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Legacy effects of crop sequencing on biomass and their variability on farmers' fields in Finland are shaped by weather, farm conditions and rationales for land use

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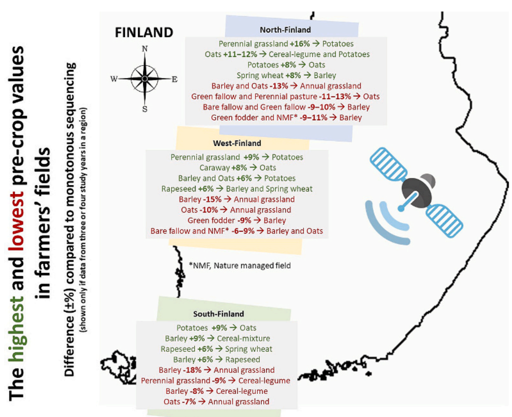
HIGHLIGHTS

- On-farm realized pre-crop values were estimated from Sentinel-2 images in total on >1,818,000 field parcels in Finland.
- Pre-crop values may range from positive to negative depending on conditions which may challenge planning of rotations.
- A higher mean temperature and fewer rainy days during pre-crop's season often reduced the legacy effects.
- A higher number of rainy days and elevated temperatures during subsequent crop's season often increased the pre-crop effects.
- Farmers' current use of grasslands did not support the realization of pre-crop benefits of grasslands for croplands.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: The legacy effect of a previous crop on a subsequent crop in rotation is a valuable and often underutilized ecosystem service which can provide benefits when designing cropping systems, especially in the case of cereal-based land use.

OBJECTIVE: To support future diversification of crop sequencing in Finland, this study was carried out with the aims to identify the variation in the pre-crop values of relevant crop combinations in farmers' fields in Finland, depending on the weather and farm conditions.

METHODS: We used a method developed to estimate on-farm realized pre-crop value from *Sentinel* − *2* images available annually for 120,174–711,828 field parcels in Finland during 2016–2020 (the total number of observations was >1,818,000).

RESULTS AND CONCLUSIONS: Both the weather and farming conditions explained the variation in the pre-crop values, which might range from positive to negative. For example, a higher mean temperature and fewer rainy days during the growing season of a previous crop often reduced the legacy effects of crop sequencing, however,

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this was dependent on the crop choices. A higher number of rainy days and elevated temperatures during the subsequent crop's season often increased the pre-crop value, while prolonged droughts in either of the growing seasons tended to reduce these. The farmers' current land use did not support the realization of pre-crop value – especially in the case of potential benefits provided by grasslands for croplands.
SIGNIFICANCE: This study highlights the challenges that weather variation and complexity of the production systems may cause for a farmer when aiming to identify the impacts of crop sequencing on yields, ecosystem services, and farm economy. Hence, there is an evident need to develop a decision support system that recognizes regional farming systems, available crop choices, crop management, weather conditions, and the farmers' rationale concerning decision making.

1. Introduction

The legacy effects of crop sequencing refer to the benefits that a previous crop may bring for the following crop in rotation. This is often called as the pre-crop value. Traditionally this considers the impacts of a previous crop in rotation on the yield of the following crop. Nitrogen fixing legumes have often resulted in high yield advantages for the following crops due to delivery of residual nitrogen (Angus et al., 2015; Carof et al., 2019; Grange et al., 2022; Zhao et al., 2022). As in the case of the legacy effects of legumes, yield benefits of crop sequencing originate from various potential effects of the previous crop on the cropping system including those on soil conditions and functionality, crop protection, and through many other ecosystem services (Nemecek et al., 2015; Melander et al., 2020; Skinulienė et al., 2022; Xiao et al., 2022; Heinen et al., 2023;). Legacy effects do not only concern the crop right after the use of a break-crop, but they may also be available for the crops thereafter, although the effects decline over time (Angus et al., 2015).

Even though the pre-crop value is often considered to be a benefit for the cropping system, legacy effects may also be negative and can vary widely depending on conditions. The acknowledgement of this variation in impacts calls for large-scale, long-term experiments to produce regionally relevant, novel data and understanding of the prevailing production conditions and systems (Peltonen-Sainio and Jauhiainen, 2020; Skinulienė et al., 2022). Such studies are, however, resource intensive (Ayalew et al., 2021), while funding is increasingly allocated to projects with a short lifespan (Meirmans et al., 2019). Understanding the legacy effects calls for large datasets, which may limit the number of previous and subsequent crops included in experiments (Angus et al., 2015; Götze et al., 2017). If one aims to use long-term experimental data beyond the original focus (e.g., for estimation of pre-crop values), challenges and limitations must be carefully considered (Berti et al., 2016). On the other hand, farmers need up-to-date information about benefits of crop sequencing to support transition towards more diverse land use (Peltonen-Sainio and Jauhiainen, 2020). They may, however, consider the findings of field experiments on the legacy effects of crop sequencing too optimistic to be fully realized in on-farm conditions. As an answer to these challenges, meta-analyzes have been used to compile, synthesize, and highlight mega-trends in legacy effects of crop sequencing (Angus et al., 2015; Zhao et al., 2022), and remote sensing methods have been utilized to support the adoption of diversifying actions by farmers (Peltonen-Sainio et al., 2019; Peguero et al., 2023).

Recognized challenges in producing large-scale, implementable, up-to-date information about pre-crop values for a high number of relevant previous and subsequent crops in rotation were motivations to carry out this work. Not least because many regional changes in cash crop choices have taken place in Finland primarily due to climate warming (Peltonen-Sainio and Jauhiainen, 2020). With this study we provide "down-to-earth data from the sky" or more precisely, farm-based information about the legacy effects of crop sequencing by using remote sensing. We applied a method developed to estimate the pre-crop value for a high number of regionally relevant previous and subsequent crop combinations (Peltonen-Sainio et al., 2019). Instead of estimating the pre-crop value as an impact on the yield per se, this method gives estimates for the above-ground biomass production capacity, hereon called the legacy effect and pre-crop value when considering the results of this study. The aims of this work were to 1) identify variation in the realized on-farm pre-crop value for the most common, regionally relevant crop choices in four main production regions in Finland, 2) to understand how this variation is dependent on the weather and farm conditions, and 3) how pre-crop value materializes on Finnish farms.

2. Materials and methods

2.1. Data on crops and crop sequencing

We used data from the Finnish Food Authority on the allocation of field parcels for different crops in four crop production regions of Finland: South-West (called as "South" hereon), West, East and North Finland. Based on this data all the possible previous crop and subsequent crop combinations were identified for each study region. To estimate the pre-crop value for a crop species, parcel scale data (boundaries of each parcel and cultivated crops) was linked to the Normalized Difference Vegetation Index (NDVI)-values derived from satellite images. The *Sentinel* − *2* image was cut using boundaries of the parcel. NDVI-value was calculated from *Sentinel-2* pixels located within boundaries. The original study was carried out in 2016 and 2017 in South-Finland only (Peltonen-Sainio et al., 2019) and at that time the exact position of the agricultural parcel within the field parcel was not yet registered by Finnish Food Authority. Therefore, a field parcel was included in the analyses if the largest agricultural parcel covered at least 70% of the area of the field parcel. Typically, a field parcel with more than two agricultural parcels contained a buffer strip at the margin of the field. If fields with 70% criterion were not included, the sample of parcels would have been biased. For example, parcels next to a waterway would have been left out more frequently than those located more faraway. In 2018–2020 agricultural parcels (i.e., segments of a field parcel with different crops) were defined in the data, but the 70% rule was still used if the parcels were not the same in different years. Data requested from Finnish Food Authority comprised the following total numbers of parcels for different regions: $N = 120{,}174$ (2016) + 118,116 (2017) + 258,516 (2018) in South-Finland, $N = 221{,}721$ (2017) + 221,134 (2018) + 201,945 (2019) + 217,677 (2020) in West-Finland, $N = 75{,}974$ (2017) + 73,034 (2018) + 75,229 (2019) + 75,401 (2020) in North-Finland, and $N = 159{,}144$ (2018) in East-Finland.

