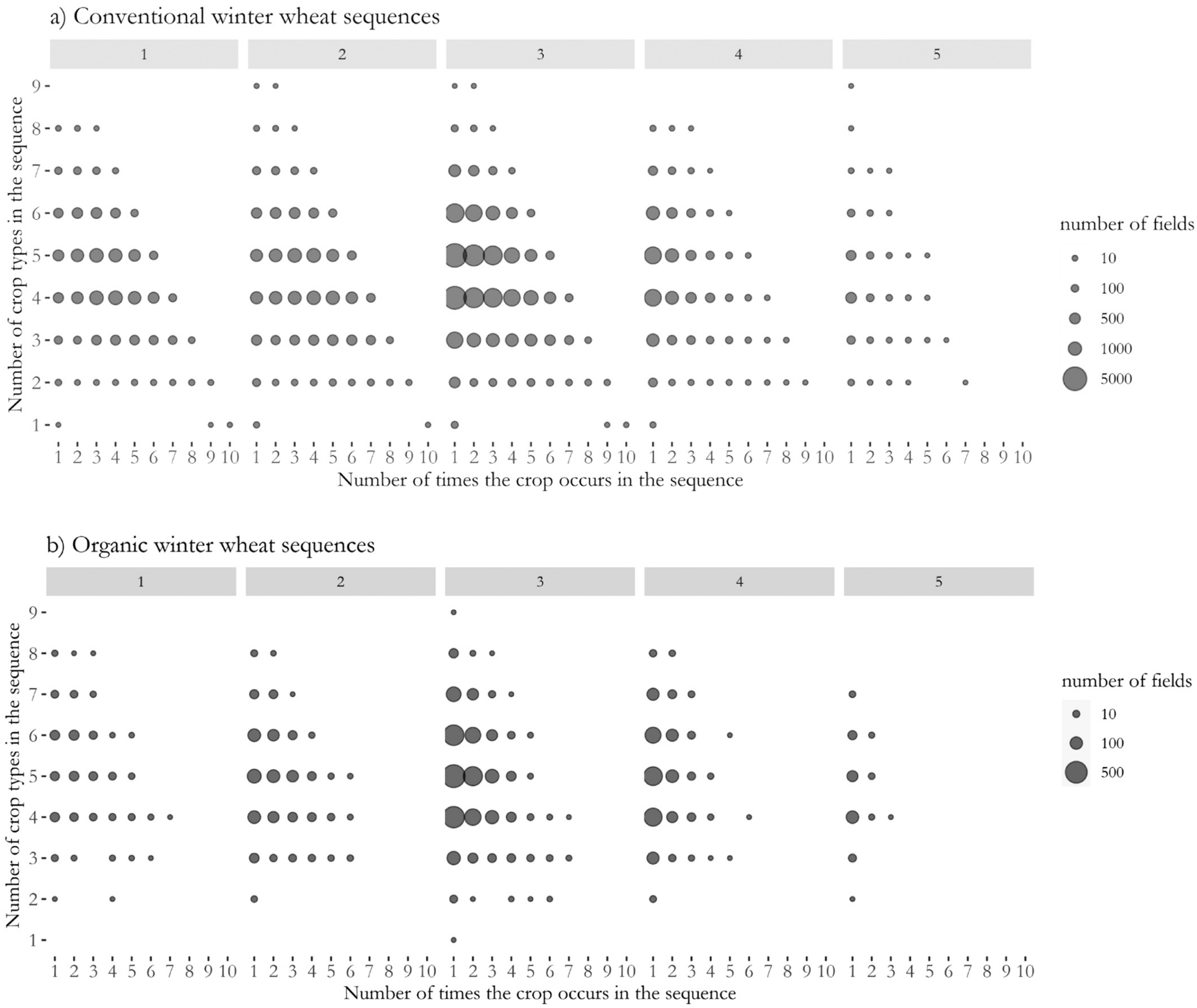


Fig. 3. Crop type diversity (y-axis) and intensity of winter wheat (a, b) or spring barley (c, d) production (x-axis) in (a, c) conventional and (b, d) organic systems in productivity zones 1–5. The intensity is shown as the number of times the winter wheat or spring barley crop occurs in the 10-year 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

