Agricultural Systems 174 (2019) 73–82

Contents lists available at ScienceDirect

Agricultural Systems

journal homepage: www.elsevier.com/locate/agsy

Unexploited potential to diversify monotonous crop sequencing at high latitudes

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ARTICLE INFO

Keywords:
Crop production
Crop rotation
Diversity
Farm size
Land allocation
Monoculture

ABSTRACT

Cereal-based rotations dominate the prime production regions of Finland without any signs of noteworthy shifts towards more diverse systems. To estimate the potential for the future expansion of more diverse crop rotations we used multinomial logistic regression to model the probability that a field parcel would suit for crops other than cereals by acknowledging farmer's preferences in land allocation depending on field parcel characteristics (size, shape, slope, distance to farm center, proximity to waterway, soil type and ownership). This study covered ca. 700,000 field parcels in the prime production region and all the farm types. We identified parcels that were currently used for pure cereal rotations but were also suitable for the cultivation of more diverse crops, especially rapeseed and grain legumes as the most potential ones. There was substantial potential to shift from the current cereal rotations towards more diverse crop sequencing patterns in all farm types, but especially on pig, poultry and cereal farms, where some 18–20% of the cereal monoculture rotations could be shifted towards break crop rotations and 24–41% to diverse rotations. The diversification potential was dependent on the farm size and was higher on large farms with more suitable land for minor crops and with better logistic advantages. Hence, the ongoing increase in farm size and reduction in the number of farms could further support the transition towards more diverse crop sequencing. Diversity in both crop rotation and the agricultural landscape can be achieved simultaneously. Due to the characteristics of field parcels allocated to perennial grasslands and green-fallow rotations they were not suitable for diversifying arable crops. To enhance use of more diverse crop rotations, coherent policies and sufficient incentives are needed to encourage farmers to exploit the existing potential in a timely fashion despite the current socio-economically challenging situation that farmers are facing in Finland.

1. Introduction

Increasing diversity of agricultural land use has been one of the main goals of the policy incentives of the Agri-Environmental Program (AEP) that was launched when Finland joined the EU in 1995. During the AEP program there have been actions aiming to reduce the diversity loss in agricultural landscapes. For example, the AEP encourages restoring and sustaining traditional biotopes and landscapes such as pasturage and meadows. It also aims to establish green fallows, less-intensively nursed nature managed fields and buffer zones with permanent crop cover next to waterways, to diversify crop rotations with grain legumes and rapeseed (*Brassica rapa* L. and *B. napus* L.) and to establish wetlands. Even though the implementation of such activities in rural areas apparently supports diversification of agricultural landscapes, prominent steps have not been taken in agricultural fields or their crop selection and rotations towards higher levels of diversification. Cereal-based rotations dominate Finnish land use and shifts during the EU-membership period towards more diverse cropping systems have been marginal, if any (Peltonen-Sainio et al., 2017). For example, although the area managed under green fallow rotations has increased in southern crop production farms, the area used for grasslands has reciprocally been reduced due to lost EU subsidies that were earlier available for seed production of grass and clover crops. By this means, one cannot consider that the AEP has yet been successful in achieving all the set environmental targets related to farmland and landscape diversity, partly because policies have not been fully coherent and the incentives have not been sufficient to encourage diversification (Roesch-McNally et al., 2018). Farmers consider that enhancing biodiversity per se is important but suppose that the costs should be borne by society (Firbank et al., 2013).

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https://doi.org/10.1016/j.agsy.2019.04.011
Received 10 July 2018; Received in revised form 29 April 2019; Accepted 30 April 2019
Available online 09 May 2019

The recent and current monotonous crop rotations and the domination of only a couple of major cereal species in the landscapes of the prime crop production region of Finland likely contribute to stagnated yields and high yield gaps (Peltonen-Sainio et al., 2015; Schils et al., 2018) as well as compacted soils with lost functionality and reduced carbon stocks (Heikkinen et al., 2013). Furthermore, it is apparent in the light of numerous published papers that diversification of crop rotations and thereby agricultural landscapes may enhance many valuable ecosystem services that are not evident in the case of monotonous crop sequencing, i.e. by having only a couple of crops dominating crop rotations and agricultural landscapes (Duru et al., 2015b; Therond et al., 2017). Diverse cropping systems may enhance yield stability, food security and climate variability buffering (Lin, 2011; Gaudin et al., 2015; Raseduzzaman and Jensen, 2017). They may also have instant and long-term impacts on soil condition and functionality (Ball et al., 2005; Brankatschk and Finkbeiner, 2015). Furthermore, fixed nitrogen (N) provided by leguminous species as pre-crops (Mayer et al., 2003; Nemecek et al., 2008; Nemecek et al., 2015), pest and disease suppression (Nemecek et al., 2008; Lin, 2011) and favoring pollinators and benefitting from their pollination services for nectar producing crops (Garibaldi et al., 2017; Nicholson et al., 2017) are examples which highlight some well-recognized ecosystem services that may be enhanced by more diverse cropping systems and agricultural landscapes. Farmers who favour diverse land use also consider it to be a means to adapt to climate change (Roesch-McNally et al., 2018).

When aspiring towards long-term developments in the sustainability of agricultural systems, diversification is a core field of actions for sustainable intensification, which simultaneously aims to improve productivity and profitability while reducing the environmental footprint. However, both socio-economic and environmental opportunities differ from one country to another in Europe (Scherer et al., 2018). Therefore, currently lacking, regionally relevant information on potential for diversification is needed to encourage future transition towards more diverse land use at high latitudes of Europe, where in general less crop choices are available for cultivation than in the more southern regions. Because the socio-economic opportunities for sustainable intensification are currently challenging in Finland (Scherer et al., 2018), it is important that the diversification activities considered in this study are not an additional economic burden for farmers, but may even support the farming economy (both in short and long run) in order to be implementable (Roesch-McNally et al., 2018).

As in the case of ecological intensification (Caron et al., 2014), a successful transition towards more diverse agricultural systems is a knowledge intensive process which should acknowledge traditional practices and farmers in decision making to enable the smooth implementation of diversification actions. With this study we aimed to identify the potential for diversification of cereal-based rotations of Finnish farms in the main crop production region by acknowledging the farmer's preferences in making decisions concerning land use and allocation to different crops and crop rotations (Peltonen-Sainio et al., 2018b) depending on the farm size and type.

