

Research Paper

Characterizing implementers of on-going large-scale diversification of land use in Finland – One of the northernmost agricultural regions in Europe

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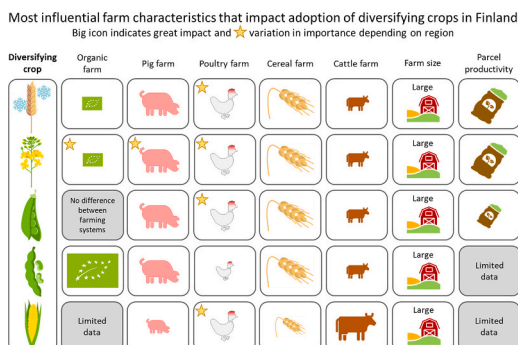
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HIGHLIGHTS

- Climate warming and established markets have enabled diversification in Finland.
- Implementers and allocation of six diversifying crops were characterized in three timesteps.
- Area on winter wheat and peas has expanded, faba bean stagnated, and oilseed rape declined.
- Diversifying crops were mostly adopted on pig, poultry and cereals farms.
- Novel crops were mainly grown on larger parcels.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Finland is one of the northernmost crop production regions in Europe, where monotonously sequenced spring cereals and grasslands dominate the agricultural land use. Climate warming has, however, enabled diversification supported by established markets and adapted cultivars.

Objective: This study focused on six diversifying crops: winter wheat, oilseed rape, peas, faba beans, maize, and oil hemp. The aims were to characterize recent changes in cultivation intensity and their likely drivers, identify implementers, understand how the novel crops were allocated on farms, and whether all these varied over time.

Methods: We used farm- and parcel scale-data from Finnish Food Authority to study the number of parcels allocated to diversifying crops in grid cells of 10 × 10 km across Finland and to characterize implementers and allocation of crops on a farm on three regions in 2011, 2016 and 2021. Sentinel-2 satellite images were used to estimate productivity gaps.

Results and conclusion: The cultivation area of diversifying crops has substantially increased but plenty of unexploited potential still exists. The area of winter wheat and peas has continued to expand compared with 2016. Due to the challenge of climate resilience, the area of faba bean has stagnated, while oilseed rape has declined also due to a high pest risk. Oil hemp and silage maize are very novel crops with growing interest, cultivated in small, scattered areas. Farmers who had large farms and produced pigs, poultry, and cereals were key implementers of diversifying crops, which were typically allocated to large parcels. The farm types of primary adopters of different crops varied slightly over time, but not how crops were allocated on a farm, depending on parcel

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characteristics. Winter wheat was adopted especially by conventional farmers, who allocated it to highly productive parcels with break-crop and diverse rotations. Organic farmers especially implemented faba beans more frequently, as well as peas, but this was not the case in 2021. Pig farmers have adopted grain legumes likely to substitute for imported soya. In 2011, implementers of oilseed rape had typically a high cereal share on farms, while in 2021, adoption was independent of cereal share. Oilseed rape was favored by conventional farmers, who allocated it to highly productive parcels likely to avoid problems with root penetration.

Significance: This study gives examples of how large-scale adoption routes may differ, depending on the crop, and indicates sensitivity to external factors that either motivate or hinder transition despite warmer northern climates, established markets, and adapted cultivars.

1. Introduction

Finland is one of the northernmost agricultural regions in Europe, with an agricultural area of ca. 2.5 million hectares, which corresponds to 7 % of the total land area. In Sweden, some 90 % and in Norway about half of agricultural land is at lower latitudes (<60°N) than in Finland. Such a northern location sets many limits for the availability of sufficiently adapted crop species but especially for the cultivation of overwintering types grown elsewhere in Europe, e.g., oats (*Avena sativa* L.) and barley (*Hordeum vulgare* L.) (Farkas et al., 2021; Howarth et al., 2021; Wójcik-Jagła and Rapacz, 2023), turnip rape (*Brassica rapa* L.) and oilseed rape (*B. napus* L.) (together rapeseed) (Rapacz and Markowski, 1999; Andert et al., 2021), and faba beans (*Vicia faba* L.) and peas (*Lathyrus oleraceus* Lam.) (together grain legumes) (Mikić et al., 2011; Castel et al., 2017; Falconnier et al., 2020; Carrillo-Perdomo et al., 2022). The climate is warming more quickly at higher latitudes (Ceglar et al., 2019; Ruosteenoja et al., 2019), with various advantages and disadvantages for agricultural production. Some have already materialized, such as higher accumulated temperature sums during the thermal growing season (Ceglar et al., 2019; Ruosteenoja et al., 2019; Peltonen-Sainio and Jauhiainen, 2020). Farmers have therefore started sowings a couple of weeks earlier than some decades ago (Kaukoranta and Hakala, 2008; Peltonen-Sainio and Jauhiainen, 2014; Zhao et al., 2020). They have also expanded cultivation areas of many minor crops, adopted novel crops, and introduced them to new regions (Peltonen-Sainio and Jauhiainen, 2020). However, weather constraints, especially warm spells with longer and severer droughts, have been experienced by farmers more frequently during recent growing seasons. A manifold increase in heat wave days (i.e., the number of days with the mean temperature above the 90th percentile of the frequency distribution of June–August in 1961–2000) is projected for future growing seasons (Ruosteenoja and Jylhä, 2023).

The cultivation areas of the main arable crops have varied considerably during the last one hundred years (Fig. 1) but since around the year 2000 for the first time as a response to the changing climate (Peltonen-Sainio and Jauhiainen, 2020). The only exception is from the 1930s, when exceptionally warm conditions encouraged Finnish farmers to grow spring wheat (*Triticum aestivum* L.) at exceptionally high latitudes (Mukula et al., 1977). Oats especially, but also winter rye (*Secale cereale* L.), were the dominant arable crops in the early 20th century, but they were gradually replaced by barley, which became the most common crop from the early 1970s. Peas and faba beans were cultivated as nitrogen (N) fixing crops on 10 to 15 thousand hectares until chemical fertilizers were adopted after the middle of the century (Trnka et al., 2016). Their production area fell to approximately one tenth of the area in the preceding decades and remained there until their cropping areas started to increase in the 2010s, reaching >40,000 ha. today. Winter turnip rape was a novel crop introduced in the 1950s in Finland (Mäkelä et al., 2011), but only in the 1970s, when spring turnip rape and to a smaller extent spring oilseed rape were introduced, these oil crops obtained permanent minor crop roles (Fig. 1). However, in the 2010s, cropping areas halved despite high demand, due mostly to yield declines following repeated challenges caused by pests, diseases, and elevated temperatures that shortened the flowering and fruiting period

(Peltonen-Sainio et al., 2007). Turnip rape has been gradually replaced by oilseed rape in Finland's prime rapeseed production regions, but turnip rape has maintained its role as a pioneer crop, with cultivation expanding to new regions (Peltonen-Sainio and Jauhiainen, 2020).

As during the last one hundred years, cereals still dominate agricultural landscapes in Finland (Fig. 1). However, the total calories and macronutrient production of the main arable crops (Cassidy et al., 2013) steadily increased, with the only exceptions being during the war in the 1940s and again in the 2010s (Fig. 2). The dip in the trend since about 2000 is probably attributable to a switch in crops and changes in