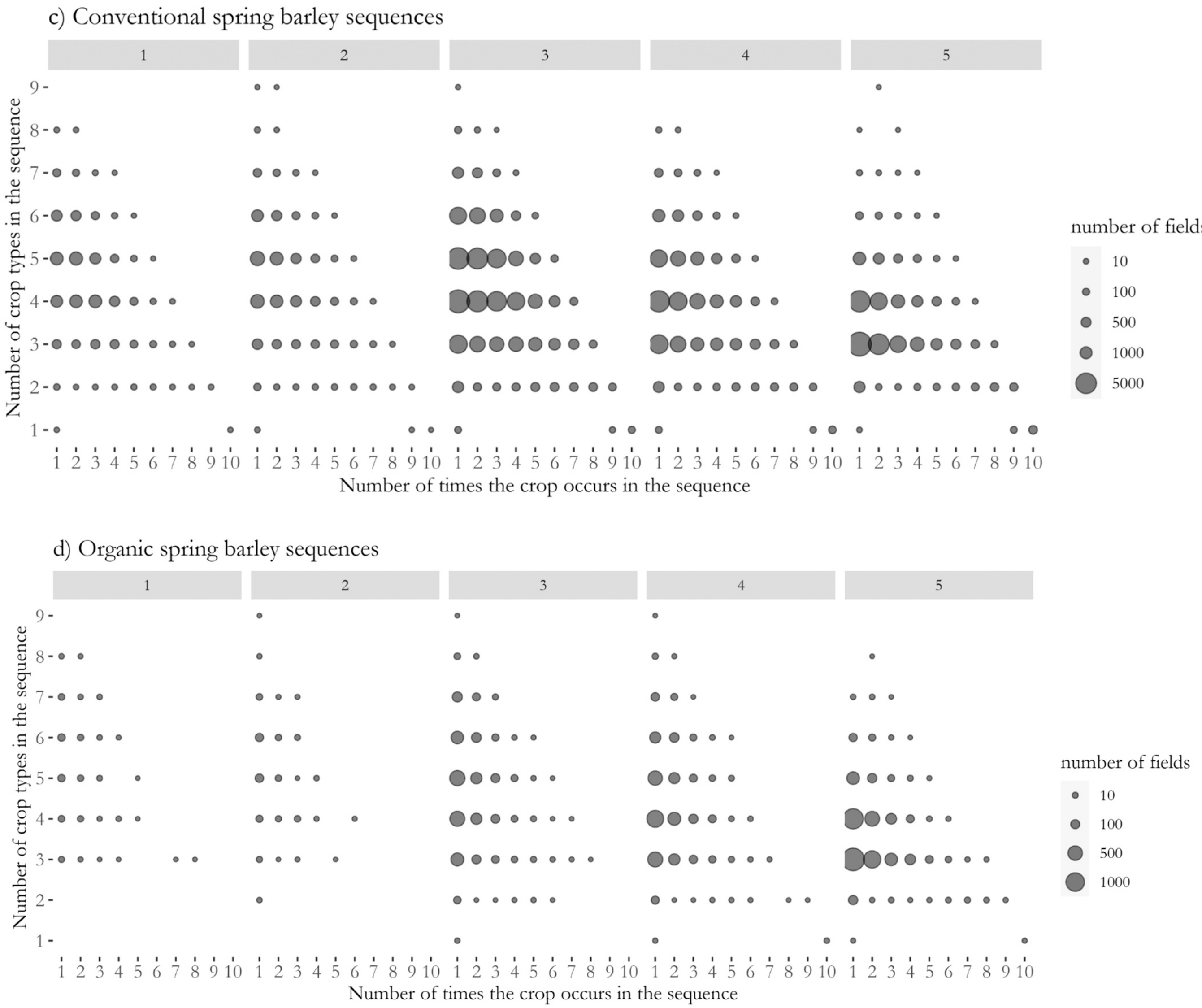


Fig. 3. (*continued*).