2. Materials and methods

Data from the Agency of Rural Affairs (Mavi) on crops grown in Finnish field parcels was used to define the most typical Finnish crop rotation types in two time periods: 1995–1999 (early), which was right after EU-membership and the introduction of the Common Agricultural Policy (CAP) and for the 2007–2011 period (late). The datasets were available and published for these time periods, which enabled benefitting from the understanding gained with the earlier studies (Peltonen-Sainio et al., 2017; Peltonen-Sainio et al., 2018b). Furthermore, not too many changes had yet taken place in official statistics e.g., in field parcel arrangements and coding of crop species. This study focuses on the prime crop production region of Finland which has the most opportunities to diversify crop rotations. This study comprises 698,185 field parcels from the primary south-western production region of Finland. Four arable crop sequencing patterns were defined as described earlier (Peltonen-Sainio et al., 2017). These were flexible, non-cyclical and fixed for a 5-year period (Castellazzi et al., 2008). They consisted of: (1) cereal species monoculture rotations, in which the same cereal species was grown in a field for 4–5 years while another cereal species was grown only once, if ever; (2) cereal monoculture rotations, in which two or more cereal species (spring or winter types) were included in the rotation but for less than 4 years each; (3) crop rotations with a break-crop, in which cereals dominated, but some other crop species appeared as a break-crop once; and (4) diverse crop rotations, in which spring cereals appeared for 1 or 2 years as did winter cereals and at least two other crops were included in a 5-year rotation. In addition to these, an uncategorized crop sequencing pattern was included as an additional rotation type in the assessment. This did not fulfil the criteria set for any of the four arable crop rotations and it was neither perennial grassland nor a green fallow dominated rotation, which are characterized in detail in Peltonen-Sainio et al. (2017). The crops cultivated in cereal species and cereal monoculture rotations were: spring barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), wheat (*Triticum aestivum* L.), winter wheat and rye (*Secale cereale* L.). In addition to these cereal species, spring rye, peas (*Pisum sativum* L.), faba beans (*Vicia faba* L.), rapeseed, i.e., turnip rape (*Brassica rapa* L.) and oilseed rape (*B. napus* L.), potatoes (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris* var. *altissima*), perennial grasslands, green fallows and some minor crops were cultivated in break-crop, diverse and uncategorized rotations.

Crop sequencing patterns of different crop rotations were assessed according to Castellazzi et al. (2008). A square transition matrix was used as a mathematical representation of crop rotations. The matrix has as many rows and columns as there are distinct crops. The number of crop choices in rotations varied from five to 14 depending on the crop rotation. The element in row i and column j in the transitions matrix represents the probability under the rotation that crop i was grown in the previous year following crop j in the current year. The occurrence of different rotations is related to the size of the farm (Peltonen-Sainio et al., 2017). Thereby, transition matrices were estimated for all crop rotations for four farm sizes (< 30 ha, 30–59 ha, 60–99 ha, ≥100 ha), and for two different time periods in order to characterize differences in crop sequencing patterns depending on crop rotation types, the farm size and time period by acknowledging all the relevant crop choices. The probability that the same crop was grown in the previous and the current year was calculated as the sum of the diagonal elements of the transition matrix divided by the sum of all elements. The overall transition matrix was estimated according to Castellazzi et al. (2008). This is a block diagonal matrix including transition matrix of each rotation multiplied by the probability of remaining within their respective rotations in the diagonal blocks. Off-diagonal blocks represent the probability of a transition between rotations. The transition matrix of each rotation is a right stochastic matrix with each row summing to one. In general, the probability transition going from any state to another state in a finite Markov chain given by the matrix $\boldsymbol{T}$ in k steps is given by $\boldsymbol{T}^k$. Long-term average proportions for j^{th} crop was calculated using following limit by the SAS/IML (Interactive Matrix Language) software:

$$\lim_{k\to\infty} (T^k)_{i,j}$$

Thereafter, the current, unutilized potential for diversification of crop sequencing was assessed by allocating cereal dominated field parcels also for other crops according to the land allocation preferences of the farmers. This work was based on the study by Peltonen-Sainio et al. (2018b), in which the importance of different field parcel characteristics as drivers for farmer's decision-making concerning land allocation for different crops was characterized. In addition to considering the impacts of farm size, the following field parcel characteristics were acknowledged: field size, field shape, slope, distance of a field parcel to farm center, the proximity to a waterway, soil type and whether the land was leased or owned by the farmer. Multinomial logistic regression (SAS/LOGISTIC procedure) was used to model the probability that a field parcel would suit for different crops. In a previous study (Peltonen-Sainio et al., 2018b) the basic idea was that all eight characteristics were included in the model at the same time. Results were given as odds ratios with 95% confidence intervals (CI). All characteristics were categorical, having two or more groups. One group from each variable was selected as a reference (Supplementary Table S1). The odds ratio reflected relative odds for the tested and reference groups with value > 1.00, a crop of interest more likely occurred in fields of the tested group than in the reference group fields. If the 95% CI did not include the value of 1.00, the difference between tested and reference groups was statistically significant. Using this model field parcels were divided into four equal-sized categories: very unsuitable, quite unsuitable, quite suitable and very suitable. The main aim was to quantify the potential to abandon cereal and cereal species monoculture rotations by favoring alternative crop choices when feasible, such as: rapeseed, pea, faba bean, sugar beet and potato as possible cases considering the study region. Thereby, potential shifts from the two cereal monoculture rotation types towards more diverse rotation systems, and their concomitant impacts on the relative shares of different rotation types, were evaluated. Distributions of the four different suitability categories were estimated for all rotation types. The odds for each rotation type and each diversifying crop were calculated as the ratio of the two suitable and unsuitable categories. The odds ratio was calculated by comparing the odds of the monoculture rotation type to the odds of the diversified systems. If the odds ratio was < 1, field parcels, e.g., under a monoculture type of rotation were less suitable for the cultivation of diversified crops than those under rotation with break-crops and diverse rotation where they already exist (i.e., the reference rotations). If the odds ratio was > 1, field parcels of the monoculture rotations were better suited for diversifying crops than the field parcels where they were currently used.

The potential for a transition between rotations was calculated using the modelled probability of whether a field parcel would be suitable for pea, faba bean or rapeseed. If a field was under the rotation of cereal species or cereal monoculture and the field was also in the most suitable category for pea, faba bean or rapeseed, the field was reallocated for break-crop rotation. If a field was in the most suitable category for pea or faba bean and also rapeseed, the field was reallocated to the diverse rotation category.

3. Results

This study focusses on arable crop dominated rotations, which differ in their spatial distribution within the prime crop production region of Finland. Pure cereal species rotations and rotations with break-crops were concentrated in the southern and western coastal areas (i.e., the study region), the latter rotation being slightly more prominent in the south (Fig. 1). Cereal monoculture and uncategorized rotations were less frequent though basically located in the same areas as monoculture rotations of cereal species and rotations with break-crops. Only < 10% of field parcels were allocated to diverse crop rotations.