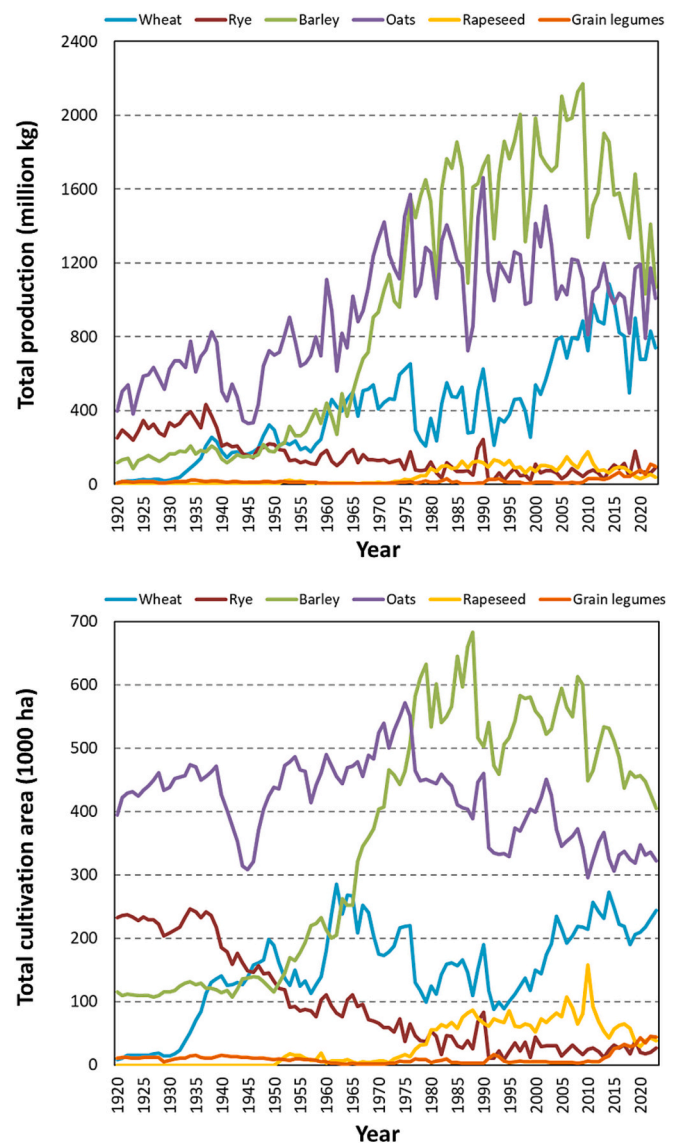


Fig. 1. Total production and cultivation areas of the most common grain crops (cereals, rapeseed, and grain legumes) in Finland since 1920.

cultivation areas as well as challenging weather conditions, i.e., severer, longer-lasting droughts, coupled with elevated temperatures. The diversification of crop rotations and land use may improve climate resilience both directly and indirectly (Abson et al., 2013; Degani et al., 2019; Dardonville et al., 2020; Nelson et al., 2022). Despite the current cereal domination and the first encouraging trends in more diverse land use (Peltonen-Sainio and Jauhiainen, 2020), there is substantial potential for diversification given farmers' preferences for land allocation to different crops, depending on farm and field characteristics (Peltonen-Sainio and Jauhiainen, 2019). Nor should be forgotten the need for existing markets, profitability, and capacities to replace, e.g., imported soya [*Glycine max* (L.) Merr.] with domestic protein crops in the EU (Karges et al., 2022; van Loon et al., 2023; Notz et al., 2023).

The diversification of agricultural land and crop sequences, e.g., by using diverse crop choices, genetically diverse cultivars, cereal mixtures, intercropping, intermediate crops, and cover crops, is a multifunctional key measure of regenerative agriculture (EASAC, 2022). It is therefore also recognized in the Farm to Fork, Biodiversity, and Soil Strategies of the European Union (EU), and progress has been made in adopting different diversification measures. A recent study indicated that the cultivation of many diversifying crops has expanded in their original production regions and has been introduced to novel regions since 1996, when Finland joined the EU (Peltonen-Sainio and Jauhiainen, 2020). It is likely that novel crops have replaced monotonously sequenced barley and oats (Peltonen-Sainio and Jauhiainen, 2019), especially since their entry to northern and inland virgin production regions. Despite quite systematic changes, some retreat may also have occurred, e.g., due to challenges with profitability, weather constraints, a lack of experience in the cultivation of novel crops, and pest and disease infestations.

This study updates previously published data on land-use changes (Peltonen-Sainio and Jauhiainen, 2020) to include the most recent five-year step. The work focused on six diversifying crops, winter wheat, oilseed rape, peas, faba beans, maize (*Zea mays* L.), and oil hemp (*Cannabis sativa* L.), representing winter crops, oil crops, protein crops, and/or very novel crops with recently recognized shifts in cultivation intensity. If not stated otherwise, the crops were grown as spring types. The aim of this study was: 1) to identify the implementers; 2) understand

how novel crops were allocated, depending on farm and field parcel characteristics; and 3) whether implementers and allocation patterns varied over time with a focus on years 2011, 2016, and 2021. Understanding the possible evolution in the adoption of diversifying crops is valuable when supporting farmers other than those characterized as implementers – and likewise when acknowledging the potential barriers to change on certain farms.

2. Material and methods

First, the changes in cropping intensities published by Peltonen-Sainio and Jauhiainen (2020) were updated with data from 2021. The focus was on four common (oilseed rape, peas, faba beans, and winter wheat) and two very novel (maize and oil hemp) diversifying crops. All crops have a specific use and/or markets. They have good opportunities for further cultivation expansion, but they also differ in potential constraints that may limit the shifts in area or produce a downward trend. The official data from the Finnish Food Authority (FFA) were used to analyze spatiotemporal shifts in crop areas. The data contained more than one million field parcels in a year and were analyzed in five-year steps (2011, 2016, and 2021). To make sure that these years did not differ from the general trend of changes in cultivation intensities, similar maps were produced between the study years. The data included information about all parcels (owned and leased) in use on each farm as well as the parcel coordinates and crop(s) grown in each parcel. The parcels were first classified in grid cells of 10×10 km across Finland. These grid cells were used to identify regional differences in cultivation intensity of each studied diversifying crop. The number of parcels for each crop in a grid cell was categorized as 1–9, 10–19, 20–39, 40–79, 80–160, and > 160 . The total number of parcels in a grid cell varied, depending on the shares of agricultural and forest land, and was thus largest in the southern and southwestern regions, and lowest in the inland, eastern, and northern regions (Peltonen-Sainio et al., 2017).

In the next phase, both the adopters and the allocation of the diversifying crops on a farm were characterized in the three primary agricultural regions (Figs. 3 and S1), the southeast, southwest, and northwest. The regions were selected because they had the highest

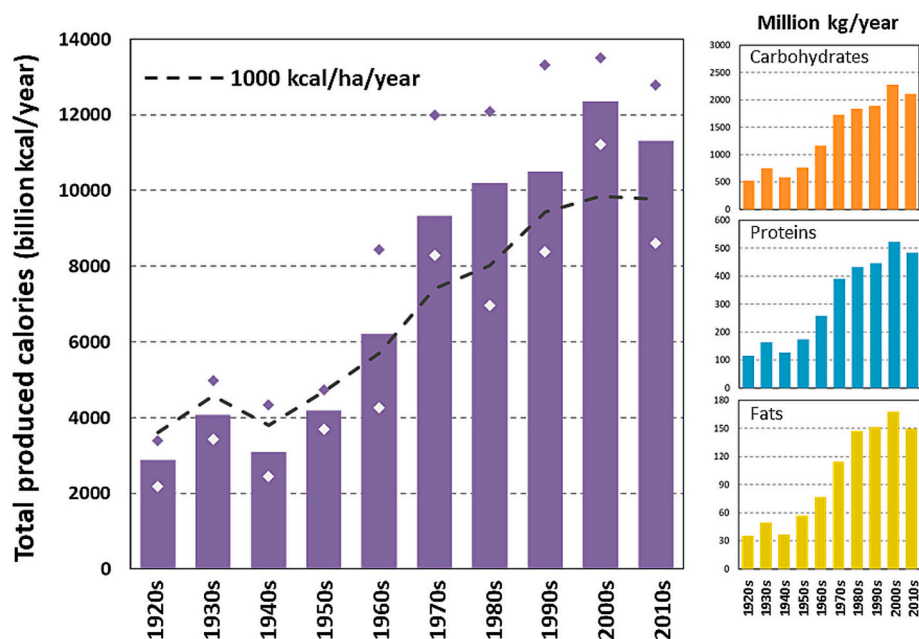


Fig. 2. Total decadal means for the produced calories of grain crops (cereals, rapeseed, and grain legumes) in Finland since the 1920s (left panel), with minimum (unfilled square) and maximum year (filled square) in each decade. The decadal mean calories per hectare per year are shown with a dashed line (data from <https://www.luke.fi/en/luonnonvaratiето/science-and-information/finnish-feed-tables-and-nutrient-requirements>). The right small panels show the decadal means for produced macronutrients per year since the 1920s.