(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

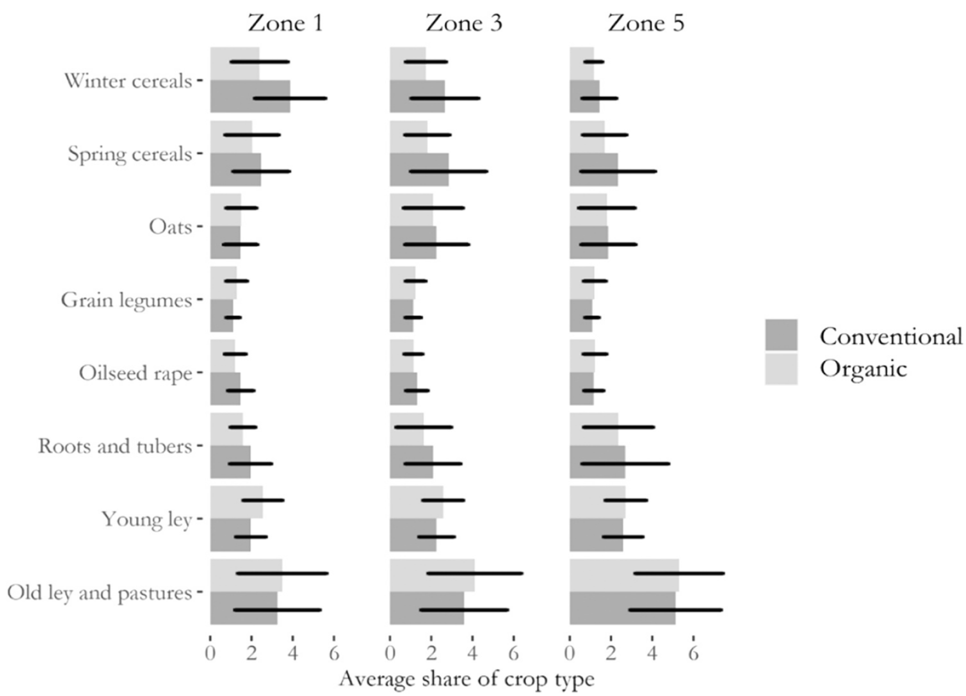


Fig. 4. Average number of times winter and spring cereals, spring oats, grain legumes, oilseed rape, roots and tubers, young ley, old ley and pastures are grown in sequences in which they actually occurred in conventional and organic sequences in the high (1), medium (3) and low (5) productivity zones 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).

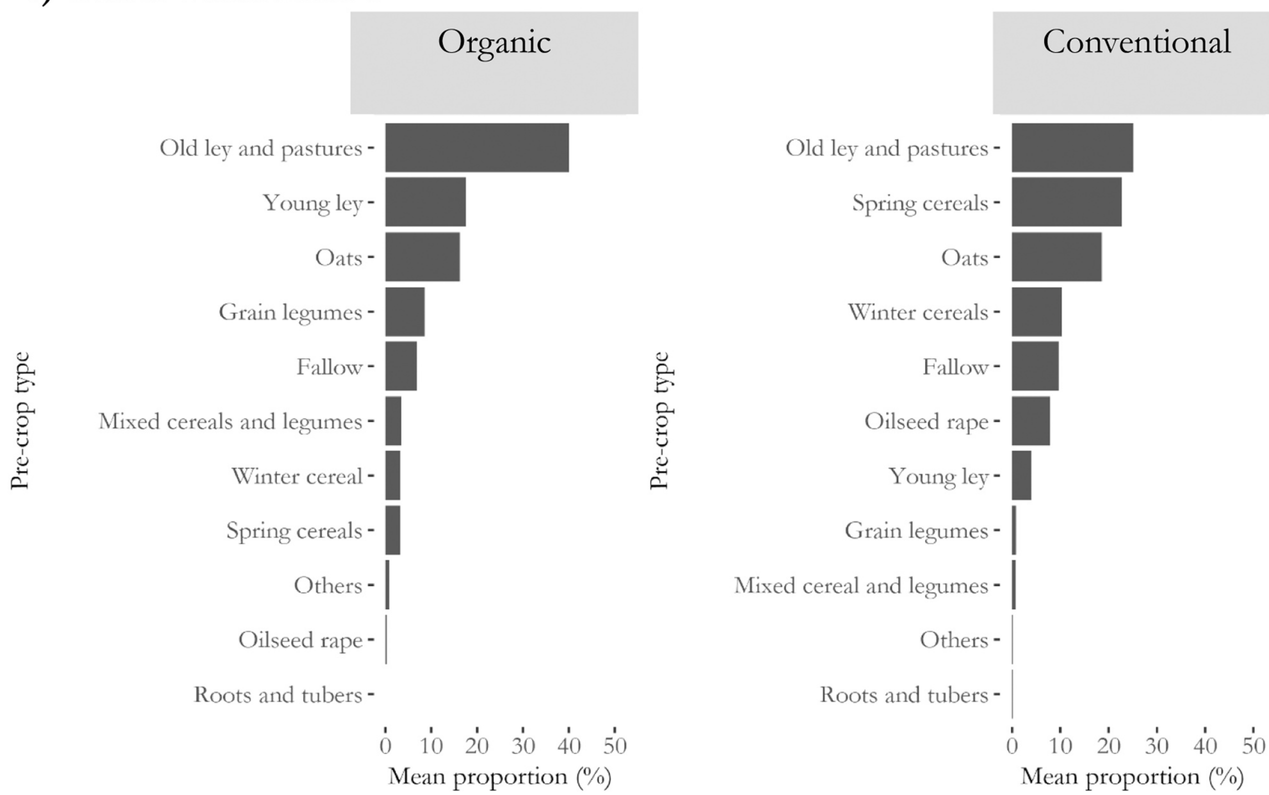
4.2. Crop sequence diversity and shares of crop types vary between organic and conventional systems