The previous crop species, their mixtures, and other types of biomasses and land uses (all called "previous crops" hereon in) were identified at the agricultural parcel scale to estimate the legacy effects of previous crops on biomass production of the subsequent crop in rotation. These included: spring barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.) and wheat (*Triticum aestivum* L.), cereal mixtures, winter wheat and rye (*Secale cereal* L.), spring turnip rape (*Brassica rapa* L.) and oilseed rape (*B. napus* L.) (together called rapeseed hereon in), peas (*Pisum sativum* L.), faba beans (*Vicia faba* L.), cereal-legumes intercrops, sugar beet (*Beta vulgaris* var. *altissima* L.), potatoes (*Solanum tuberosum* L.), caraway (*Carum carvi* L.), oilseed radishes (*Raphanus sativus* var. *oleiformis* L.), bare fallow, stubble fallow, green fallow, green manuring crop, nature managed field, diverse game fields, perennial grasslands (for feed/seed production), perennial pastures, annual grasslands and pastures (for feed; called as "annual grasslands" hereon), and fresh-harvested green forage.

The value of different previous crops was estimated for the subsequent crops or groups of crops (called as "subsequent crops" hereon) that were common in all study regions from south to north. These included: spring barley, oats and wheat, cereal mixtures, cereal-legume intercrops, rapeseed, potatoes, and annual grasslands.

2.2. Estimation of on-farm pre-crop value from satellite images

The method used to estimate on-farm data based, field-parcel scale pre-crop values for the subsequent crop in rotation was first published in (Peltonen-Sainio et al., 2019). This method was applied as such in this study with the only exception than since publishing the article (Peltonen-Sainio et al., 2019), the data from Finnish Food Authority became available on the agricultural parcel scale, as previously it was given on the field parcel scale (i.e., at a courser level).

The study regions were in South-, West-, East- and North-Finland. In all these regions there are typically >1000 field parcels in an area of 100 km^2. The regions are climatically different. A large part of Finland's arable land is within a distance of 150 km from the coast. The East-region is the only inland region with >1000 field parcels within an area of 100 km^2. Four *Sentinel*-2 satellite data tiles were selected from each region: South-Finland (34VEN, 34VEM, 34VFN, 34VFM), West-Finland (34VEQ, 34VER, 34VFQ, 34VFR), East-Finland (35VML, 35VMK, 35VNK, 35VNL) and North-Finland (34WFT, 34WFS, 35WMM, 35WMN) (Fig. 1). Each tile has a size of 110 × 110 km with a 10 km overlap. The overlap was taken into account when four tiles of the same region were combined. The Finnish Geospatial Research Institute (FGI) processed the satellite data by using a process they had developed on the EODC platform ('Earth observation data center' (EODC) GmbH, Vienna, Austria) where all *Sentinel-2* data was provided for the L1C at the 'top of atmosphere' level and on-site processing was possible. After masking the NDVI-image with a cloud mask, the mean NDVI-values were extracted per field parcel, and imagery where clouds covered no >1% of the field area were included. More detailed information is available in (Peltonen-Sainio et al., 2019).

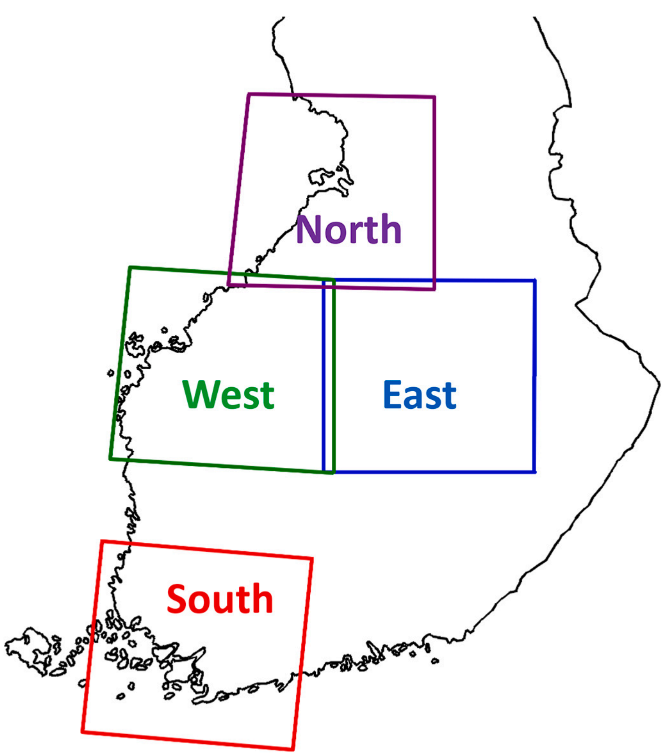

Fig. 1. A map of Finland indicating the four study regions.

Weather conditions vary significantly between the four study-regions and an NDVI-value of a field is feasible to compare only nearby fields. The NDVI-value depends on the crop also. Therefore, four study regions and all crops were analyzed separately. In each analysis an NDVI-value of a field parcel was compared to a distribution of the NDVI-values of the same crop in field parcels within the same region.

For grasslands, the *Sentinel*-2 data was utilized between 10th May and 23rd June. In Finland, the 1st cut is typically done between 15th and 25th June and the NDVI-values for grass are mutually comparable only before that. Only the NDVI-values before the 1st cut were included in the analysis. For spring crops the utilized period was between 10th June and 31st July, and for winter crops between 10th May and 31st July.

The NDVI-values have been demonstrated to be strongly correlated with above-ground biomass according to numerous studies (e.g., Liu et al., 2017; Chapungu et al., 2019). Hence, NDVI-value of a field parcel was converted to an NDVI-based estimate of productivity gap for each parcel as follows:

$$gap_i = \begin{cases} 0, & if\ x_i \geq g_{90} \\ a + bx_i, & if\ g_{90} < x_i \leq g_{50} \\ c + dx_i, & if\ x_i < g_{50} \end{cases}$$

Where x_i is the NDVI-value for the i[th] field parcel, g_{90}, g_{50} and g_{25} are 90th, 50th and 25th percentiles of the distribution of NDVI-values from the same region and crop. A segmented regression was utilized: parameters a and b are the intercept and slope for the first interval, and c and d for the second interval. Within the first interval the gap is 0 and 0.30 at g_{90} and g_{50}, respectively. Within the second interval, the gap is 0.30 and 0.55 at g_{50} and g_{25}, respectively. Additionally, if an NDVI-value of a parcel is higher than the 90th percentile, the gap is 0. If an NDVI-value reaches the median (g_{50}), the gap is 0.30. These gap-values were obtained from the official yield statistics produced by Luke. The segmented model was needed because the variation between parcels was lower for small and high NDVI-values than values near 0.50. Without this model, some crops or regions would have had higher gaps than others without any true rationale. The gap was calculated for all dates where satellite data was available within the utilized period. The utilized period depended on the crop, as defined earlier. The median of the gap values was calculated for each parcel. In the presence of outliers, or extreme values, the median is more robust than the mean. Despite the cloud mask, some extreme small values exist, also the first cutting of silage could be very early in some fields. An example of an NDVI-curve as a function of the date is shown in Fig. 2 to demonstrate that an outlier has no effect on the estimate of an NDVI-gap. Hence, the method is robust to the skewness of the distribution and individual outlier values. Clouds or their shadows are in any case the main reasons for outliers even in the case of using a cloud mask.

To estimate the pre-crop value, the mean of the NDVI-gaps was calculated for each previous and subsequent crop combination. The mean was utilized in the later analysis if at least a sample of 20 outcomes was found, because initial tests indicated that higher number of observations was not needed to ensure the accuracy of the results. Thereafter the mean was compared to the mean of the case where the previous and subsequent crops were the same (i.e., monocultural crop sequencing).

The developed method allows pre-crop value estimation of permanent grassland for other crops, but the method had clear limitations estimating the pre-crop value of other crops than perennial grasslands because the estimation of the pre-crop value was biased. All the other crops seemed to have negative values compared to production grassland as its own pre-crop. This was attributable to the fact that when the other crops were pre-crops, it was the 1st year of the grassland, and after that yields become higher until the grassland is three or four years old. Hence, this developed method can only be applied for the estimation of the pre-crop value of grasslands for other crops.