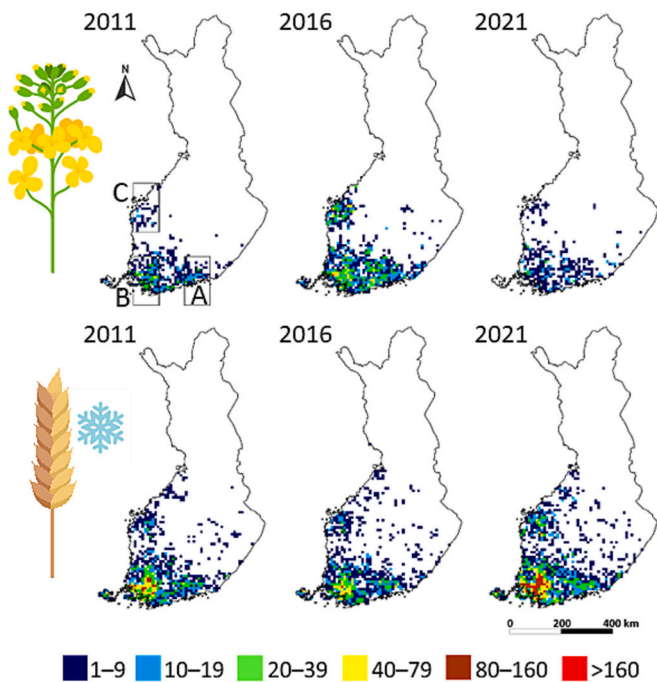


Fig. 3. Number of parcels of oilseed rape and winter wheat shown in grid cells of 10×10 km in 2011, 2016, and 2021. The three specific study regions in the southeast (A), southwest (B), and northwest (C) are framed for the map of oilseed rape in 2011 (up in the lefthand side).

adoption intensity of these six diversifying crops. The official farm-scale data from FFA for each study region included: 1) farm size (<30, 30–49, 50–99, 100–149, and ≥ 150 ha); 2) farming system (organic and conventional); and 3) farm type (cereal, cattle, pig, poultry, and other farms, including horticulture and horse and sheep farms).

Based on the FFA data, field parcel characteristics were grouped as: 1) parcel size (<0.5, 0.5–0.99, 1.0–2.49, and ≥ 2.5 ha) and 2) the calculated distance from the parcel center to the farm center (<300 m, 300–599, 600–1199, 1200–2499, 2500–4999, and ≥ 5000 m). Furthermore, the dominant soil type in each parcel was grouped according to Lilja et al. (2006) (coarse mineral soils like *Haplic Podzol 1* and 2, clay soils 1 of *Vertic Cambisol*, clay soils 2, including *Eutric Cambisol*, *Gleyic Cambisol*, and *Gleysols*, and organic soils, including *Fibric/Terric Histosol 1* and 2 and *Dystric Gleysol*).

Land use was characterized as: 1) the share of a farm's cereal area (<25 %, 25–50 %, and ≥ 50 %); 2) the share of a farm's special crop area including turnip rape, oilseed rape and grain legumes (0 %, 0.1–10 %, and > 10 %); 3) the share of a farm's grassland area (<25 %, 25–50 %, and ≥ 50 %); 4) the share of a farm's tuber and root crops [potatoes (*Solanum tuberosum* L.) and sugar beet (*Beta vulgaris* var. *altissima* L.)] area (<25 %, 25–50 %, and ≥ 50 %); 5) the crop rotation used in a parcel in 2014–2018 [monospecies cereal sequence (the same cereal species at least four times during the five successive years), multispecies cereal sequence (various cereals), break crop rotation (four years of cereals and one break crop), diverse rotation (three years of cereals and two break crops), green fallow rotation (at least three years of green fallow), grassland rotation (at least three years of grassland), and any other crop sequence patterns not meeting the requirements set for the previous rotations]; 6) the parcel's productivity gap [no gap, i.e., set as 0 %, when compared with the best 10 % of parcels in the same region (data available in northwestern Finland only, Fig. S1), <20 %, 20–29 %, 30–39 %, and ≥ 40 %]; and 7) the variation between years in a productivity gap (<10 %, 10–14.9 %, 15–19.9 %, and ≥ 20 %). If the crop rotation could not be determined, the parcel was not included in the analysis: e.g., when two parcels were combined into one parcel during the study period, or the parcel was divided to sub-parcels (called

agricultural parcels) differing in crop and none of these crops dominated with a share ≥ 70 % of field area. The productivity gap was determined from timeseries data of Sentinel 2 satellite images of individual parcels by calculating the Normalized Difference Vegetation Index (NDVI) values during the growing season and comparing them with the NDVI value of other parcels in the same region with the same crop. If the parcel was in the top 10 %, the gap was set to 0 % (Peltonen-Sainio et al., 2019a). Parcel-specific data to estimate the productivity gap and variation between years in the gap (2017–2020) were only available for 2021 in northwestern Finland.

The results were presented as an under- or overrepresentation of each crop in categories of fields with certain attributes such as size, productivity and so on. The values were calculated separately for each region and year. For example, if 2.0 % of the parcels in the region were less than 0.5 ha in size, but 0.5 % of the oilseed parcels were allocated to such parcels, the value was 0.5 % divided by 2.0 %, resulting in an underrepresentation of 0.25. Respectively, value exceeding 1.00 indicates overrepresentation of parcels allocated to a diversifying crop. These estimated values do not require the use of any statistical program. However, in some cases the observed difference in estimates was so small that the difference might be a mere coincidence. Therefore, the differences also had to be compared statistically. The over-/underrepresentation parameter is difficult to test, because there is no formal test for it. On the other hand, logistic regression is suitable for this kind of binomial data, but it gives a different statistic, the odds ratio, which is slightly different from the overrepresentation parameter but is still closely related to it. In the example above, the odds ratio is $(0.5 \% / (100 \% - 0.5 \%)) / 2 \% / (100 \% - 2 \%) = 0.246$. The difference between these two parameters is small, but the overrepresentation parameter is easier to interpret. In contrast, the odds ratio is appropriate when the inference is based on testing. The odds ratio values of the logistic regression were calculated without selecting any level of characteristic as the reference level. Statistical testing was done using the SAS/Logistic software. Equation for the logistic regression is $\ln(P/(1-P)) = \alpha + \beta x$, where \ln is natural logarithm function, P is the modelled probability of a diversifying crop, α is the intercept, β is inverse scale parameter, and x is vector of a predictor (e.g., farm size, field size, soil type). If the logistic regression analysis did not find statistically significant differences, it is likely that results can be explained by chance.

3. Results

Oilseed rape gained more field area by 2016 in comparison to 2011 but had retreated everywhere by 2021 (Fig. 3). More area was allocated to winter wheat especially in the southeastern and southwestern regions by 2021, and to a smaller extent in the northwestern and inland regions. The cultivation area of peas has continued to progress steadily throughout Finland, while faba beans have stagnated after the steep rise from 2011 to 2016 (Fig. 4). Maize and oil hemp have been introduced as very novel crops especially since 2011, and scattered fields can be found throughout the country, with no regional concentration (Figs. 5 and 6).

The allocation of diversifying crops depended on the variety of crops cultivated on a farm. More parcels were allocated to winter wheat by farmers who already had a high share of land used for cereals and special crops (turnip rape, oilseed rape and grain legumes). However, fewer parcels were allocated to winter wheat by those who already had a high share of land used for grassland, potatoes and sugar beet (Tables 1, S1 and S2). This finding concerned all regions and years. In the southeastern and southwestern regions, grain legumes were grown more frequently by farmers who had farms with a cereal area of 25–50 % – and in the southwest, > 10 % for special crops (Tables 2, S1 and S2). In the northwest, peas and faba beans were more novel crops, and no systematic allocation time trend was found, depending on cropping history. However, grain legumes were often least preferred by farmers with high shares of land used as grassland and for tuber and root crops. A trend was observed in oilseed rape in the southeast: In 2011, it was especially

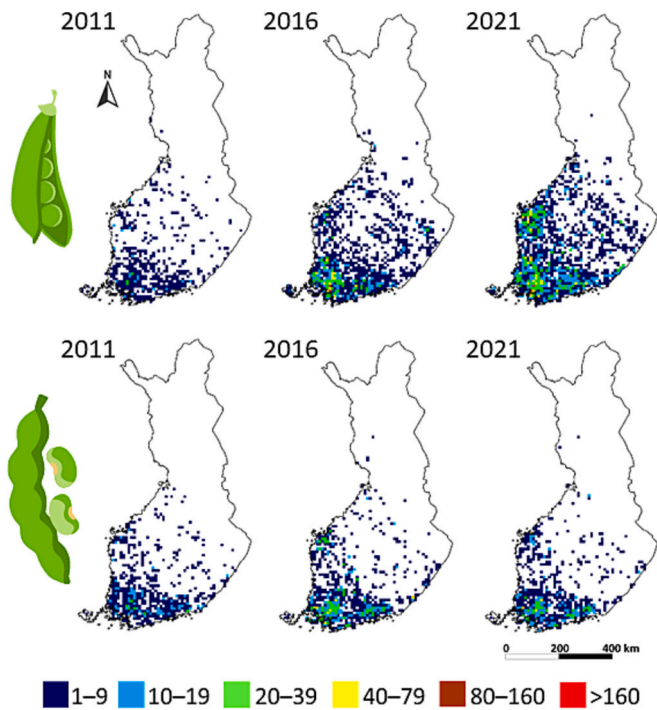


Fig. 4. Number of parcels of peas and faba beans in grid cells of 10 × 10 km in 2011, 2016, and 2021.