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

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

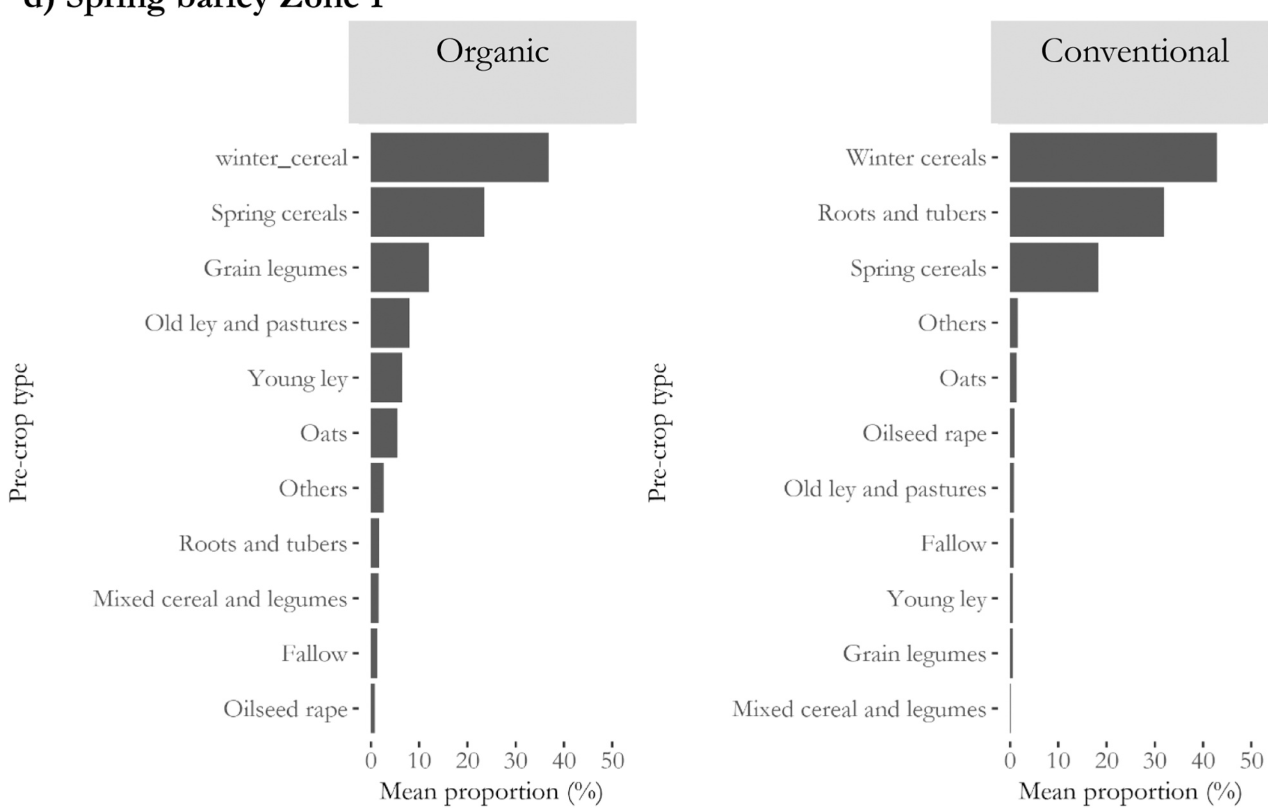


Fig. 5. (*continued*).