3.1. Crop sequencing patterns

Spring cereals, barley, oats and wheat were more frequent than winter cereals in rotations having only one dominating cereal species (Supplementary Table S2). The average proportions of spring wheat and barley increased with increasing farm size, while the proportion of oats decreased. Depending on the farm size, barley was followed by barley, oats by oats and spring wheat by spring wheat in 88–89%, 76–90% and 72–84% of assessed field parcels, respectively. For winter wheat the corresponding figures ranged from 37% to 46%, while for winter rye only from 16% to 30%. Barley was the most frequently cultivated cereal species that breaks the monotonous sequence of another cereal species. Oats again broke the monotonous barley sequence. In addition to barley, spring wheat followed winter wheat in rotation as did also oats, but only in small farms (< 30 ha). When the period of 2007–2011 was compared to 1995–1999 the average proportions of spring wheat and oats increased except in very large farms, which was contrary to barley. The average proportions of winter wheat and rye were low independent on farm size (Supplementary Table S2). The total shares of monotonous crop sequencing (i.e., the share of the cases, where a pre-crop was same as the following crop) tended to be higher for smaller farms: and were 67%, 64%, 60% and 62% for small, medium (30–59 ha), large (60–99 ha) and very large farms (≥100 ha), respectively.

Crop sequencing patterns were naturally more diverse for cereal monoculture rotations than for cereal species monoculture rotations – and they both were affected by farm size. The total shares of monotonous crop sequencing were 37%, 33%, 32% and 30% for small, medium, large and very large farms, respectively (Supplementary Table S3). Barley was the most frequently cultivated crop in cereal monoculture rotations followed by oats. They both had a slightly decreased role in time (except oats for very large farms) contrary to spring wheat in rotations. Increase in farm size increased the probability for having a higher share of winter rye and winter and spring wheat, which was contrary to oats. Barley was the most common following crop for itself and also often for other cereal species. Spring wheat often followed itself, but also winter wheat and rye in cereal monoculture rotation. The role of oats as a following crop to any other cereal species tended to decrease with increasing farm size. The “others”-category, including primarily barley-oat mixtures, was typically followed by itself (Supplementary Table S3).

As rotations with a break-crop were defined to be cereal dominated with only one non-cereal break-crop, it was apparent that the most widely grown barley, spring wheat and oats, in variable rank orders, were the most typical following crops for the diverse choice of pre-crops (Table 1). Hence, their average proportions in break-crop rotations were high, followed by rapeseed. The proportions of spring and winter wheat and rapeseed increased with increasing farm size opposite to that of oats and green fallow. Rapeseed was a frequent following crop for all cereals. On small farms, rapeseed, peas and faba beans were primarily used as pre-crops for barley, spring wheat and oats. On medium sized farms grain legumes were especially important pre-crops for barley and wheat at the expense of oats as a following crop. The role of grain legumes as pre-crop for winter wheat tended to increase with an increasing farm size. The other break-crops, potatoes, sugar beet, grasslands, green fallow and a variety of minor crops were often followed by barley, oats and spring wheat in rotation (Table 1). The total shares of monotonous crop sequencing in rotations with break-crops were only 17%, 14%, 13% and 12% for small, medium, large and very large farms, respectively.

Diverse crop rotations were more typical for large farms. The average proportions of rapeseed, barley, winter and spring wheat and the group of other minor crops were highest in diverse rotations, ranging from 12% to 17% depending on the crop (Table 2). Cereals were common pre-crops for rapeseed in diverse crop rotations. The role of oats was marginal as a pre-crop, except for rapeseed, itself, winter wheat and green fallow. Grain legumes and rapeseed were the most common pre-crops for winter wheat, rapeseed also for barley and spring wheat. Barley and rapeseed were again the most frequent following crops for potatoes, while spring wheat and barley were the most common subsequent crops for sugar beet. Grasslands, green fallow fields and crops like caraway (*Carum carvi* L.) were frequently followed by themselves, because they all are perennials. Otherwise they were mostly followed by winter wheat and rye, while occasionally by rapeseed and spring cereals except spring rye. In diverse crop rotations, the