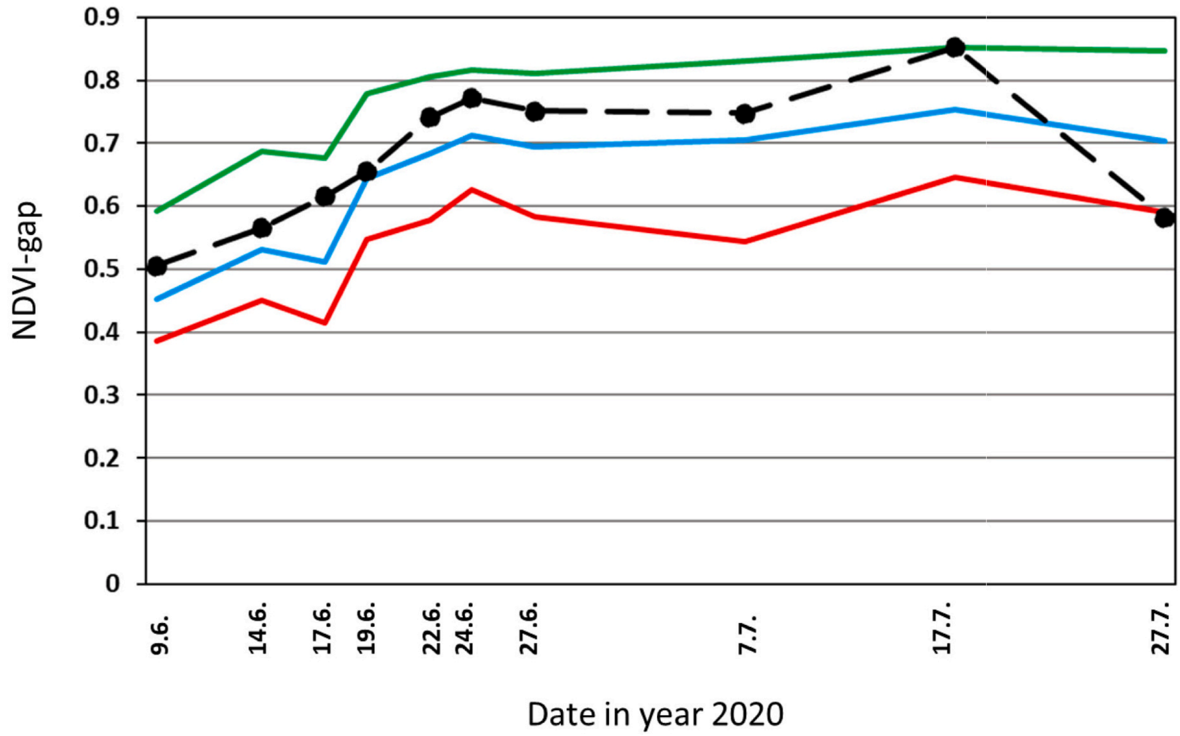

Fig. 2. An example of an NDVI-curve of a field parcel (black dashed line) as a function of date in 2020 (black circles). This example curve runs between the two upper reference limits, which correspond to the NDVI-gaps 0.00 (green line) and 0.30 (blue line), except in the case of the last date when the NDVI-gap is below the reference limit of 0.55 (red line). The median of NDVI-gap of the studied field parcel is calculated based on ten estimates (dates) and it is 0.17. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.3. Analyzing impacts of year, region, weather, and farm characteristics on variability of pre-crop values

When analyzing the weather impacts on the pre-crop value, the pre-crop value was first calculated for all available year-by-region combinations (chapter 2.2.). After that, the weather variables were combined with the data on pre-crop values. The weather variables were selected based on earlier studies that highlight their contribution to growth: the mean daily temperature of the previous crop's growing season, mean daily temperature of the subsequent crop's growing season, number of rainy days (≥1 mm) during the previous crop's growing season, number of rainy days (≥1 mm) during subsequent crop's growing season, duration of drought period during the previous crop's growing season, and the duration of drought period during the subsequent crop's growing season. The duration of the drought period was calculated from the longest period during growing season when the daily precipitation did not exceed 4 mm. The relationship between the pre-crop value and weather variables were analyzed with scatter plots with regression lines. The analysis was carried out separately for all crops. Regression models were fitted using SAS-software.

To identify potential sources of variation in the pre-crop values, a variance component model was fitted to the data including all regions, years, previous crops, and subsequent crops. The background information on the parcels was added to the data (e.g., the farm size, parcel size, and the soil type). In practice, a random effect model was fitted to obtain estimates of the contributions that different factors made to the overall variability of the pre-crop values, as expressed by their variance. Variation explained by subsequent crop, previous crop, year, region, and farm and parcel characteristics on variation in the data were estimated, including the interactions year-by-region, parcel characteristic-by-previous crop, and parcel characteristic-by-subsequent crop. The analysis was performed separately for each farm and parcel characteristic. The analysis was performed using SAS/MIXED software. In addition, another variance component model was fitted separately for all region-by-year data. These analyses examined the importance of the farming system (organic and conventional), farm type (cereal, special crop, horticulture, pig, poultry, horse/sheep, and others), parcel size (<0.5 ha, 0.5–1.99 ha and ≥ 2.0 ha), and soil type (coarse mineral soils, clay soils, other clay soils, and organic soils) as an explanation of variation, as well as their interaction effects with previous crops, and subsequent crops.

3. Results

3.1. Variation in the pre-crop values

The basic idea of the used estimation method (Peltonen-Sainio et al., 2019) was to scale the legacy effect of each alternative previous crop by comparing the advantage/disadvantage it provided for the biomass production of the subsequent crop in rotation – i.e., the same crop following itself (called hereon monotonous sequencing) was set as zero. Because we set the requirement that each previous and subsequent crop combination consisted of a minimum sample of 20 outcomes, and at least eight out of 12 potential cases (year and region -combinations) were available, we got 23 representative previous crops for barley, 20 for oats, five for cereal-legume intercrops, four for spring wheat, cereal mixtures, and rapeseed, and three for potatoes and annual grasslands (Tables 1–3).

Large annual and regional variations were found in the on-farm legacy effects provided by previous crops for the following crops in rotations. The pre-crop values were often higher for barley, but not so clearly for oats, when special crops (rapeseed, grain legumes, potatoes, and caraway) were used as previous crops in rotation instead of other cereals (Tables 1 and 2). Oilseed radish tended to have negative pre-crop

Table 1
Pre-crop values (%) of spring and winter cereals, cereal-mixtures, cereal-legume intercrops, special crops, fallows, environmental grasslands, production grasslands, and green fodder for barley as the subsequent crop in rotation for South-Finland, West-Finland, North-Finland, and East-Finland. Dot indicates that there was not sufficiently data (≥20 cases) to estimate the pre-crop value. Means ($\bar{x}$) of all pre-crop values for each year in a region, and across all years and regions are shown.