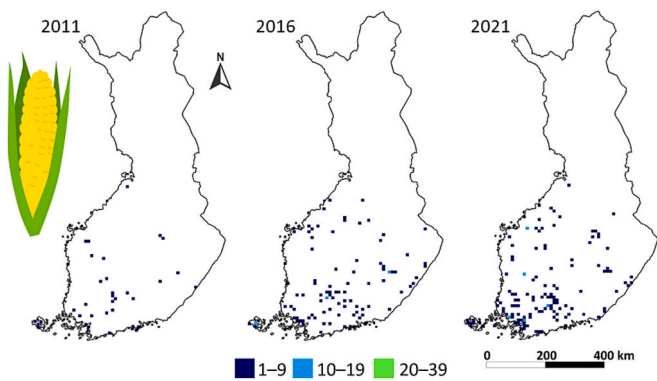


Fig. 5. Number of parcels of maize in grid cells of 10 × 10 km in 2011, 2016, and 2021.

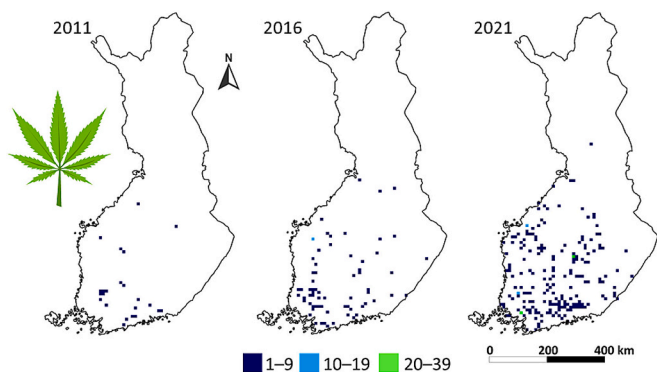


Fig. 6. Number of parcels of oil hemp in grid cells of 10 × 10 km in 2011, 2016, and 2021.

implemented by farmers with a high cereal share of their land area, and in 2016, by those with a moderate share, while in 2021, the adoption of oilseed rape was unrelated to cereal share. Furthermore, in all regions, farmers with a > 10 % share of special crops and < 25 % of grassland allocated more land to oilseed rape in all years of observation (Tables 2, S1 and S2). Parcel numbers for maize and oil hemp increased after 2016 (Figs. 5 and 6), and by 2021, data on oil hemp were sufficient for analyses. Oil hemp was adopted in all regions by farmers who also had experience with tuber and root crops (Table 1). Maize is primarily used as silage in Finland, and it was more common in farms with a high share of grassland. However, the data were sufficient for analyses only in the southwestern region (Tables 1 and S1). To summarize, farms with large cereal share adopted primarily winter wheat and oilseed rape, grassland farms primarily maize and farms growing special crops and tuber crops primarily hemp. Farms growing special crops were among the primary adopters for all crops considered.

In all regions and years, all the studied diversifying crops were adopted more frequently on large farms that had a field area of at least 100 ha, in the northwest at least 150 ha (Tables 3, 4, S3, and S4). Oilseed rape and winter wheat were overrepresented on conventional farms and faba beans on organic farms. The adoption of peas did not differ by farming system in 2021, but previously, organic farmers were more active implementers. Pig, poultry, and cereal farmers (with changing order of overrepresentation depending on year and region) often pioneered the introduction of oilseed rape, grain legumes, and winter wheat. Cattle farmers were especially overrepresented as adopters of maize in the southeastern and northwestern regions – and poultry farms as well – in the northwest (Table 4). The data did not allow identifying farm characteristics of those farms more likely to adopt cultivation of oil hemp. Pig farms constantly overrepresent pea, faba bean and winter wheat adoption, hinting at their use as on-farm feed, whereas cereal farms most often overrepresent oilseed rape adoption, which might point at its importance as a marketable break crop.

Regardless of region and year, all diversifying crops were usually overrepresented on large parcels bigger than 2.5 ha (Tables 5, 6, S5, and S6). In fields with sizes < 2.5 ha, none of the crops studied were overrepresented. Hence, small fields seemed to benefit little from crop diversification. Of the soil types, many of the studied diversifying crops, especially grain legumes and winter wheat, were overrepresented on clay soils. Occasionally, oilseed rape and faba beans were overrepresented on organic soils, even in the southeast, where organic soils are less common than elsewhere. Oilseed rape, peas, faba beans, and winter wheat were underrepresented in parcels that were close to the farm center. No shifts in time were found in the allocation of the studied diversifying crops according to field parcel characteristics.

High productivity parcels tended to be allocated to oilseed rape and winter wheat slightly more often than to peas, which were underrepresented in fields with a < 20 % productivity gap (Table 7). Furthermore, winter wheat tended to be allocated more often to parcels characterized by more variable gap between years. In all regions, oilseed rape, grain legumes, and winter wheat were overrepresented in parcels that had a history of break-crop and diverse rotations (Table 8). Hence, adoption of these crops did not result in diversified monotonous multi- or monospecies cereal sequences. Winter wheat was more common in multispecies cereal sequences and those with at least one break crop in all regions. Grain legumes and oil hemp were often grown in parcels with unidentified rotational history – oil hemp also in diverse rotations in the northwest (Table 8).

4. Discussion

This study focused on characterizing the adoption and expansion of six diversifying crops, winter wheat, oilseed rape, peas, faba beans, maize, and oil hemp, representing winter crops, oil crops, protein crops, and/or very novel, emerging crops. These crops have undergone significant increases in cultivation area in Finland over the last couple of

Table 1

Underrepresentation (<1.00) and overrepresentation (>1.00) of adoption of winter wheat, hemp, and maize in 2021 in three study regions, depending on land use on a farm. Means with the same letter in the same column do not differ significantly.

Crop shares	Southeast		Southwest			Northwest	
	Winter wheat	Hemp	Winter wheat	Maize	Hemp	Winter wheat	Hemp
<i>Cereals:</i>							
<25 %	0.21 c	1.25 a	0.17 c	6.32 a	2.86 a	0.27 c	0.97 a
25–50 %	0.67 b	1.27 a	0.65 b	1.04 b	3.19 a	0.40 b	3.17 a
≥50 %	1.33 a	0.83 a	1.20 a	0.25 c	0.22 b	1.47 a	0.25 b
<i>P</i> -value	<0.001	0.99	<0.001	<0.001	<0.001	<0.001	<0.001
<i>Special crops:</i>							
0 %	0.71 b	0.68 b	0.76 c	1.12 b	0.34 b	0.57 b	0.69 b
0.1–10 %	1.73 a	1.59 ab	1.27 b	2.02 a	1.98 a	1.81 a	1.07 a
>10 %	1.32 a	1.47 a	1.37 a	0.06 c	1.87 a	2.10 a	2.12 a
<i>P</i> -value	<0.001	0.05	<0.001	<0.001	<0.001	<0.001	<0.001
<i>Grassland:</i>							
<25 %	1.33 a	1.06 a	1.17 a	0.16 b	0.90 a	1.53 a	1.44 a
25–50 %	0.72 b	1.50 a	0.49 b	5.02 a	1.66 a	0.43 b	0.74 a
≥50 %	0.21 c	0.21 a	0.20 c	3.32 a	1.07 a	0.07 c	0.07 b
<i>P</i> -value	<0.001	0.10	<0.001	<0.001	0.09	<0.001	<0.01
<i>Tuber and root crops:</i>							
<25 %	1.08 a	0.59 b	1.08 a	0.42 b	0.69 c	1.09 a	0.28 b
25–50 %	0.57 b	2.79 a	0.82 b	3.45 a	0.90 b	0.53 b	2.37 a
≥50 %	0.17 c	7.80 a	0.35 c	2.61 a	6.16 a	0.87 b	8.06 a
<i>P</i> -value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table 2

Underrepresentation (<1.00) and overrepresentation (>1.00) of adoption of oilseed rape, peas, and faba beans in 2021 in three study regions depending on land use on a farm. Means with the same letter in the same column do not differ significantly.