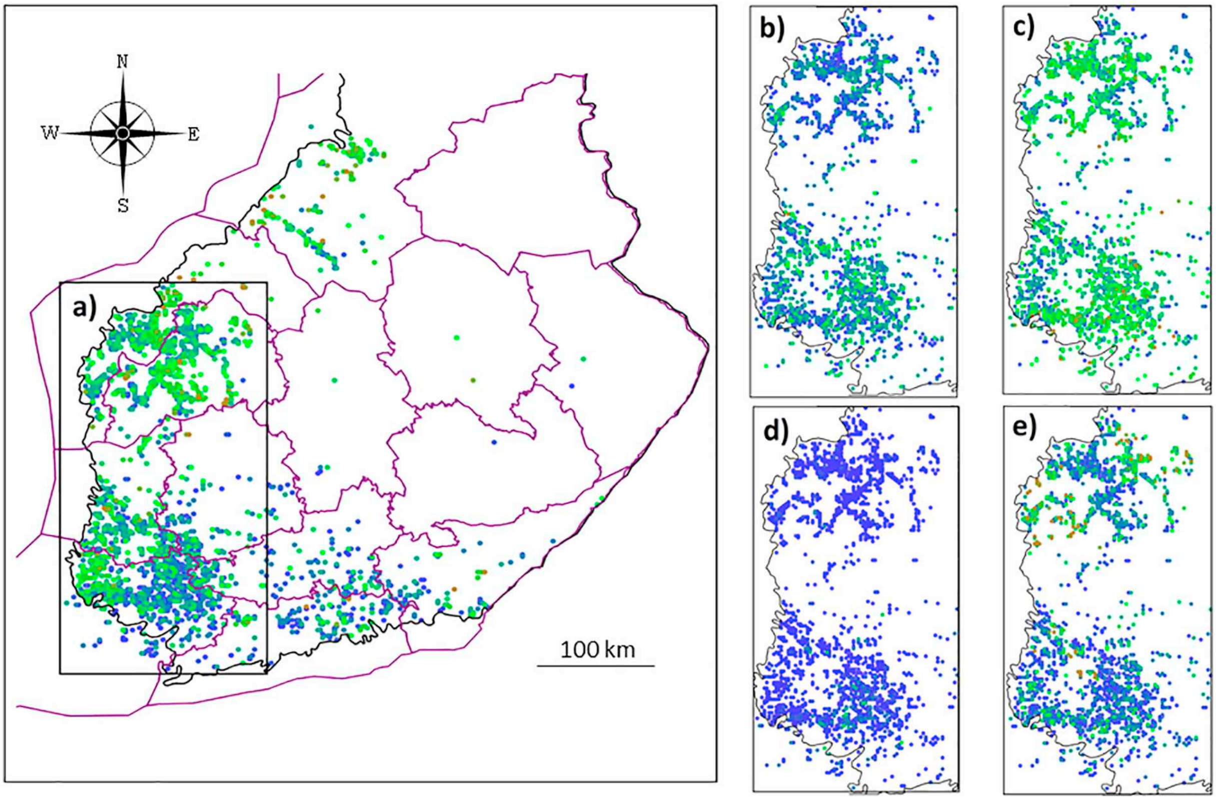

Fig. 1. Maps illustrating the spatial variability of different crop rotations in Finland. Each dot indicates that ≥30 field parcels were identified for a rotation in a 2 × 2 km area. The blue dot indicates that < 10% were allocated to a specific rotation type in the 2 × 2 km area, light blue 10–19.9%, green 20–29.9% and red ≥30%. Panels: (a) cereal species monoculture rotation, (b) cereal monoculture rotation, (c) rotation with break-crop, (d) diverse crop rotation and (e) uncategorized crop rotation, however, excluding perennial grassland and green fallow rotations. The study region is framed in grey in panel (a). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

total shares of monotonous crop sequencing were 25%, 23%, 22% and 18% for small, medium, large and very large farms, respectively (Table 2).

In the uncategorized rotations, the average proportions of barley, rapeseed, group of other minor crops, oats, spring wheat and green fallow were highest ranging from 11% to 21% depending on the crop (Supplementary Table S4). Virtually any crop was primarily followed by itself and/or rapeseed. The only exception were grain legumes (grown more on medium and large farms), which were most often followed by spring and winter wheat, barley, oats and even rapeseed (Supplementary Table S4), but not to a large extent by themselves in the following year (data not shown). In contrast to this, on small farms peas were followed by peas with as much as a 20% share, rapeseed with a 26% share and faba beans even with a 32% share (data not shown). Grasslands and green fallow were often followed by barley and oats (Supplementary Table S4). Potatoes followed potatoes almost in a monoculture manner (73–83%), while the figures for sugar beet ranged from 56% to 77% and the share was systematically lower for larger farms, as was also the case in spring wheat-spring wheat, spring rye-spring rye, barley-barley, oat-oat and rapeseed-rapeseed pre-crop-following crop combinations (data not shown). Hence, the share of the same pre- and following crop combinations in the undefined crop rotation category was high: standing at 48%, 39%, 34% and 33% for small, medium, large and very large farms, respectively.

3.2. Potential to diversify crop sequencing

In general, crops with the potential for diversification from monotonous crop sequencing were primarily cultivated in field parcels that were characterized as very suitable for their cultivation. This held true for 50%, 61%, 52%, 56% and 53% of rapeseed, peas, faba beans, sugar beet and potatoes, respectively (Tables 3 and 4). Some 23–28% of the field parcels were suited only reasonably well for their cultivation, while again 16–25% were quite unsuitable and 2–8% were very unsuitable. When assessing the current potential for diversification of monotonous cereal sequencing, we found that 31% and 21% of field parcels in cereal and cereal species monoculture rotations, respectively, were actually very suitable for the cultivation of rapeseed, while an additional 30% of field parcels were quite suitable. However, for grain legumes the figures were lower as 24% and 14% of fields were very suitable for cultivation of peas and 19% and 11% for faba beans in cereal and cereal species monoculture systems, respectively (Table 3). Some half of the field parcels currently under cereal monoculture rotations was quite or very unsuitable for peas and faba beans. In general, close to half of the field parcels of cereal species monoculture rotations were quite or very suitable for rapeseed and grain legumes, and even some 70% of those with cereal-based rotations. Grassland and green-fallow rotations had low potential however for the cultivation of rapeseed (Table 3) and sugar beet (Table 4), and the latter rotation type also for peas and faba beans. However, 34% and 29% of field parcels under perennial grassland rotation were quite or very suitable for the cultivation of peas and faba beans. Field parcels allocated for monocultures of cereal and cereal species were suited almost equally or better for potatoes and sugar beet than more diverse arable crop rotations. Thereby, only these five non-cereal case crops already exhibited substantial potential to break out of cereal monoculture domination.

As an outcome of the general diversification estimations based on the field parcel suitability for special crops, we estimated potential shifts from monoculture rotations of cereals and cereal species to break-crops and diverse rotations in the case that either one or both of the most potential diversifying crop groups, rapeseed and grain legumes, were suitable for the field parcels presently cultivating pure cereal

Table 1
Transition matrix showing crop sequencing (%) in rotations with break-crops depending on farm size for the 5-year period of 2007–2011. Each crop as its own pre-crop is highlighted in grey. Also long-term average proportions (%) of different crops in rotation are shown.