Previous crop in rotation	South-Finland				West-Finland					North-Finland					East-Finland	$\bar{x}$
	2016	2017	2018	$\bar{x}$	2017	2018	2019	2020	$\bar{x}$	2017	2018	2019	2020	$\bar{x}$	2018	
Oats	0	-3	3	0	0	0	0	1	0	0	0	-2	-2	−1	1	0
Spring wheat	−2	1	−1	−1	2	−2	2	−2	0	−2	−1	2	1	0	0	0
Winter wheat	−2	5	−2	0	1	−1	4	−1	1	−4	9	·	18	8	4	3
Winter rye	1	5	−1	2	2	−2	4	−1	1	·	·	·	−10	−10	5	0
Cereal-mixture	−7	·	−1	−4	−5	−1	−8	−4	−5	−5	−4	−4	−6	−5	3	−4
Cereal-legume intercrop	1	·	−9	−4	−6	1	−7	0	−3	·	1	−9	−9	−6	−3	−4
Turnip rape	5	3	1	3	4	3	1	0	2	0	5	1	6	3	4	3
Oilseed rape	5	6	3	5	8	3	7	6	6	·	·	·	·	·	11	6
Peas	3	7	−1	3	3	6	1	−3	2	·	12	5	−3	5	8	3
Faba beans	6	6	0	4	1	6	7	6	5	·	·	·	·	·	12	6
Potatoes	4	0	11	5	−5	0	−13	−8	−7	5	0	4	5	3	·	0
Caraway	4	5	4	4	4	4	3	7	5	5	·	6	·	5	14	5
Oilseed radish	−4	1	−4	−2	−7	2	−8	0	−3	·	5	·	·	5	·	−1
Bare fallow	−3	−5	−11	−6	−6	−5	−12	−7	−8	−7	−12	−10	−11	−10	−1	−8
Stubble fallow	−1	−6	−2	−3	−3	−5	−7	−5	−5	0	−8	−10	−8	−7	2	−5
Green fallow	0	−8	−2	−4	−1	−5	−14	−7	−7	−3	−4	−15	−16	−9	0	−6
Green manure	5	−1	9	4	−6	0	−6	−4	−4	0	−2	−3	0	−1	0	−1
Nature managed field	1	−10	−2	−4	−3	−8	−18	−5	−8	4	−20	−10	−11	−9	−8	−7
Diverse game field	8	−1	3	3	0	2	−5	2	0	3	3	−3	3	1	7	2
Perennial grassland	1	−7	−1	−2	−7	4	−7	−3	−3	−3	−1	−3	−4	−3	3	−2
Perennial pasture	−3	2	10	3	−5	−5	−12	−3	−6	−2	−2	−4	−2	−2	3	−2
Annual grassland	4	0	−4	0	−13	1	−7	1	−5	·	1	−7	−8	−5	2	−3
Green fodder	1	·	·	1	−13	−13	−9	−2	−9	·	−9	−11	−13	−11	·	−8

Table 2
Pre-crop values (%) of spring and winter cereals, cereal-mixtures, cereal-legume intercrops, special crops, fallows, environmental grasslands, production grasslands, and green fodder for oats as the subsequent crop in rotation for South-Finland, West-Finland, North-Finland, and East-Finland. Dot indicates that there was not sufficiently data (≥20 cases) to estimate the pre-crop value. Means ($\bar{x}$) of all pre-crop values for each year in a region, and across all years and regions are shown.

Previous crop in rotation	South-Finland				West-Finland					North-Finland					East-Finland	$\bar{x}$
	2016	2017	2018	$\bar{x}$	2017	2018	2019	2020	$\bar{x}$	2017	2018	2019	2020	$\bar{x}$	2018	
Barley	6	6	3	5	1	3	3	1	2	0	4	3	2	2	4	3
Spring wheat	4	4	−1	2	3	1	4	2	3	−3	−12	1	−6	−5	4	0
Winter rye	6	3	−2	2	0	−2	0	−1	−1	−1		6	1	2	2	1
Cereal-mixture	11	3	1	5	−4	0	−3	−6	−3	4	−5	3	7	2	−3	1
Cereal-legume intercrop	3	−2	·	0	−4	−1	−12	0	−4	−7	−13	−10	4	−7	11	−3
Turnip rape	6	1	4	4	4	3	2	0	2	0	2	6	1	2	6	3
Oilseed rape	8	7	0	5	8	2	1	4	4	·	·	·	·	·	−20	2
Peas	0	4	−1	1	1	1	−5	−5	−2	·	19		−11	4	1	1
Potatoes	5	11	12	9	−3	−1	−8	−1	−3	4	8	5	14	8	·	4
Caraway	9	−3	1	2	6	8	4	13	8	·	·	11	·	11	1	6
Oilseed radish	4	8	−1	4	5	4	−2	7	3	·	9	·	·	9	·	5
Bare fallow	−1	2	−5	−1	−4	−6	−13	−11	−9	−5	−14	−9	−8	−9	−7	−7
Stubble fallow	4	0	−7	−1	2	−4	−4	−7	−3	3	−7	−1	−3	−2	−1	−2
Green fallow	0	−3	−6	−3	−1	−6	−12	−2	−5	−6	−17	−15	−16	−13	−1	−7
Green manure	5	−1	−3	1	−4	0	−3	1	−2	4	3	1	5	3	−3	1
Nature managed field	1	−6	−2	−2	−3	−6	−14	−1	−6	−1	−9	−8	−7	−6	−7	−5
Diverse game field	1	−7	5	0	4	3	−4	2	1	8	2	−4	3	2	6	1
Perennial grassland	1	−2	−3	−1	−4	−2	−7	−4	−4	−5	−6	−5	−3	−5	−1	−3
Perennial pasture	4	−4	−4	−2	−2	−3	−8	−9	−5	−5	−16	−10	−14	−11	−3	−6
Annual grassland	4	2	2	3	−4	−1	−5	−4	−4	−2	−2	−3	4	−1	−10	−1

value for barley, while they were positive for oats. The legacy effects of cereal mixtures, cereal-legume intercrops, different fallows, green manuring crops, nature managed fields, diverse game fields, but also perennial and annual grasslands were only sporadically positive for barley and oats. As a subsequent crop, spring wheat had sufficient data available only for four previous crops in rotation, barley, oats, turnip rape, and perennial grasslands (Table 3). The pre-crop values for spring wheat tended to be higher (often positive) in South- and West-Finland, while lower and/or negative in East- and North-Finland. The legacy effects of barley, oats, and perennial grasslands and pastures were often negative or only slightly positive to cereal-legume intercrops, except in case of barley and oats in North-Finland. Barley, oats, and perennial grasslands had quite systematic, positive pre-crop values for cereal mixtures only in South-Finland. Perennial grasslands tended to have a negative pre-crop value for rapeseed in all regions (except in East-Finland). In South- and East-Finland, spring cereals had positive legacy effects on rapeseed, while in West-Finland, in 2018 and 2019 cereals had positive pre-crop values for rapeseed opposite to 2017 and 2020 as was also the case for North-Finland (no data for 2019 due to low rapeseed area). Barley, oats, and perennial grasslands had positive legacy effects on potatoes on their primary production areas, while the effects were negative in South-Finland (Table 3). Annual grasslands did not benefit on Finnish farms from barley, oats, and perennial grasslands as previous crops in rotation.

Table 3
Pre-crop values (%) of various crops and grasslands for spring wheat, cereal mixtures, cereal-legume intercrops, rapeseed, potatoes, and annual grassland as the subsequent crops (*in italics*) in rotation for South-Finland, West-Finland, North-Finland, and East-Finland. Dot indicates that there was not sufficiently data (≥20 cases) to estimate the pre-crop value. Means ($\bar{x}$) of all pre-crop values for each year in a region, and across all years and regions are shown.

Sequenced crops Previous crop	South-Finland				West-Finland					North-Finland					East-Finland	$\bar{x}$
Subsequent crop	2016	2017	2018	$\bar{x}$	2017	2018	2019	2020	$\bar{x}$	2017	2018	2019	2020	$\bar{x}$	2018	
Spring wheat:																
Barley	8	6	2	5	0	4	4	2	3	−2	1	−2	4	0	3	2
Oats	6	0	4	3	−1	1	0	3	1	−4	−3	−5	−1	−3	−7	0
Turnip rape	8	1	8	6	3	8	4	10	6	·	·	2	·	2	·	5
Perennial grassland	6	−2	3	2	−7	2	−4	2	−2	−8	−5	−14	2	−6	2	−2
Cereal-mixture:																
Barley	10	12	7	9	1	0	0	−1	0	0	−2	−1	5	1	−1	3
Oats	3	2	3	3	0	−2	2	1	0	0	−8	−3	5	−1	−5	0
Cereal-legume intercrop	−5	·	·	−5	−4	−7	−2	5	−2	·	8	−1	·	3	2	−1
Perennial grassland	7	−4	7	3	−4	−4	−2	0	−2	−3	−2	−4	−1	−2	−2	−1
Cereal-legume intercrop:																
Barley	−4	−16	−5	−8	1	−5	3	−3	−1	−7	13	9	1	4	−2	−1
Oats	−4	−6	−1	−3	1	−7	3	−6	−2	·	11	7	18	12	−2	2
Cereal-mixture	·	·	·	·	−1	−3	4	2	1	−7	8	·	5	2	−9	0
Perennial grassland	−9	−14	−3	−9	0	−2	−3	−6	−3	−4	2	4	2	1	−4	−3
Perennial pasture			2	2	6	−3	−9	−11	−4	·	−13	−7	−5	−8	−14	−5
Rapeseed:																
Barley	5	10	5	6	−7	8	3	−10	−2	−10	13	·	−2	0	15	2
Oats	3	8	1	4	−8	5	3	−10	−2	−10	8	·	−3	−2	18	1
Spring wheat	3	8	2	4	−5	5	4	−11	−2	·	13	·	·	13	13	4
Perennial grassland	−5	0	1	−1	−16	−3	−1	−7	−7	−15	7	·	−3	−4	9	−3
Potatoes:																
Barley	−7	−4	−1	−4	2	4	10	9	6	6	·	6	8	7	·	3
Oats	2	−3	−5	−2	1	0	12	12	6	12	·	10	10	11	·	5
Perennial grassland	·	·	−4	−4	7	1	10	17	9	18		13	17	16		9
Annual grassland:																
Barley	−14	−14	−26	−18	−11	−21	−12	−16	−15	−19	−15	−13	−6	−13	−14	−15
Oats	3	−4	−20	−7	−4	−16	−5	−15	−10	−6	−14	−17	−17	−13	−10	−10
Perennial grassland	0	−5	−13	−6	−3	−8	−11	−6	−7	−3	0	−6	−11	−5	−13	−6