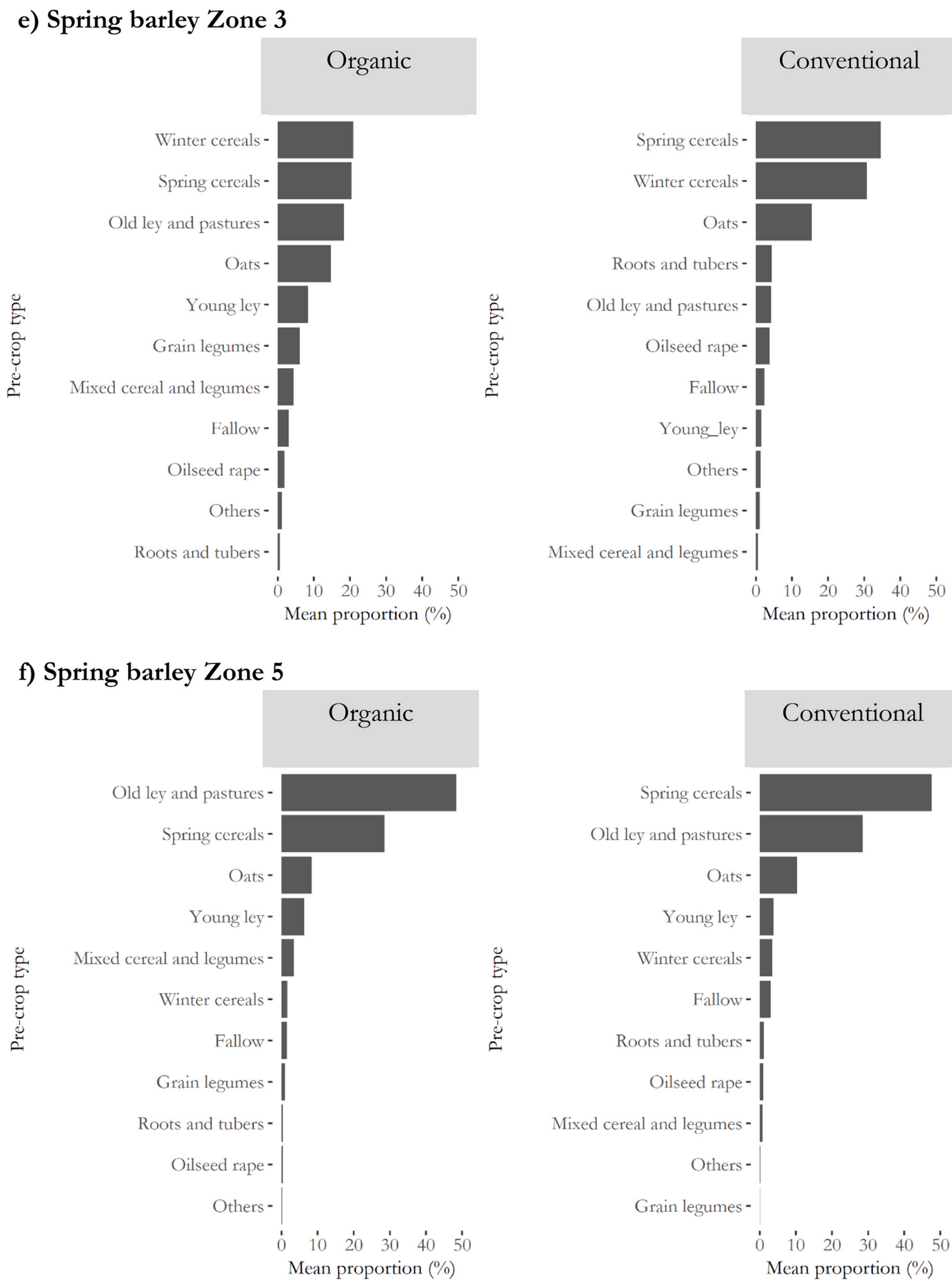


Fig. 5. (*continued*).

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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