Pre-crop	Following crop: Winter wheat	Spring wheat	Winter rye	Spring rye	Barley	Oats	Rapeseed	Green fallow
<30 ha:								
Winter wheat	28.4	14.7	4.0	0.9	20.8	8.3	16.2	2.5
Spring wheat	1.8	44.5	0.4	0.2	18.3	8.0	18.9	4.0
Winter rye	1.4	10.3	20.2	0.4	21.6	20.6	18.8	3.2
Spring rye	0.9	16.4	0.0	23.3	14.7	25.9	10.3	6.9
Barley	0.9	6.4	0.8	0.2	55.3	11.5	15.1	6.3
Oats	0.2	2.8	0.4	0.2	15.5	58.9	7.4	8.9
Peas	12.8	12.8	4.3	0.0	38.3	29.8	0.0	0.0
Faba beans	0.0	38.8	2.0	0.0	38.8	20.4	0.0	0.0
Rapeseed	2.3	24.8	0.4	0.6	48.3	23.8	0.0	0.0
Potatoes	2.1	10.3	0.0	0.0	28.9	58.8	0.0	0.0
Sugar beet	0.0	11.4	0.0	2.5	64.6	21.5	0.0	0.0
Grassland	0.7	5.3	0.5	0.2	29.9	63.4	0.0	0.0
Green fallow	1.5	7.2	4.8	0.1	35.3	51.1	0.0	0.0
Others[a]	1.2	7.8	2.1	0.8	39.1	41.2	0.0	0.8
30–59 ha:								
Winter wheat	22.2	15.4	2.5	0.2	26.2	8.4	21.8	1.0
Spring wheat	1.9	35.2	1.3	0.5	26.2	7.5	21.7	1.8
Winter rye	1.5	19.6	17.0	0.9	26.4	12.2	15.6	2.7
Spring rye	0.6	16.2	1.1	17.9	26.8	13.4	17.3	1.7
Barley	1.5	11.3	1.3	0.2	49.5	11.9	18.5	2.7
Oats	0.7	6.0	0.5	0.3	23.2	47.6	13.8	4.5
Peas	17.3	35.6	9.6	5.8	26.0	5.8	0.0	0.0
Faba beans	11.8	47.1	2.0	0.0	29.4	9.8	0.0	0.0
Rapeseed	3.5	30.7	0.8	0.4	45.4	19.2	0.0	0.0
Potatoes	1.0	22.9	2.9	1.0	48.6	23.8	0.0	0.0
Sugar beet	0.0	39.3	0.0	0.9	43.0	16.8	0.0	0.0
Grassland	2.0	12.4	2.3	0.0	31.9	50.9	0.0	0.0
Green fallow	3.6	11.4	6.6	0.0	41.6	36.7	0.0	0.0
Others[a]	1.1	16.5	2.9	0.0	45.6	31.3	0.0	0.0
60–99 ha:								
Winter wheat	18.2	14.7	1.6	0.4	33.2	5.8	20.3	0.4
Spring wheat	3.3	31.5	1.2	0.2	31.7	6.8	21.4	1.1
Winter rye	1.4	15.6	10.9	0.2	33.9	11.5	21.0	0.9
Spring rye	5.3	14.4	0.8	34.1	10.6	11.4	15.9	1.5
Barley	2.5	13.5	1.3	0.1	47.9	10.2	19.6	1.9
Oats	0.9	7.3	0.4	0.3	24.4	43.8	17.3	2.6
Peas	23.4	34.0	6.6	0.0	24.4	11.7	0.0	0.0
Faba beans	25.2	24.3	6.3	0.9	34.2	9.0	0.0	0.0
Rapeseed	4.8	33.8	1.0	0.1	45.0	15.3	0.0	0.0
Potatoes	0.0	35.0	0.0	0.0	32.5	32.5	0.0	0.0
Sugar beet	0.0	39.7	0.0	0.0	41.1	19.2	0.0	0.0
Grassland	3.3	18.3	3.8	0.5	40.4	33.8	0.0	0.0
Green fallow	5.0	12.8	6.5	0.5	41.1	34.0	0.0	0.0
Others[a]	5.1	19.0	4.2	0.4	48.1	20.3	0.4	0.4
≥100 ha:								
Winter wheat	18.0	18.6	2.1	0.3	33.6	5.7	18.2	0.7
Spring wheat	3.7	31.8	1.5	0.0	30.2	6.0	22.8	0.8
Winter rye	0.4	21.6	15.1	0.2	24.1	7.8	27.6	1.3
Spring rye	0.0	11.3	0.0	10.0	27.5	28.8	20.0	1.3
Barley	3.0	16.5	1.8	0.1	46.0	8.7	19.5	1.4
Oats	1.1	9.1	0.9	0.3	25.6	39.7	18.8	2.0
Peas	33.6	17.8	17.8	0.0	25.3	5.5	0.0	0.0
Faba beans	21.9	31.3	3.9	0.0	36.7	6.3	0.0	0.0
Rapeseed	6.3	37.0	0.6	0.3	42.3	13.5	0.0	0.0
Potatoes	0.0	23.1	0.0	0.0	46.2	30.8	0.0	0.0
Sugar beet	0.0	41.4	0.0	0.0	53.5	5.2	0.0	0.0
Grassland	5.0	23.9	6.3	0.0	27.7	36.5	0.0	0.0
Green fallow	3.9	16.4	4.0	0.0	45.4	30.3	0.0	0.0
Others[a]	5.6	26.7	2.3	0.0	44.4	17.7	1.1	0.0

Farm size[b]	Long-term average proportion (%): Winter wheat	Spring wheat	Winter rye	Spring rye	Barley	Oats	Rapeseed	Green fallow
<30 ha	1.5	12.6	1.1	0.3	35.4	29.7	10.4	5.5
30–59 ha	2.3	18.1	1.5	0.4	37.9	20.2	14.6	2.3
60–99 ha	3.5	19.7	1.4	0.3	39.3	16.3	15.8	1.4
≥100 ha	4.2	22.8	1.8	0.2	38.0	13.3	16.4	1.0

[a]others include e.g. cereal mixtures, triticale, caraway, reed canary and their long-term proportions were 3.6, 2.7, 2.5 and 2.4% for < 30 ha, 30–59 ha, 60–99 ha and ≥ 100 ha, respectively.

[b]total shares of monotonous crop sequencing (i.e., the share of the cases, where a pre-crop was same as the following crop) were 17, 14, 13 and 12% for < 30 ha, 30–59 ha, 60–99 ha and ≥ 100 ha, respectively.

rotations. This potential was again highly dependent on the farm type (Table 5). Presently the highest shares of cereal monoculture rotations, and thereby also the highest potential for diversification of land use with rapeseed and grain legumes was found for pig, poultry and cereal farms. In our study region, on cereal farms, 16% of fields with monoculture rotations of cereal species could be allocated for break-crop rotation and 24% could be allocated for diverse rotation, while 18% and 25% on pig farms and again 20% and 26% could be similarly allocated on poultry farms, respectively (Table 6). Furthermore, on cereal farms 16% of fields utilizing cereal monoculture rotations could be allocated for break-crop rotations and 34% for diverse rotations, while 18% and 41% on pig farms and again 18% and 35% on poultry farms could be similarly allocated, respectively.