3.2. Impacts of temperature and precipitation on pre-crop values

Weather conditions during the growing season of both previous and subsequent crops explained the large variation in the pre-crop values. When the mean daily temperature was high during the pre-crops' growing season, the legacy effects of various previous crops for barley and oats declined in farmers' fields except in the case of spring wheat (and winter rye for barley) (Figs. 3 and S1). When temperatures were elevated during the growing season of the subsequent crops, barley, spring wheat, and rapeseed, the legacy effects of various previous crops strengthened (Figs. 4 and 5), which was the opposite to cases where oilseed rape was a previous crop for oats as well as oats and perennial grasslands for potatoes.

When the number of rainy days during the growing season of previous crops increased, the pre-crop value for barley and oats tended to improve except in the case of slight decline when spring wheat preceded barley in rotation (Fig. 6). Nonetheless, the pre-crop values tended to remain negative in most cases. The number of rainy days during the subsequent crop's growing season varied a lot, i.e., declined or increased depending on previous and subsequent crop combination (Figs. 7 and 8), but these remained negative except in the case of potatoes following perennial grasslands in rotation. Long drought period during the growing season of either previous or subsequent crops tended to reduce the legacy effects in rotation (Figs. 9 and S2).

3.3. Variation explained by year, region, and farm and parcel characteristics on the pre-crop values

The subsequent crop in rotation explained most, 21–44% depending on farm and parcel characteristics, of the variation in pre-crop values realized in farmers' fields (Table 4), i.e., more than previous crop did (11–19%). Variation explained by the pre-crop value varied depending on farming system (5%), farm type (10%), farm size (14%), soil type (5%), and the distance to the farm center (5%). In general, year, region, and year × region interaction explained a negligible share of the variation in pre-crop values, and 34–49% of the variation remained unexplained, depending on farm and parcel characteristic (Table 4).

When assessing the situations in more detail when a significant deviation from the general contributions of covariance parameters occurred (Table 4), it was found that, e.g., occasionally the contribution of the previous crop to the variation in pre-crop value was clearly higher than that of subsequent crop in West- and North-Finland (Tables 5 and 6). There was also variation between years and regions as to whether the previous crops and/or subsequent crops differed in their contribution to the variation in pre-crop values, depending on the farming system, farm type, parcel size and soil type.

4. Discussion

4.1. Realized on-farm legacy effects or previous crops and reasons for underperformance

Cereal species often had either a small positive or a negative pre-crop value for barley, oats, and spring wheat (Tables 1 and 2). Diversifying special crops, rapeseed, grain legumes, and/or caraway had positive pre-crop value for cereals, but this was variable for peas in the West- and North-Finland, which are novel production regions (Peltonen-Sainio and Jauhiainen, 2020). This may be attributable to lack of experience with cultivation methods, insufficient rhizobium population, and limitations caused by weather conditions. The pre-crop value is an outcome of the production of various ecosystem services depending on e.g., crop choices in rotation, the amount and quality of crop residues, and the used crop management (McDaniel et al., 2014; Nemecek et al., 2015; Skinulienė et al., 2022; Xiao et al., 2022; Heinen et al., 2023). Benefits of using diversifying crops in rotation that were earlier demonstrated in field experiments were, in general, realized on Finnish farms. Oilseed

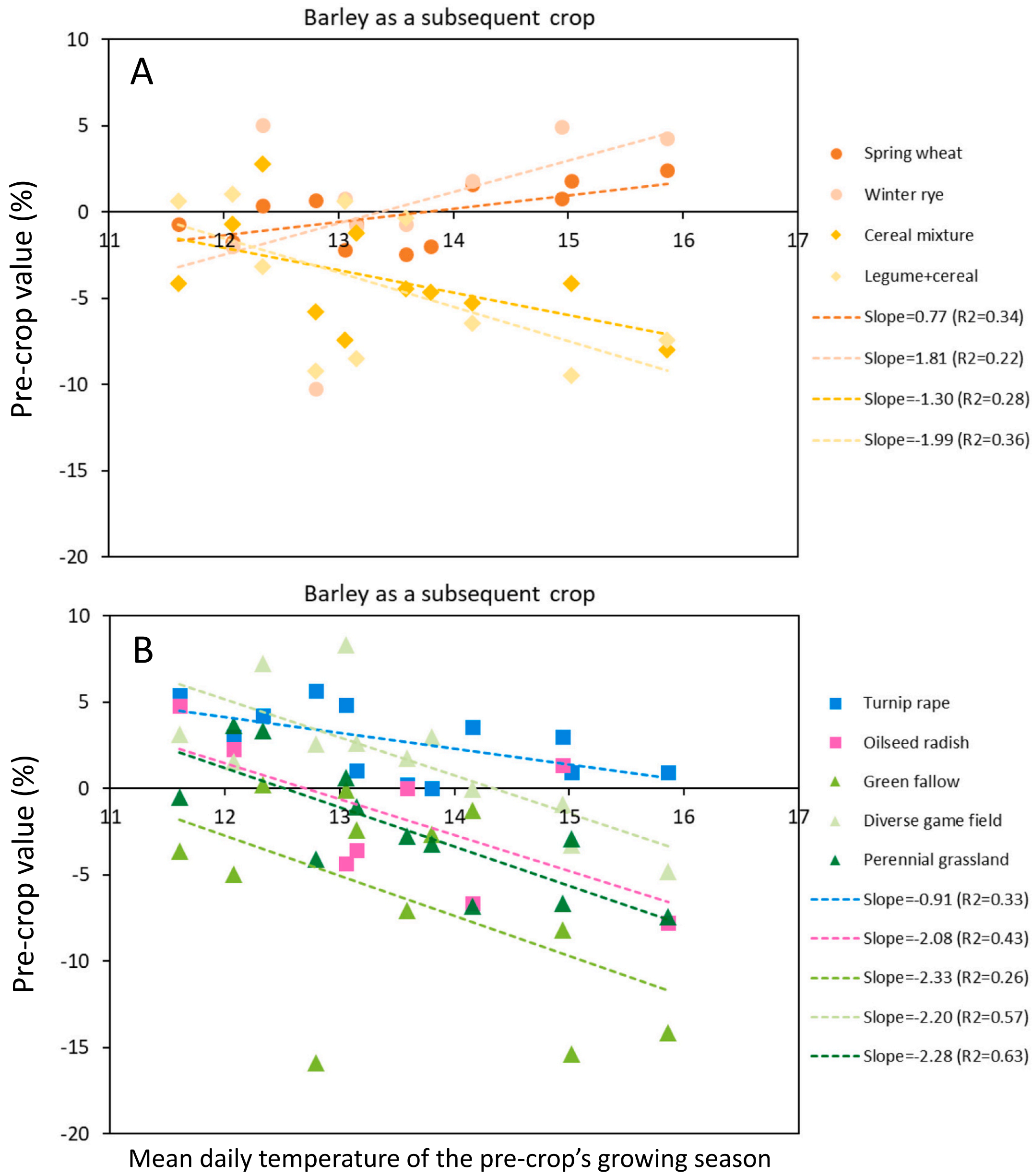

Fig. 3. Correlations between the mean daily temperature during the growing season of a previous crop and the pre-crop value of different cereals and mixtures (panel A) as well as special crops, fallow, and perennial grasslands (B) for barley as a subsequent crop in rotation.

radish was introduced to Finnish farms in 2010s as a catch crop (Peltonen-Sainio et al., 2024), e.g., to heal soil structural and functional weaknesses following long-term use of cereals only (Munkholm and Hansen, 2012). Its pre-crop value ranged from positive to negative depending on year and location – and it was slightly higher for oats than barley. Oilseed radish is an intermediate crop between cash crops and hence, farmers likely pay less attention to its cultivation.