Crop shares	Southeast			Southwest			Northwest		
	Oilseed rape	Peas	Faba beans	Oilseed rape	Peas	Faba beans	Oilseed rape	Peas	Faba beans
<i>Cereals:</i>									
<25 %	0.79 a	0.56 c	1.24 b	0.16 b	0.96 b	1.16 a	0.44 b	0.83 b	0.97 a
25–50 %	0.96 a	1.33 a	1.56 a	1.39 a	1.11 a	1.30 a	0.20 b	1.09 a	0.78 b
≥50 %	1.07 a	0.99 b	0.72 b	1.02 a	0.98 a	0.91 a	1.48 a	1.03 a	1.08 a
<i>P</i> -value	0.24	<0.001	<0.001	<0.001	<0.01	0.23	<0.001	<0.001	<0.001
<i>Special crops:</i>									
0 %									
0.1–10 %	0.75 b	1.75 a	1.28 b	0.48 b	1.55 b	1.39 b	1.11 b	2.06 b	1.74 b
>10 %	3.45 a	2.96 a	3.19 a	3.63 a	2.93 a	3.03 a	4.68 a	4.09 a	4.29 a
<i>P</i> -value	<0.001	0.22	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
<i>Grassland:</i>									
<25 %	1.45 a	1.21 a	1.03 b	1.21 a	1.06 a	0.99 b	1.48 a	1.36 a	1.12 a
25–50 %	0.58 b	1.01 a	1.41 a	0.32 b	1.16 a	1.33 a	0.53 b	0.73 b	1.59 a
≥50 %	0.00 c	0.27 b	0.40 c	0.03 c	0.39 b	0.73 c	0.11 c	0.27 c	0.24 b
<i>P</i> -value	<0.01	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
<i>Tuber and root crops:</i>									
<25 %	1.08 a	1.07 a	1.01 a	1.12 a	1.10 a	1.09 a	1.14 a	1.05 a	1.19 a
25–50 %	0.59 a	0.66 b	1.09 a	0.68 b	0.68 b	0.83 b	0.18 b	0.63 b	0.21 b
≥50 %	0.00 a	0.07 c	0.01 b	0.06 c	0.32 c	0.14 c	0.89 a	1.11 a	0.18 c
<i>P</i> -value	0.11	<0.001	<0.001	<0.001	<0.001	<0.001	0.01	<0.001	<0.001

decades (Peltonen-Sainio and Jauhiainen, 2020), and still have potential for further expansion (Peltonen-Sainio and Jauhiainen, 2019). The cultivation areas of winter wheat, peas, oil hemp, and maize have started or continued to expand by 2021, while faba beans have stagnated, and oilseed rape fell to the same level as in 2011 (Figs. 3–6). Our findings highlight that the systematic south-to-north shift in maize areas in Europe since the turn of the millennium (Elsgaard et al., 2012) has progressed and eventually reached the northern regions. Furthermore, the recognized need in EU to significantly increase domestic protein crop production has taken steps forward in many countries (van Loon et al., 2023) including Finland with its historically highest pea yield in 2024 (Luke Statistics, 2024). In addition to climate change, many other megatrends, including demographic change, productivism shifts, and increasingly stringent environmental regulations put pressure on the European agricultural sector with effects that vary by region (Debonne et al., 2022). In Finland, many simultaneous changes have supported diversification of land use. For example, land purchase and leasing have

increased farm size, subsidies have supported cultivation of protein crops, cover crops and environmental grasslands, and certified organic land area has doubled since 2005 corresponding up to 14 % of the total farmed area, though with some signs of turning down in 2023 (Finnish Food Authority, 2024).

4.1. Steady or wavy trajectory, depending on diversifying crop

Turnip rape and oilseed rape (together rapeseed) have a faltering cultivation history in Finland. Despite consistent high demand from the food and feed industry, the production of turnip rape, the most common oil crop, faced serious challenges that resulted in a steep yield decline in the 1990s (Peltonen-Sainio et al., 2007). Failures were identified as primarily attributable to multiple challenges that varied from year to year, region to region, and depending on the farm. These were identified as: 1) elevated temperatures that significantly shortened the flowering and fruiting period; 2) infestations caused by pests and diseases

Table 3

Underrepresentation (<1.00) and overrepresentation (>1.00) of adoption of oilseed rape, peas, and faba beans in 2021 in three study regions depending on farm characteristics. Means with the same letter in the same column do not differ significantly.

Farm characteristic	Southeast			Southwest			Northwest		
	Oilseed rape	Peas	Faba beans	Oilseed rape	Peas	Faba beans	Oilseed rape	Peas	Faba beans
<i>Farm size:</i>									
<30 ha	0.47 bc	0.31 c	0.39 c	0.25 d	0.35 d	0.50 b	0.11 d	0.63 d	0.62 d
30–49 ha	0.38 c	0.46 c	0.71 b	0.44 c	0.59 c	0.69 b	0.77 c	0.60 d	0.56 cd
50–99 ha	0.72 b	0.93 b	0.94 b	0.89 b	0.87 b	0.97 ab	1.14 b	0.79 c	0.88 bc
100–149 ha	1.08 b	1.16 ab	1.44 a	1.40 a	1.19 a	1.24 a	1.92 a	1.13 b	1.16 ab
≥150 ha	1.69 a	1.48 a	1.15 a	1.29 a	1.34 a	1.15 a	0.78 c	1.63 a	1.53 a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
<i>Farm type:</i>									
Cereal	1.05 a	1.07 b	1.11 b	1.21 a	1.05 a	1.03 b	1.30 a	1.14 b	1.04 b
Cattle	0.74 a	0.58 c	0.36 c	0.23 c	0.78 b	0.87 c	0.38 c	0.46 c	0.50 c
Pig	2.61 a	2.01 a	2.35 a	0.77 b	1.35 a	1.36 a	0.93 bc	1.67 a	2.46 a
Poultry	0.00 a	9.45 a	0.00 d	0.86 b	0.76 b	0.73 c	1.26 a	1.10 b	0.12 c
Others	0.00 a	0.21 d	0.59 c	0.15 c	0.24 c	0.35 d	0.78 bc	0.72 b	0.76 bc
P-value	0.98	<0.001	<0.001	<0.001	<0.001	<0.001	0.03	<0.001	<0.001
<i>Farming system:</i>									
Conventional	1.07 a	1.00 a	0.94 b	1.05 a	1.00 a	0.97 b	1.07 a	1.00 a	0.93 b
Organic	0.93 b	1.00 a	1.06 a	0.95 b	1.00 a	1.03 a	0.93 a	1.00 a	1.07 a
P-value	0.02	0.27	<0.001	<0.01	0.24	<0.001	0.97	0.91	<0.001

Table 4

Underrepresentation (<1.00) and overrepresentation (>1.00) of adoption of winter wheat, maize, and oil hemp in 2021 in three study regions depending on farm characteristics. Means with the same letter in the same column do not differ significantly.