4. Discussion

4.1. Crop sequencing patterns of different crop rotations and shifts since 1995

Since the beginning of this study period spring cereals have dominated Finnish crop rotations (Fig. 1) and agricultural landscapes. Obviously crop sequencing patterns are less diverse for cereal species monoculture rotations and cereal monoculture rotations (Supplementary Tables S2 and S3) than for other arable crop rotation types. Rotations with break-crops have not been very heterogeneous either in the sense that spring cereals, barley, oats and increasingly also wheat have dominated the crop sequencing in these rotations, while average proportions of winter cereals have remained low (Table 1). Grain legumes and rapeseed are typical pre-crops (Kirkegaard et al., 2008; Angus et al., 2015) that break up the 4-year monotonous cultivation of cereals. This was also true for Finland, where other alternative arable crop choices are limited due to the short growing season at high latitudes. Grain legumes provide fixed N for the following crops (Nemecek et al., 2008; Nemecek et al., 2015), while high residual N in the soil (ca. 40 kg/ha) emphasizes the value of rapeseed as a pre-crop (Peltonen-Sainio and Jauhiainen, 2010). Most of the available N may, however, be lost due to heavy precipitation during autumn and winter (Syväsalo et al., 2006). Therefore, nutrient capturing winter cereals instead of spring cereals as the following crops in break-crop rotations would be environmentally and economically a more sustainable solution (Peltonen-Sainio et al., 2018a). The role of winter wheat as a subsequent crop for peas was higher farm size increased, while the role of winter rye was quite modest except in very large farms (Table 1). Rapeseed again was rarely followed by winter cereals in break-crop rotation. Hence, the role of winter cereals as the following crops for grain legumes and rapeseed could be increased in break-crop rotation to improve nitrogen capture, however, within the limits set by the short growing season at high latitudes. Harvest of a previous crop must match with sowing time of the following winter cereal and e.g., rapeseed and faba bean may often be too late maturing to meet this requirement.

Highly valued pre-crops, grain legumes and rapeseed, have been set to occur only once in a 5-year break-crop rotation. This is due to the need for sufficiently long breaks in their cultivation due to the high risk of pests and diseases (Bainard et al., 2017). However, in diverse and also uncategorized crop rotations the numbers of special crops have been higher including e.g., triticale (× *Triticosecale*), caraway and reed canary grass (*Phalaris arundinacea* L.) (Table 2 and Supplementary Table S4). Hence, the allocation patterns of crops in these more diverse rotations have also differed compared to the break-crop rotations. For example, grain legumes have primarily been followed by winter wheat in diverse crop rotations and this has been especially so on the larger farms. Also rapeseed was quite frequently followed by winter wheat. The role of winter rye as a following crop for grain legumes has been quite marginal likewise in break-crop rotation, even though 18% of rye (compared to only 4% for any other cereal) is organically produced (Finnish Food Industry Statistics, 2017), and this production line favors exemplary, diverse rotations including grain legumes.

Monotonous crop sequencing has not been typical just for cereals because even in the case of diverse crop rotations, potatoes have often been followed by potatoes and sugar beet by sugar beet. The results are even more striking for uncategorized rotations, as in 73–83% of the cases potatoes followed potatoes and in 56–77% of cases sugar beet followed sugar beet (data not shown). The latter crop has exhibited a tendency towards a higher rate of monotony on the smaller farms. A likely rationale for such monotonous sequencing patterns is that specialized farms have invested in special machinery and maintenance of high field productivity with inputs (such as liming, water management and weed control) and hence, aspire for short payback periods for their investments with high production volumes of a niche crop. On the other hand, especially small farms may run short of suitable field parcels. This likely enhances their monotonous cultivation. Furthermore, another excuse for monotonous sequencing of potato and sugar beet is that crop protection risks are low in high-latitude conditions (Hannukkala et al., 2014). For example, nematodes produce only one generation per season. Thus, they cannot multiply very rapidly within one parcel. Rhizomania (BNYVV) has never been found on sugar beet in Finland. Several soil-borne potato diseases have been slowly accumulating in potato fields and problems are now gradually increasing, which indicates that growing potato without proper rotations cannot be continued forever. This indicates how farmers make compromises due to logistic and economic reasons (Myyrä et al., 2005; Pouta et al., 2012) and thereby, miss available opportunities for diversified crop sequencing, even with their existing crop selection.

4.2. Potential for diversified crop sequencing while acknowledging farmer's preferences in land allocation

This study highlighted the potential for more diverse crop sequencing because the total share of monotonous pre-crop-following crop combinations were high, ranging from 60% to 67% for the uttermost monoculture rotations of cereal species to 12–17% for rotations with break-crops and from 18% to 48% for the rest depending on farm size. Even though the share of the same pre- and following crop combinations was lower in all the other arable crop rotations than for cereal species monoculture rotations and uncategorized rotations, the domination of cereals in land use, low share of land allocation for diverse crop rotations (Peltonen-Sainio et al., 2017) and high frequency of potatoes after potatoes and sugar beet after sugar beet in uncategorized rotations further highlights the opportunities for goal-directed diversification of high-latitude agricultural systems. Especially the current groups of minor crops, grain legumes and rapeseed have a high degree of potential for expanded production (Peltonen-Sainio et al., 2013) without requiring additional investments in machinery in the current cereal production oriented farms contrary to potato and sugar beet. Some half of the field parcels allocated for cereal-based rotations, break-crop rotation and diverse rotation were, however, quite or very suitable for potatoes and sugar beet (Table 4).

There has proved to be substantial, unexploited potential for diversification when estimating potential for land allocation for special crops such as rapeseed, grain legumes, potatoes and sugar beet by

Table 2
Transition matrix showing crop sequencing (%) in diverse crop rotations on very large farms (≥100 ha) for the 5-year period of 2007–2011. Each crop as its own pre-crop is highlighted in grey. Also long-term average proportions (%) of different crops in rotation are shown.

Pre-crop	Following crop[b]									
	Winter wheat	Spring wheat	Winter rye	Spring rye	Barley	Oats	Rapeseed	Grassland	Green fallow	Others
Winter wheat	8.9	17.1	0.9	0.7	23.7	4.7	29.1	2.4	3.3	3.1
Spring wheat	12.1	10.6	4.2	1.0	9.9	0.4	30.7	8.5	6.1	7.8
Winter rye	0.0	13.1	7.3	1.2	21.3	11.7	27.7	2.3	4.4	3.5
Spring rye	0.0	6.3	6.3	0.0	25.0	0.0	62.5	0.0	0.0	0.0
Barley	16.9	10.1	11.1	0.5	11.3	1.8	21.2	7.5	7.3	5.0
Oats	13.5	6.1	6.1	0.0	6.1	16.9	17.6	9.5	13.5	4.1
Peas	61.5	9.0	15.4	0.0	3.9	0.0	2.6	2.6	1.3	0.0
Faba beans	69.4	12.2	4.1	0.0	6.1	0.0	6.1	0.0	0.0	2.0
Rapeseed	26.6	22.7	3.1	0.2	26.2	3.0	6.4	3.0	4.6	1.0
Potatoes	0.0	7.1	7.1	0.0	28.6	0.0	21.4	0.0	0.0	7.1
Sugar beet	1.2	31.8	0.0	0.0	15.3	1.2	8.2	1.2	1.2	7.1
Grassland	12.4	5.6	12.1	0.0	6.8	5.9	4.4	49.7	2.8	0.0
Green fallow	13.1	7.9	17.0	0.0	12.4	4.5	6.1	2.9	35.3	0.7
Others[a]	14.0	11.7	20.3	0.0	6.3	2.3	4.5	0.9	2.7	36.9
Long-term average proportion (%)	14.3	12.6	6.1	1.9	14.4	5.0	16.9	7.9	8.6	12.4