Cropping systems can be temporally diversified with crop rotations and spatially, for example with use of intercrops (Kumar et al., 2021). Intercropping is a means to increase diversity within a field parcel, provide yield benefits and various ecosystem services, improve climate resilience, and control pests and diseases (Trenbath, 1993; Raseduzzaman and Jensen, 2017; Brooker et al., 2015; Li et al., 2020; Puliga et al., 2023;). With the selection of compatible companion crops, intercropping materialized as higher yields compared to pure stands (Bedoussac and Justes, 2011; Kumar et al., 2021). On Finnish farmers' fields neither cereal-mixtures nor cereal-legume intercrops provided systematic benefits for barley, oats, or mixtures following them. In Finland, cereal-mixtures most often compose of barley and oats. Hence, these do not likely have a much better pre-crop value as a mixture than sole crops. On the other hand, crop choices of cereal-legume intercrops and the shares of each companion crop may vary largely. Hence, these are not a uniform group for a nation-wide study: e.g., the shares of legumes and cereals in an intercrop cause differences in competition, growth, and nitrogen dynamics depending on growing conditions (Corre-Hellou et al., 2006; Neugschwandtner and Kaul, 2014; Peltonen-Sainio et al., 2017b). If a cereal is dominant over a legume, one cannot necessarily expect positive legacy effects for following barley, oats, and their intercrops (Table 1).

Grasslands have various characteristics that are apt to provide valuable legacy effects for the following crops in rotations, e.g., improved soil structure and functionality (Franzluebbers et al., 2014; Dardonville et al., 2020; Hoeffner et al., 2021; Riah-Anglet et al., 2021). In this study the pre-crop values of perennial grasslands varied depending on the region and year but were very often negative for cereals, rapeseed, and annual grasslands. When these were sporadically

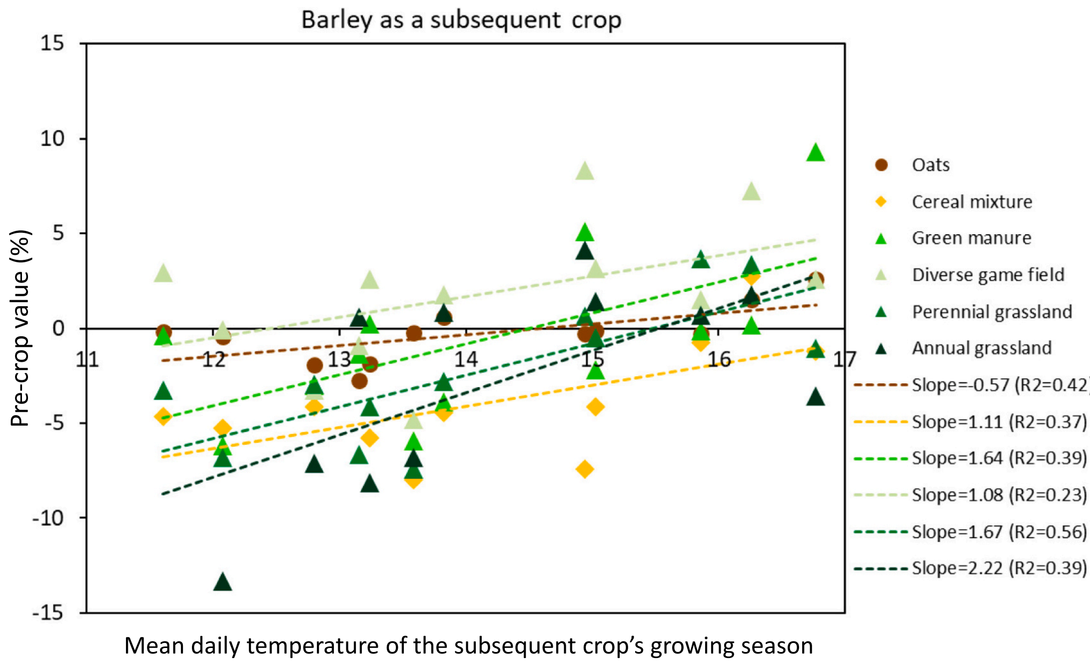

Fig. 4. Correlations between the mean daily temperature during the growing season of a subsequent crop and the pre-crop value of oats, cereal-mixture, and different types of environmental and production grasslands for barley as a subsequent crop in rotation.

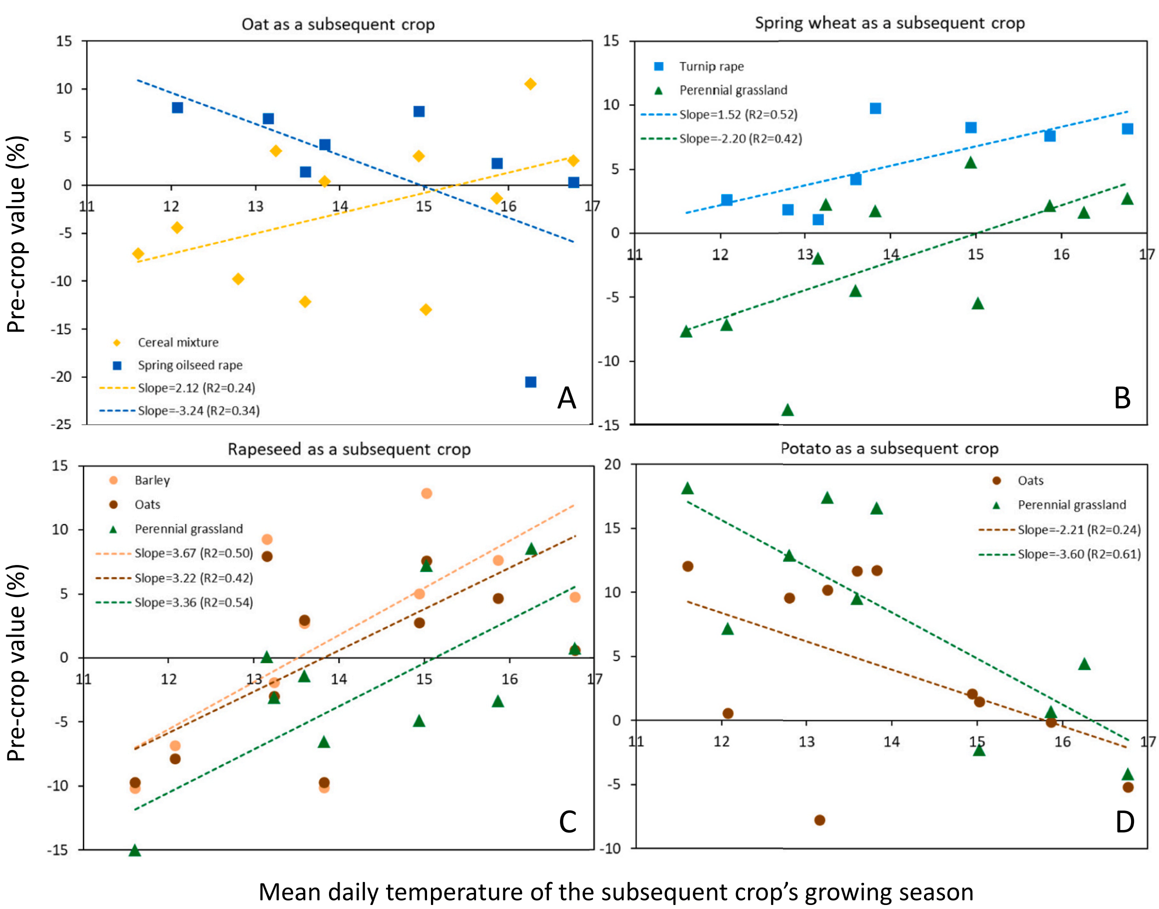

Fig. 5. Correlations between mean daily temperature during the growing season of a subsequent crop and the pre-crop value of different crops and grassland for oats (panel A), spring wheat (B), rapeseed (C), and potatoes (D) as a subsequent crop in rotation.