Farm characteristic	Southeast		Southwest			Northwest		
	Winter wheat	Hemp	Winter wheat	Maize	Hemp	Winter wheat	Maize	Hemp
<i>Farm size:</i>								
<30 ha	0.27 d	0.06 b	0.32 d	0.12 b	0.35 bc	0.38 d	1.06 b	0.36 c
30–49 ha	0.43 c	0.21 b	0.54 c	0.11 b	0.08 c	0.74 c	0.00 b	0.40 c
50–99 ha	0.94 b	1.02 ab	0.93 b	0.41 b	0.97 ab	0.91 b	0.14 b	1.25 b
100–149 ha	0.96 b	1.58 a	1.25 a	1.41 a	0.65 bc	0.99 b	0.28 b	0.52 c
≥150 ha	1.62 a	1.33 ab	1.29 a	1.84 a	1.76 a	1.65 a	3.21 a	1.80 a
P-value	<0.001	0.04	<0.001	<0.001	<0.001	<0.001	<0.01	<0.001
<i>Farm type:</i>								
Cereal	1.02 b	1.12 a	1.05 c	0.17 b	1.31 a	1.01 c	0.34 b	1.63 a
Cattle	0.67 c	0.64 a	0.40 e	8.08 a	0.00 a	0.32 d	2.78 a	0.18 b
Pig	3.95 a	0.00 a	1.36 a	0.00 b	0.30 a	1.35 b	0.00 b	0.24 b
Poultry	0.00 d	0.00 a	1.24 b	0.00 b	0.78 a	5.51 a	1.33 a	0.00 b
Others	0.59 c	0.00 a	0.48 d	0.02 b	0.18 a	0.18 d	0.00 b	0.00 b
P-value	<0.001	0.99	<0.001	<0.001	0.21	<0.001	<0.01	<0.01
<i>Farming system:</i>								
Conventional	1.06 a	0.84 a	1.03 a	1.05 a	0.96 b	1.02 a	1.07 a	0.99 a
Organic	0.94 b	1.19 a	0.97 b	0.95 a	1.04 a	0.98 b	0.93 a	1.01 a
P-value	<0.001	0.10	<0.001	0.45	<0.001	0.05	0.98	0.72

(Peltonen-Sainio et al., 2007); and 3) cultivation of rapeseed on compacted soils, typical for cereal-dominated rotations, where rapeseed was used as a break-crop. appeared to be incapable of penetrating compacted soil layers (Lisson et al., 2007; Peltonen-Sainio et al., 2011b). Yield penalties were further reinforced by an early summer drought (Peltonen-Sainio et al., 2021). Attempts were made in early 2000 to revitalize rapeseed production with national programs focusing especially on oilseed rape as a more robust, later maturing, and higher yielding oil crop.

Oilseed rape gained ground from turnip rape in traditional rapeseed production regions, but turnip rape remained the pioneer crop entering new regions (Peltonen-Sainio and Jauhiainen, 2020). Following this switch, the cultivation area of turnip rape declined by 2016 and remained almost the same until 2021, when oilseed rape partially withdrew from the earlier captured regions and fields (Fig. 3). The cultivation intensity of these oil crops has therefore continued to fluctuate until today probably because none of the above mentioned cultivation constraints has yet been alleviated. When comparing 2020s to the previous three decades, warm spells coupled with droughts during flowering have become more frequent e.g., in South-Europe (Toreti et al., 2024). In 2018, neonicotinoids were banned in the EU without

alternative low-risk pesticides (EASAC, 2023). Farmers' concern about the risks caused by pest infestations has increased (Andert et al., 2021) also in Finland. Cereal-based rotations remain common in Finland, and despite diversified land use, recovery from long-lasting monocultures may take time (Nunes et al., 2018; Wang et al., 2022; Walder et al., 2023). Some farmers have sought solutions from the use of winter rapeseed (Mäkelä et al., 2011) and have been successful, but winter types are still not sufficiently winter-hardy to largely replace spring types. The earlier flowering of winter types may also alleviate pest pressure, and this pressure may increase in the future climate (Fricke et al., 2023). It is anticipated that substitution will take place around the middle of the century in Finland's current primary rapeseed production regions (Peltonen-Sainio et al., 2009), when cold winters are projected to become mild due to climate warming (Ruosteenoja et al., 2019; Ruosteenoja and Jylhä, 2021).

Year-round vegetation on arable land may provide various advantages to the soil and environment compared with bare soil or stubble (Daryanto et al., 2018; Crotty and Stoate, 2019; Lamichhane and Alletto, 2022), especially as fall and winter precipitation, exposing soil to compaction, erosion, and nutrient leaching, is high and projected to increase in the future (Peltonen-Sainio et al., 2018; Ruosteenoja and

Table 5

Underrepresentation (<1.00) and overrepresentation (>1.00) of adoption of oilseed rape, peas, and faba beans in 2021 in three study regions depending on field characteristics. Means with the same letter in the same column do not differ significantly.

Field characteristic	Southeast			Southwest			Northwest		
	Oilseed rape	Peas	Faba beans	Oilseed rape	Peas	Faba beans	Oilseed rape	Peas	Faba beans
<i>Field size:</i>									
<0.5 ha	0.28 c	0.33 c	0.21 d	0.23 d	0.38 c	0.41 d	0.29 b	0.47 d	0.27 c
0.5–0.99 ha	0.52 b	0.42 bc	0.34 c	0.41 c	0.40 c	0.56 c	0.32 b	0.66 c	0.65 b
1.0–2.49 ha	0.56 b	0.53 b	0.67 b	0.56 b	0.66 b	0.88 b	0.29 b	0.82 b	0.69 b
≥2.5 ha	1.14 a	1.15 a	1.13 a	1.15 a	1.12 a	1.07 a	1.33 a	1.11 a	1.16 a
<i>P</i> -value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
<i>Distance:</i>									
<300 m	0.64 c	0.42 e	0.87 b	0.43 c	0.67 c	0.95 c	1.25 a	0.77 bc	0.44 b
300–599 m	1.05 bc	0.92 cd	0.78 b	0.99 bc	0.80 c	0.83 c	1.17 a	0.71 c	0.51 b
600–1199 m	0.98 c	0.78 d	1.30 a	1.03 b	0.97 b	1.09 a	0.82 a	0.89 a	1.01 a
1200–2499 m	0.40 c	0.99 bc	0.99 a	1.23 a	1.02 b	1.14 ab	1.04 a	1.09 a	0.98 ab
2500–4999 m	1.65 ab	1.37 a	0.95 ab	1.14 a	1.14 a	0.92 b	0.58 a	1.05 a	1.33 a
≥5000 m	1.40 a	1.23 ab	0.96 ab	0.79 bc	1.12 ab	0.96 b	1.44 a	1.10 ab	1.00 ab
<i>P</i> -value	<0.001	<0.001	0.03	<0.001	<0.001	<0.01	0.74	<0.01	<0.001
<i>Soil type:</i>									
Coarse mineral	1.11 a	0.64 b	0.49 c	0.56 b	0.60 b	0.74 b	0.72 b	0.99 b	0.78 b
Clay 1	1.04 a	1.18 a	1.17 a	1.12 a	1.18 a	1.14 a	0.59 ab	1.23 a	0.96 b
Clay 2	0.75 a	0.72 b	1.01 ab	0.56 b	0.57 b	0.56 b	1.56 ab	1.32 a	0.75 b
Organic	0.64 a	0.49 b	0.53 b	1.28 a	0.54 b	0.66 b	1.60 a	0.88 c	1.58 a
<i>P</i> -value	0.73	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.001	<0.001

Table 6

Underrepresentation (<1.00) and overrepresentation (>1.00) of adoption of winter wheat, maize, and oil hemp in 2021 in three study regions depending on field characteristics. Means with the same letter in the same column do not differ significantly.