[a] others include cereal mixtures, triticale, caraway, reed canary.
[b] total shares of monotonous crop sequencing (i.e., the share of the cases, where a pre-crop was same as the following crop) were 25, 23, 22 and 18% for < 30 ha, 30–59 ha, 60–99 ha and ≥ 100 ha, respectively.

acknowledging the preferences of farmers for crop allocation depending on the field parcel characteristics and conditions (Peltonen-Sainio et al., 2018b). As much as 50–61% of field parcels not currently in rapeseed, pea or faba bean rotation, would be very suitable for them across all rotation types (Table 3). However, this was especially true for cereal monoculture rotations, in which ≥70% of field parcels matched the preferences that farmers have set for their cultivation. The share was somewhat lower (42–48%) for rotations of cereal species monocultures and particularly so for grassland (28–41%) and green-fallow rotations (20–24%) indicating that field parcels in these rotation systems were not as suitable for special crops as in the case of cereal-based rotations. In general, production, biotic and abiotic risks, are higher for oil and leguminous crops than for spring cereals (Peltonen-Sainio et al., 2013) and biotic risks may even further increase if cultivated in expanded areas (Huusela-Veistola and Jauhiainen, 2006; Bainard et al., 2017). However, we did not consider expansion beyond their current cultivation regions and hence, rapeseed and grain legumes are not likely to be more prone to weather constraints in these expansion scenarios (Peltonen-Sainio et al., 2016b).

The highest potential for the diversification of crop sequencing was found on pig, poultry and cereal farms (Tables 5 and 6). This is further supported when considering how common they are, how the harvested yields could be utilized on the farm to complement the on-farm feed supply (Partanen et al., 2006), how well established the markets are for these most frequently used diversifying crops, rapeseed and grain legumes, and how much better incomes the farmers could generate compared to growing low-quality bulk cereals for use as on-farm feed (Peltonen-Sainio and Niemi, 2012). Simply allocating suitable field parcels presently under cereal monoculture rotations, to rapeseed and grain legumes (out of many other alternative crop choices) would substantially increase the share of break-crop rotations (by up to 20%) and diverse rotations (even by up to 41%) without requiring additional investments on the farm. Diversification through introducing crops such as rapeseed and grain legumes, that do not require any additional structural investments, is a decent means to exploit the potential for sustainable intensification in the current socio-economically challenging situation that farmers are facing in Finland (Scherer et al., 2018).

Utilization of the recorded diversification potential, by acknowledging farmers' preferences for land allocation to different crop species, would induce instant shifts in the shares of different rotation types. The challenge in achieving diverse crop rotations, and not only favoring rotations with break-crops in the future, is the need for sufficient, 4-year lag-periods in crop sequencing between rapeseed cultivations as well as faba bean and pea cultivations. Hence, it is apparent that land

Table 3
Share (%) of each diversifying crop grown in field parcels divided into quartiles according to their suitability for the crop: VUS = very unsuitable, QUS = quite unsuitable, QS = quite suitable, VS = very suitable. The odds ratio (OR) indicates the share of fields under cereal or cereal species monoculture rotations, perennial grassland or green fallow rotations, compared to the mean of suitability of rotation with break-crops and diverse rotations (OR = 1.00), that could be allocated to each of the diversifying crops.

Rotation	Rapeseed					Peas					Faba beans				
	VUS	QUS	QS	VS	OR	VUS	QUS	QS	VS	OR	VUS	QUS	QS	VS	OR
Across all rotations	8.2	16.3	25.3	50.2		2.3	13.6	22.7	61.4		8.0	15.3	24.7	52.0	
Cereal species monoculture	22.7	28.0	28.6	20.7	0.48	37.9	27.1	20.8	14.2	0.42	34.8	31.7	22.1	11.4	0.42
Cereal monoculture	16.4	23.5	29.6	30.5	0.74	27.2	25.9	23.0	23.9	0.70	25.1	29.4	26.4	19.2	0.70
Rotation with break-crop	13.5	22.1	30.2	34.2	1.00	24.1	24.4	24.9	26.7	1.00	22.2	27.8	27.4	22.6	1.00
Diverse rotation	10.5	19.6	28.1	41.8		16.8	22.2	25.2	35.8		15.6	24.4	28.8	31.2	
Perennial grassland rotation	32.5	30.7	22.7	14.0	0.28	40.6	25.1	19.5	14.8	0.41	41.9	29.2	19.4	9.5	0.34
Green fallow rotation	40.7	29.9	18.4	11.0	0.20	54.5	22.0	13.9	9.7	0.24	50.9	28.2	13.5	7.4	0.22

Table 4
Share (%) of each diversifying crop grown in field parcels divided into quartiles according to their suitability for the crop: VUS = very unsuitable, QUS = quite unsuitable, QS = quite suitable, VS = very suitable. Odds ratio (OR) indicates the share of fields under cereal or cereal species monoculture rotations, perennial grassland or green fallow rotation, compared to the mean of suitability of rotation with break-crops and diverse rotations (OR = 1.00), that could be allocated to each of the diversifying crops.

Rotation	Sugar beet					Potatoes				
	VUS	QUS	QS	VS	OR	VUS	QUS	QS	VS	OR
Across all rotations	5.0	14.5	24.8	55.7		6.0	13.5	27.7	52.8	
Cereal species monoculture	21.9	34.4	31.6	12.2	0.79	17.2	25.8	27.8	29.3	1.36
Cereal monoculture	19.8	31.2	33.9	15.1	0.97	20.1	28.6	27.5	23.8	1.08
Rotation with break-crop	17.4	31.3	35.5	15.7	1.00	18.4	29.0	27.3	25.3	1.00
Diverse rotation	20.0	31.6	33.7	14.7		23.0	30.4	28.7	17.9	
Perennial grassland rotation	44.2	33.2	18.2	4.3	0.29	17.8	23.1	27.8	31.3	1.48
Green fallow rotation	38.1	35.5	20.8	5.6	0.36	24.5	22.7	26.5	26.3	1.14