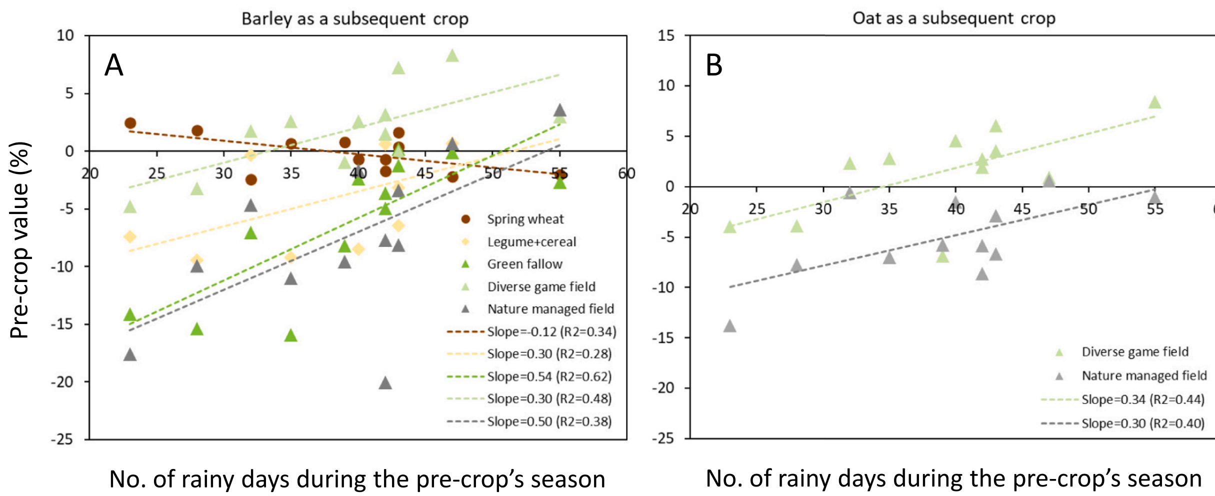

Fig. 6. Correlations between number of rainy days during the growing season of a previous crop and the pre-crop value of different crops and/or grasslands for barley (panel A) and oats (B) as a subsequent crop in rotation.

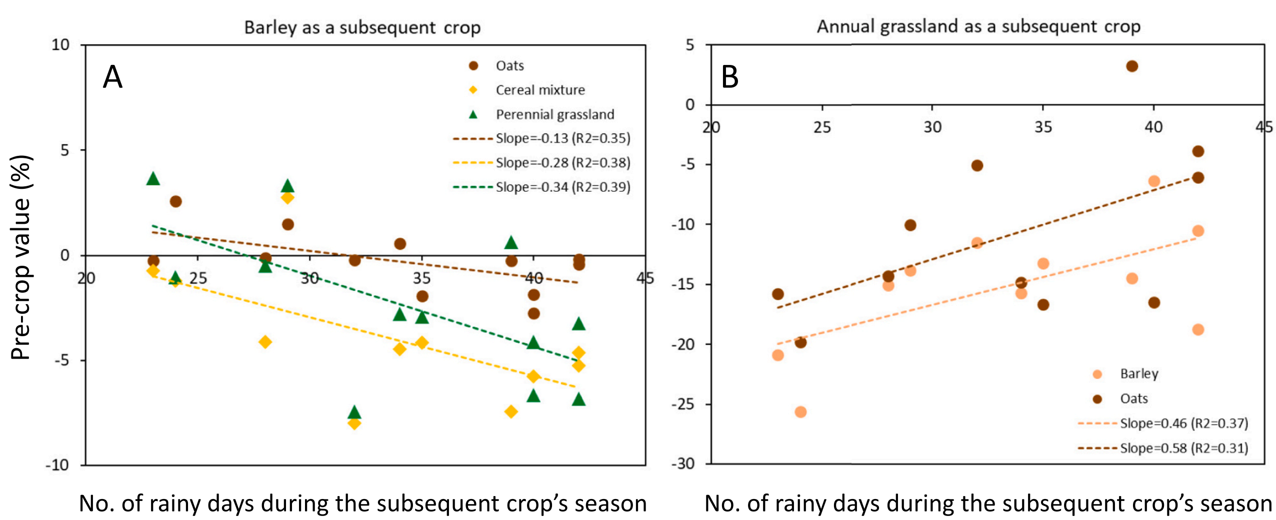

Fig. 7. Correlations between the number of rainy days during the growing season of a subsequent crop and the pre-crop value of cereals and/or grasslands for barley (panel A) and annual grassland (B) as a subsequent crop in rotation.

positive, the benefits remained marginal (Tables 1–3). This finding implies that the potential legacy effects of perennial grasslands and pastures did not largely materialize in Finnish farmers' fields, which is likely attributable to two main reasons. First, perennial grasslands and pastures may vary substantially, e.g., in their composition, inclusion of nitrogen fixing species (Grange et al., 2022), age (usually three to four years), management, and cutting schedules. Secondly, farmers often allocate grasslands to different parcels than cereals and other grain crops and especially in their primary production region, elsewhere than South-Finland. Grasslands are often close to the farm center (due to logistics reasons), while other crops are allocated to more distant fields. The land area in Finnish farms compared to cattle head numbers often limits opportunities to mix grasslands and croplands (Peltonen-Sainio et al., 2017a). Therefore, spring cereals such as early maturing barley are often cultivated during one season between perennial grasslands – as an intermediate crop with low seeding rates to support the establishment of newly sown grassland. However, grasslands provided systematic benefits for the following potatoes in rotation, especially in the main production regions of potatoes (i.e., elsewhere than South-Finland). This finding implies that grasslands are indeed valuable as previous crops, but the potential legacy effects for the following crop did not benefit Finnish farms much: partly due to logistics reasons in the allocation of field parcels (Peltonen-Sainio et al., 2018).

Merging grassland and cropland systems does not have only positive impacts. When a crop rotation is applied to a long-term grassland, the grass-based ecosystem is easily interrupted, and restoring it may require years (Riah-Anglet et al., 2021; Craft et al., 2022). Furthermore, the conversion of grasslands to croplands can be a significant disservice causing increases in greenhouse gas emissions (Buschmann et al., 2020) – especially because peatlands are common in the north, where cattle production is also centered. Opportunities provided by merged grassland and crop land systems could be achieved by introducing grasslands to monotonously cultivated cereal parcels rather than the other way round. There is plenty of potential for mixed land use without the disadvantages of compromises because the grassland area in Finland is ca. 800,000 ha, corresponding to 35% of the total agricultural land.