Field characteristic	Southeast		Southwest		Northwest	
	Winter wheat	Hemp	Winter wheat	Hemp	Winter wheat	Hemp
<i>Field size:</i>						
<0.5 ha	0.15 d	0.13 b	0.25 d	0.39 b	0.31 d	0.26 b
0.5–0.99 ha	0.29 c	ab	0.43 c	0.87 a	0.44 c	0.30 b
1.0–2.49 ha	0.53 b	0.42 b	0.65 b	0.74 a	0.61 b	0.46 b
≥2.5 ha	1.16 a	1.19 a	1.13 a	1.08 a	1.21 a	1.27 a
<i>P</i> -value	<0.001	<0.01	<0.001	<0.01	<0.001	<0.01
<i>Distance:</i>						
<300 m	0.83 cd	0.00 a	0.70 d	0.19 c	0.64 a	0.23 ab
300–599 m	0.86 cd	0.77 a	0.93 c	1.42 ab	1.34 a	5.09 a
600–1199 m	0.94 bc	1.76 a	1.01 ab	0.40 c	0.75 a	0.52 b
1200–2499 m	0.91 bc	0.61 a	1.08 a	0.75 bc	0.96 a	1.18 ab
2500–4999 m	1.30 a	1.39 a	1.05 ab	1.29 b	1.02 a	0.51 ab
≥5000 m	1.04 ab	0.98 a	1.01 bc	1.69 a	1.20 a	0.19 b
<i>P</i> -value	<0.001	0.71	<0.001	<0.001	0.10	<0.01
<i>Soil type:</i>						
Coarse mineral	0.74 b	2.31 a	0.61 b	0.43 a	0.87 c	0.51 b
Clay 1	1.13 a	0.67 a	1.18 a	1.19 a	2.14 a	1.53 a
Clay 2	0.67 b	1.01 a	0.51 c	0.89 a	1.41 b	2.73 a
Organic	0.73 b	0.88 a	0.59 c	0.55 a	0.87 c	1.50 ab
<i>P</i> -value	<0.001	0.37	<0.001	0.17	<0.001	0.01

Jylhä, 2021). It is therefore hoped that the cultivation of over-wintering cash crops, cereals and rapeseed will be possible and can be supplemented with cover and intermediate crops (Peltonen-Sainio et al., 2024). Farmers have expanded the area of winter wheat, especially in the southeastern and southwestern regions, but also to a smaller extent elsewhere (Fig. 3), contrary to the downward trend of traditionally grown winter rye (Peltonen-Sainio and Jauhiainen, 2020). Winter rapeseed has still not proved sufficiently winter-hardy, despite breeding progress in Europe (Rapacz and Markowski, 1999).

An increase in domestic protein crop production in the EU has been

Table 7

Productivity gap and variation between years in the gap (2017–2020) for crops grown in 2021 in the northwestern Finland. Means with the same letter in the same column do not differ significantly.

Characteristic	Oilseed rape	Peas	Winter wheat
<i>Productivity gap:</i>			
<20 %	1.30 a	0.91 b	0.99 ab
20–29 %	1.07 ab	1.02 ab	1.11 a
30–39 %	1.05 ab	1.06 a	1.04 ab
≥40 %	0.61 b	1.02 a	0.87 b
<i>P</i> -value	0.02	0.01	0.03
<i>Gap variability:</i>			
<10 %	1.12 a	0.86 a	0.81 a
10–14.9 %	0.69 a	0.98 a	0.80 a
15–19.9 %	1.09 a	0.96 a	0.98 a
≥20 %	1.10 a	1.19 a	1.39 a
<i>P</i> -value	0.29	0.99	0.07

targeted to improve protein self-sufficiency and thereby replace imported soya, and to gain various ecosystem services (Notz et al., 2023; Rotundo et al., 2024). Peas and faba beans have traditionally been cultivated in Finland (Stoddard et al., 2009) but were neglected for decades after the adoption of industrial fertilizers (Fig. 1). N-fixation especially has been increasingly appreciated by farmers due to recent high fertilizer prices. When cultivation area of faba beans expanded again in the 2010s, their pure stands replaced intercrops. Pure stand may be prone to, e.g., *Botrytis fabae* (Boudreau, 2013; Brauna-Morževska et al., 2023). Farmers are less concerned about late infestations, which may hasten ripening without significant trade-offs. However, faba bean areas have stagnated after the steep rise between 2011 and 2016 (Peltonen-Sainio and Jauhiainen, 2020). It was considered a frost-resistant and “weather-proof” robust crop that was well adapted to Finnish growing conditions, though maturing somewhat too late. However, increasingly severe early summer droughts (Khan et al., 2010) in the early establishment phase in Finland has proven detrimental, causing unexpected total wilting of seedlings in recent years. Larger-scale implementation has therefore presented challenges that may hold back farmers’ interest in cultivation. However, the cultivation of peas has progressed steadily throughout Finland, though it seems to be more scattered in inland and in the east (Fig. 4), which is attributable to the large share of forest instead of agricultural land (Fig. S1). Unlike other field crops, peas have grown successfully during warm spells, as

Table 8

Underrepresentation (<1.00) and overrepresentation (>1.00) of adoption of oilseed rape, grain legumes, winter wheat and oil hemp in 2021 in three study regions depending on crop rotation used on parcel in 2014–2018. Means with the same letter in the same column do not differ significantly from each other.

Crop rotation	Oilseed rape	Peas	Faba beans	Winter wheat	Hemp
<i>Southeast:</i>					
Monospecies cereal sequence	0.29 c	0.78 c	0.61 c	0.52 d	1.74 a
Multispecies cereal sequence	0.60 bc	0.80 c	0.80 c	1.22 b	1.49 a
Break crop rotation	2.63 a	1.77 a	1.40 b	1.66 a	1.57 a
Diverse rotation	0.42 c	1.74 a	2.02 a	1.48 a	1.35 a
Green fallow rotation	0.44 c	0.28 e	0.16 d	0.27 e	0.00 a
Grassland rotation	0.52 c	0.56 d	0.78 c	0.65 d	0.30 a
Some other rotation	0.84 b	1.21 b	1.59 ab	1.02 c	0.61 a
P-value	<0.001	<0.001	<0.001	<0.001	0.72
<i>Southwest:</i>					
Monospecies cereal sequence	0.69 b	0.57 c	0.45 d	0.64 d	0.09 bc
Multispecies cereal sequence	0.76 b	0.68 c	0.60 c	1.19 b	0.10 bc
Break crop rotation	1.92 a	1.45 b	1.36 b	1.52 a	0.60 b
Diverse rotation	1.68 a	2.54 a	2.08 a	1.97 a	0.00 c
Green fallow rotation	0.15 d	0.15 d	0.14 e	0.11 f	0.11 c
Grassland rotation	0.37 c	0.59 c	0.93 c	0.40 e	0.80 b
Some other rotation	0.93 b	1.46 b	1.74 b	0.84 c	4.85 a
P-value	<0.001	<0.001	<0.001	<0.001	<0.001
<i>Northwest:</i>					
Monospecies cereal sequence	0.74 bc	1.19 c	0.82 b	0.92 d	0.31 c
Multispecies cereal sequence	0.86 b	0.95 bc	1.32 b	1.24 c	0.00 c
Break crop rotation	3.03 a	1.23 c	1.68 b	1.98 b	0.77 c
Diverse rotation	1.90 ab	2.68 a	1.83 a	2.96 a	6.86 a
Green fallow rotation	0.30 bc	0.34 d	0.10 c	0.10 f	0.00 c
Grassland rotation	0.29 c	0.47 d	0.44 c	0.38 e	0.36 c
Some other rotation	0.53 bc	1.39 b	1.32 b	0.93 d	3.28 b
P-value	<0.001	<0.001	<0.001	<0.001	<0.001

was previously identified in long-term trials (Peltonen-Sainio et al., 2011a).

Maize and oil hemp are very novel crops that have been adopted since 2011 by farmers – though modestly and randomly throughout the agricultural regions (Figs. 5 and 6). Sweet maize has also been tested by farmers for a couple of years without further expansion. Silage maize especially is projected to have potential to expand to some 10 % of land area in Finland by the middle of the century (Elsgaard et al., 2012). However, cattle farms and thereby, cultivation of silage maize are especially common in the northern and eastern regions. When adopting maize in Finnish crop production systems, one should be cautious about the emerging mycotoxin risks that maize may bring to cereal-dominated rotations (van der Fels-Klerx et al., 2012). In Finland, *Fusarium* species are common, multi-host, mycotoxin-producing pathogens and are especially a risk for oats. Interest in producing oil hemp has increased in Finland. It is recognized as an interesting, old but forgotten, resilient crop producing high-quality protein, oil, and fiber (Suardi et al., 2024). Among the many benefits it brings to production and the environment (Ahmad et al., 2016; Suardi et al., 2024), as a tap-rooted crop, oil hemp may alleviate soil compaction, unlike turnip rape and oilseed rape (Peltonen-Sainio et al., 2011b), which may further support oil hemp as a niche crop (Transfarm, 2024) to follow the successful footsteps of caraway in Finland (Peltonen-Sainio and Jauhiainen, 2020).