suitability per se does not limit diversification. The diversification of crop rotations on the farm scale may be implemented in various ways (Castellazzi et al., 2010) which will allow farmers to choose a strategy that couples resilience with profitability (Lin, 2011). Farm and regional scale planning of land use and crop sequencing may result in different ecosystem services (Castellazzi et al., 2010; Benoît et al., 2012; Duru et al., 2015b; Chopin et al., 2015; Duru et al., 2015a). Increasing the spatial diversity by growing several crops in the same year increases landscape heterogeneity. This again may improve resilience to climatic variability, suppress pests and diseases and make it possible to benefit from N fixing services every year (Nemecek et al., 2008; Gaudin et al., 2015). Furthermore, this may help to compartmentalize the risk of leaching of the fixed N, as autumns and winters may considerably differ in precipitation in Finland (Peltonen-Sainio et al., 2016a) making systems highly prone to nutrient leaching. On the other hand, in the case of increasing spatial diversity, farmers do not gain logistical advantages, e.g., in farming, transport, storage or marketing (i.e., in selling sufficiently large lots of raw-material). Such logistical advantages are again achieved by increasing temporal rather than spatial heterogeneity in land use, but such an operational model does not improve resilience to weather variability (Lin, 2011) and tolerance to abiotic risks (Huusela-Veistola and Jauhiainen, 2006).

Farm size is an important driver for differences in crop choices and crop sequencing patterns. Larger farms have lower share of small field parcels and hence, less field edges (Supplementary Table S5), which may partly explain why they have logistic advantages and more potential fields for special crops. In large farms also the harvested yield lots of each crop are sufficiently large to gain logistic advantages in

Table 5
Share (%) field parcels under different crop rotations depending on the farm type (~700,000 field parcels) and estimates for potential shifts in the share of cereals, break-crops and diverse rotations in the case that all the suitable fields in cereal rotations are allocated for rapeseed and/or grain legumes. No changes in other rotations were considered (shown as dots) due to their low potential for diversification.

Farm type	Share of field parcels for each crop rotation (%)						
	Cereal species monoculture rotation	Cereal monoculture rotation	Break-crop rotation	Diverse rotation	Grassland rotation	Green-fallow rotation	Uncategorized rotation
Cattle:							
Present state	5.1	2.8	5.9	0.3	68.3	6.7	10.9
Potential	3.6	1.7	7.1	1.6	·	·	·
Pigs:							
Present state	34.6	13.9	22.3	1.2	4.6	12.5	10.8
Potential	19.5	5.7	31.2	15.5	·	·	·
Poultry:							
Present state	21.8	18.3	25.2	2.1	6.0	12.5	14.2
Potential	11.8	8.6	32.8	14.1	·	·	·
Horses/sheep:							
Present state	1.7	0.6	2.1	0.6	80.4	9.3	5.4
Potential	1.1	0.3	2.6	1.1	·	·	·
Cereals:							
Present state	17.1	11.0	20.7	2.3	11.2	18.8	18.9
Potential	10.3	5.5	25.2	10.2	·	·	·
Special crops:							
Present state	9.7	7.3	20.8	2.5	8.8	18.5	32.3
Potential	5.7	3.6	23.6	7.5	·	·	·
Horticulture:							
Present state	6.3	3.5	9.1	1.2	14.5	18.6	46.8
Potential	3.8	2.1	10.9	3.2	·	·	·
Others:							
Present state	3.6	1.5	3.6	0.6	54.7	21.3	14.8
Potential	2.7	0.9	4.3	1.4	·	·	·

Table 6
The potential share of fields that could be shifted from cereal species and cereal monoculture rotations to either break-crop or diverse rotations by allocating suitable parcels for rapeseed and/or grain legumes depending on the farm type. The total number of parcels is shown for the study region.

Farm type	Total no. of parcels	Shifted from cereal species monoculture rotation		Shifted from cereal monoculture rotation	
		Break-crop rotation	Diverse rotation	Break-crop rotation	Diverse rotation
Cattle	256,591	13.7	14.8	17.7	20.4
Pigs	40,183	18.4	25.1	18.4	40.6
Poultry	11,769	19.9	25.8	18.0	35.0
Horses/sheep	15,114	21.1	15.6	18.4	34.2
Cereals	273,310	15.7	24.3	16.3	33.9
Special crops	40,594	16.8	24.4	15.4	35.9
Horticulture	8089	16.9	22.3	20.4	18.4
Others	50,992	11.0	14.1	20.8	18.2

transport and marketing. Shifts in crop sequencing patterns have occurred when the periods of 1995–1999 and 2007–2011 of Finland's EU membership are compared and these have been attributable to substantial changes in farm size, as the total agricultural land per farm has doubled since 1995 (Finnish Food Industry Statistics, 2017). One can expect the shift towards larger farms to continue also in the future, which may enhance the transition towards more diverse, sustainable and resilient high-latitude crop production systems, provided that this transition is encouraged with coherent policies and sufficient incentives (Firbank et al., 2013; Roesch-McNally et al., 2018).

5. Conclusions

When acknowledging farmer's preferences for the allocation of field parcels for different crops and rotations, substantial, ready-to-go potential has been identified for diversification of the currently monotonous crop sequencing patterns currently prevalent in high-latitude, cereal dominated crop production systems. A transition towards diversified crop rotations is further supported by the on-going expansion of farm size. Many of the current minor crops, especially rapeseed and grain legumes are underutilized and represent hidden potential for instant expansion also driven by concomitant increases in the demand from the food and feed industry. By exploiting the current diversification potential solely provided by grain legumes and rapeseed, the share of field parcels that could shift from cereal monoculture rotations to break-crop and diverse rotations ranges from 16% to even 41% on pig, poultry and/or cereal production farms. These farm types currently have the highest shares of cereal monoculture rotations and thereby have the greatest potential for diversification. As the cereal-based rotations are especially targeted for diversification, contrary to green-fallow and perennial grassland rotations that do not have many suitable parcels for such special crops, the execution of such a diversification strategy is likely to increase the diversity in crop rotations without reducing landscape diversity. Such a transition could provide ecosystem services that need to be exploited and valued to further encourage farmers.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2019.04.011.

Acknowledgements

This work was financed by the Ministry of Agriculture and Forestry, Academy of Finland and Natural Resources Institute Finland (Luke) as a part of a consortium of projects entitled *Developing an Interactive Tool for Farmers to Facilitate Diversification of Crop Rotations (VILKAS), Boosting Integrated Assessment Modelling for Sustainability Analysis (BoostIA), Diversifying Cropping Systems for Climate Smart Agriculture (DivCSA, the Academy of Finland decision no. 316215)* and *Sustainable Intensification of Crop Production through Land Use Changes (PeltoOptimi)*. We thank Dr. Asko Hannukkala for sharing his expertise in plant protection risks on sugar beet and potato.

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