4.2. Land-use change agents and crop allocation patterns

Some overarching systematic trends were found in considering the characterization of change agent farmers in Finland. First, in all three regions and years of observation, farmers with large farms were characterized as the main, most significantly distinguished group of implementers of all diversifying crops (Tables 3, 4, S3, and S4). Farm size has steadily increased, and the number of farms has decreased since Finland joined the EU in 1995, even though farms in Finland are still small compared with many other European regions. Second, the adoption of the major diversifying crops, oilseed rape, grain legumes, and winter wheat, was often overrepresented on pig, poultry, and cereal farms, the first two being typically larger than any other farm types in Finland. Structural change in farm size has enabled large-scale diversification because more suitable land is available to provide sufficient lot sizes and rational farm operations (Peltonen-Sainio et al., 2017). The farmers keen on purchasing and leasing land to increase farm size are also probably those ready to reform and modernize agricultural systems. Furthermore, diverse crop choice often evens the workload due to differences in the timing of management practices. Third, all the studied diversifying crops, in all regions and years, were overrepresented in large parcels (Tables 5, 6, S5, and S6), which are farmers' most valued field capital (Peltonen-Sainio et al., 2019a). In general, the order of primary adopters of diversifying crops occasionally changed a little over time, but the allocation of crops to parcels depending on parcel characteristics was quite consistent throughout the study period.

Adopters of winter wheat did not differ depending on production region and year or observation. Winter wheat was adopted especially on conventional farms, by pig, poultry, and cereal farmers, who have a large share of land area for cereals and special crops (Table 1). It was allocated more frequently to highly productive parcels with clay soil and a recent history of break-crop and diverse rotations (Tables 7 and 8). In those rotations and soils, fall-sown wheat benefits resource conservation by catching the residual N available from N-fixing grain legumes (Iannetta et al., 2016), as well as from the nutrient-rich crop residues from turnip rape and oilseed rape (Peltonen-Sainio and Jauhiainen, 2010). Hence, winter wheat is a cash crop that provides soil cover over the winter on conventional farms, where cover crops are also used as an alternative. Cover crops are, however, not used on conventional farms as extensively as on organic farms (Peltonen-Sainio et al., 2024). Winter wheat was used to diversify cereal rotations but only in very few cases it was used to break monotonous use of oat and barley.

Organic farmers have been systematically more active than conventional farmers in adopting faba beans. This was also previously the case with peas, but in 2021, the two farming systems no longer differed in the adoption rate of peas (Tables 3, S3, and S4). Concerning farm types, pig farmers especially have adopted grain legumes as a part of their crop production systems. This suggests that replacing imported soya with on-farm legumes in feed is economically feasible especially on pig farms, because peas and faba beans were overrepresented on pig farms in all regions. Faba beans were, however, underrepresented on poultry farms everywhere. This is probably attributable to sensitivity of poultry to anti-nutritional compounds, vicine, and convicine, which were occasionally found, even in high concentrations, in landrace cultivars (Lessire et al., 2017; Khazaei et al., 2019). New knowledge has resulted in the breeding of faba beans with low vicine and convicine content (Vire^{BOR}, <https://boreal.fi/lajike/harkapapu/>). Grain legumes were least adopted on cattle farms with high shares of grassland as a source of protein.

Peas were not allocated to parcels that were highly productive (Table 7). Peas were probably considered to enhance productivity, as peas have a high pre-crop estimated value in Finnish farmers' fields (Peltonen-Sainio et al., 2019b). Grain legumes were frequently grown on clay soils (Tables 5, S5, and S6) – faba beans in organic soils in the northwest, where these soils are more common. Cultivating faba beans in organic soils may indicate that there was a lack of other soil types on

farms. On the other hand, farmers may have used organic soils because early summer drought is fatal for faba bean seedlings, though farmers know that organic soils may increase the risk of delayed harvests. The allocation of grain legumes and oilseed rape was underrepresented in parcels that were close to the farm center, possibly challenging the real-time identification of emerging pest and disease infestations requiring control. Farmers continued to use these crops in fields that had already a history of diverse rotations (Table 8) rather than introduced them to cereal rotations.

In the southern prime oilseed rape production regions, implementers of oilseed rape and its allocation on a farm changed in time. In 2011, it was especially implemented by farmers who had a large cereal share (>50 % of land area), and in 2016, also by those with a 25–50 % share. However, in 2021, the adoption of oilseed rape declined and was independent of the cereal share on a farm (Tables 2, S1, and S2). Furthermore, in all regions, farmers with a large share of special crops and a small share of grassland (and in some regions, tuber and root crops) allocated more land to oilseed rape in all years of observation. Oilseed rape was especially favored by conventional farmers (Table 3), and it was often allocated to highly productive parcels that had an earlier history of special crops (Tables 7 and 8). Farmers have therefore started to avoid poorly performing fields, which may have compacted soils after a long history of monotonous cereal sequencing that may hamper root penetration of deep soil layers (Peltonen-Sainio et al., 2011b). Oilseed rape was often allocated to more distant parcels which may, as with grain legumes, increase pest and disease risks, though such an allocation pattern had faded a little by 2021 in the southwestern region.

Maize and oil hemp are very novel crops in Finland (Figs. 5 and 6), and the data therefore remain limited to identifying their implementing patterns as accurately as in the case of oil seed rape, grain legumes, and winter wheat. In 2021, oil hemp was adopted in all regions and especially by farmers who also had experience of crops other than cereals (Table 1). It was often cultivated on large or medium-sized farms while avoiding small parcels (Table 6), but without a clear specification of farm type or farming system (Table 4). In the southeastern and northwestern regions, it was often allocated to parcels with another rotational history than cereals alone (Table 8). Although the data for oil hemp remain scattered today, these first findings already give some indication that contract-based production is a feasible means to support introduction of novel crops (Transfarm, 2024). As the markets have already been established, and well-adapted high-quality cultivars are available, oil hemp may also become a new, truly diversifying crop for northernmost European farmers, with various interesting benefits for enhancing sustainable crop production (Ahmad et al., 2016; Yano and Fu, 2023; Suardi et al., 2024), as the EU is striving for (European Commission, 2024).

Maize has already been cultivated in very limited areas since Finland joined the EU, but cultivation area increased in the 2010s (Fig. 5), driven by higher accumulated degree days (Peltonen-Sainio and Jauhiainen, 2020). Foreign cultivars are used, as maize is still not included in domestic breeding programs. Regional data on maize are more limited than for oil hemp. Nonetheless, in 2021, cattle farmers and those with large farms were overrepresented as adopters in the southern and northwestern regions – and in the latter, poultry farms (Table 4). In the southwestern region, it was more common in the case of farms with a large share of grassland, both in 2016 and 2021 (Tables 1 and S1), which confirms its use as silage. Data were still insufficiently available to study whether maize was allocated to cereal or grassland rotations when used as silage, which it is important to be aware of given the emerging potential mycotoxin risks if allocated to cereal-based rotations (van der Fels-Klerx et al., 2012).

5. Conclusions

In Finland, the total cultivation area of diversifying crops has

increased especially since 2010, but there is still plenty of potential for future land-use changes. The area of winter wheat and peas has continued to expand, while the adoption of oil hemp and maize has taken the first step, the area of faba beans has stagnated, and that of oilseed rape has declined. Pig, poultry, and cereal farmers with large farms were the key diversifiers. The adoption of crops differed, depending on the farming system, distance from the farm center, rotational history, and the parcel's productivity, but all diversified crops were allocated especially to large parcels. Based on this understanding, the experience gained by implementers will be used to encourage the transition on other farms, especially conventional, medium-sized, or large farms, because the available land for diversifying crops is probably limited on small farms, which are often specialized horticultural, horse, or sheep farms. The success of large-scale adoption depends on a crop's general sensitivity to climate constraints and variability, as well as external drivers, e.g., fertilizer prices and the availability of pesticides, which may either motivate or hinder the transition, despite the opportunities provided by a warmer northern climate, established markets, and well-adapted cultivars. Diverse land use is a nature-based solution to improve resilience and reduce pest and disease risks, but ironically, such risks are often higher for diversifying crops and may hold up their large-scale adoption. Additional diversification measures such as the use of cultivar mixtures and intercropping may give support for the adoption of minor crops on a larger scale.

CRedit authorship contribution statement

Pirjo Peltonen-Sainio: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Lauri Jauhiainen:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agsy.2025.104315>.

Data availability

The authors do not have permission to share data.

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