In addition to perennial grasslands and pastures, the legacy effects of different types of non-productive fallows were negative (Table 1). Fallows were often followed by barley and oats in rotation. This finding is likely to be attributable to the farmers' rationale in land allocation: environmental grasslands are usually allocated to field parcels with various disadvantages and low productivity – with the support of

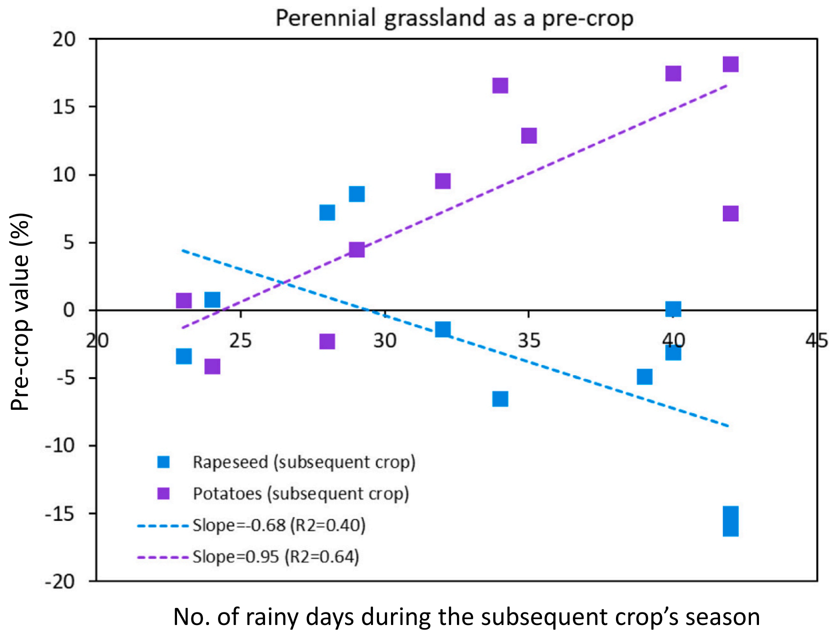

Fig. 8. Correlations between the number of rainy days during the growing season of a subsequent crop and the pre-crop value of perennial grasslands for rapeseed and potatoes as subsequent crops in rotation.

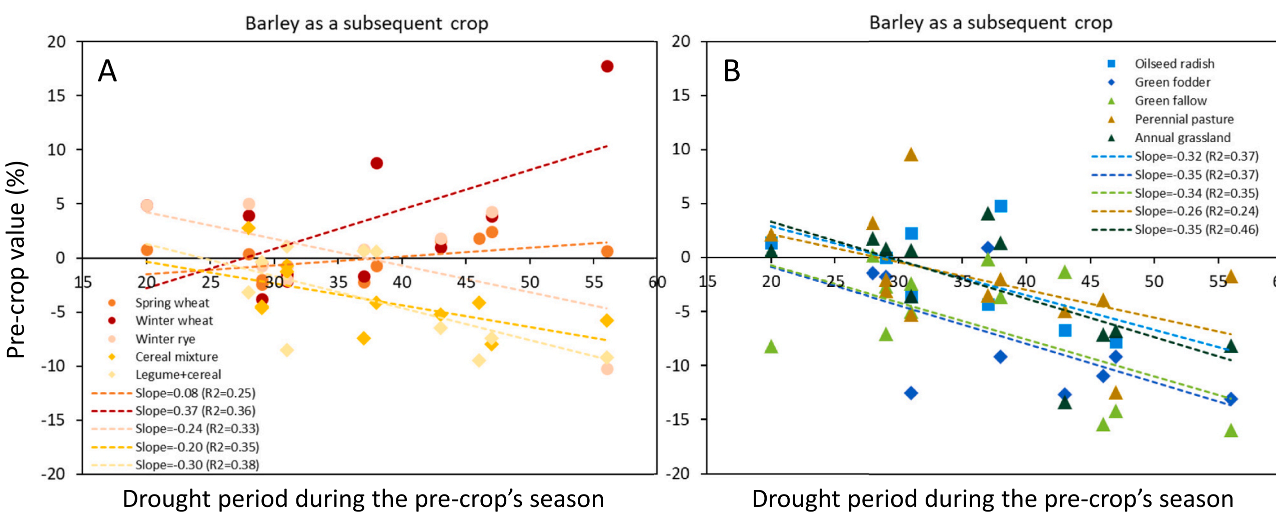

Fig. 9. Correlations between the length of the drought period during the growing season of a previous crop and the pre-crop value of different grain crops (panel A) and green biomass producing crops (B) for barley as a subsequent crop in rotation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Variation explained (%) in pre-crop values depending on farm and parcel characteristic over years and regions in Finland. Pre-crop, previous crop in crop sequencing; Subs-crop, subsequent crop in crop sequencing.

Covariance parameter	Farm characteristics		Field parcel characteristics					
	Farming system	Farm type	Size	Soil type	Shape	Slope	Distance to farm center	Distance to waterway
Characteristic	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.1
Subs-crop	30.4	31.1	20.5	43	37.6	44.2	31.3	31.1
Pre-crop	11.0	14.0	12.9	15.3	16.2	16.1	18.1	19.1
Characteristic × Pre-crop	15.0	0.0	9.1	0.4	2.8	0.0	0.2	0.0
Characteristic × Subs-crop	4.5	10.4	14.1	4.7	0.2	1.6	4.8	0.0
Year	0.4	0.3	1.0	0.7	0.1	0.6	0.6	0.1
Region	0.9	0.4	0.0	1.7	0.0	0.6	0.1	0.0
Year × Region	0.0	0.0	0.0	0.0	1.3	0.0	0.4	0.4
Unexplained	37.7	43.3	42.3	34.2	41.9	36.9	44.4	49.2

Table 5
Variation explained (%) in pre-crop values depending on farming system (FS) and farm type (FT) on eight year and region combinations in Finland. Pre-crop, previous crop in crop sequencing; Subs-crop, subsequent crop in crop sequencing.

Covariance parameter	South 2018	West 2017	West 2018	West 2019	West 2020	North 2017	North 2018	North 2019	North 2020	East 2018
	%	%	%	%	%	%	%	%	%	%
FS	6.6	0.0	0.0	0.0	0.0	6.6	0.0	0.0	0.0	0.0
Subs-crop	62.1	21.4	43.3	29.1	48.5	56.8	8.2	47.3	22.5	27.3
Pre-crop	2.2	27.0	27.8	38.2	17.0	0.6	20.2	29.7	0.0	0.0
FS × Pre-crop	11.6	0.0	0.0	3.2	0.0	2.9	9.4	0.0	44.7	41.5
FS × Subs-crop	2.3	0.0	0.0	16.3	14.2	8.9	0.0	0.0	0.2	13.0
Unexplained	15.3	51.6	28.9	13.2	20.3	24.1	62.2	23.0	32.6	18.2
FT	0.0	0.0	0.0	0.3	1.2	0.0	0.0	0.7	0.0	0.0
Subs-crop	49.3	9.1	19.8	34.8	42.5	41.8	20.7	35.8	29.5	27.4
Pre-crop	14.0	31.5	23.5	35.9	14.8	7.8	30.3	31.5	6.4	22.2
FT × Pre-crop	2.8	0.0	1.0	3.3	0.3	0.0	0.0	0.0	0.0	0.0
FT × Subs-crop	5.4	12.5	29.3	8.8	17.2	21.5	0.0	3.6	46.4	29.6
Unexplained	28.5	47.0	26.4	16.9	24.0	29.0	49.0	28.5	17.7	20.9

Table 6
Variation explained (%) in pre-crop values depending on parcel size (PZ) and soil type (ST) on eight year and region combinations in Finland. Pre-crop, previous crop in crop sequencing; Subs-crop, subsequent crop in crop sequencing.

Covariance parameter	South 2018	West 2017	West 2018	West 2019	West 2020	North 2017	North 2018	North 2019	North 2020	East 2018
	%	%	%	%	%	%	%	%	%	%
FS	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Subs-crop	66.2	10.8	77.1	22.3	29.5	10.4	11.3	20.7	16.7	22.8
Pre-crop	15.0	46.4	12.6	32.9	15.0	0.0	43.5	39.8	45.1	59.2
FS × Pre-crop	0.0	0.0	0.0	8.7	11.5	6.8	0.0	0.0	0.0	2.0
FS × Subs-crop	0.0	8.0	0.5	15.1	26.2	36.5	3.9	10.2	23.6	0.0
Unexplained	18.8	32.1	9.8	21.0	17.7	46.4	41.3	29.3	14.7	16.0
FT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Subs-crop	74.1	14.9	56.6	40.0	59.8	74.9	21.5	45.0	31.4	20.0
Pre-crop	9.0	37.5	9.3	35.5	21.1	2.2	27.3	27.6	0.0	0.0
FT × Pre-crop	0.9	10.2	0.6	3.6	0.0	0.0	0.0	2.1	47.1	0.0
FT × Subs-crop	0.0	15.0	20.9	0.0	2.4	0.0	0.0	7.1	0.0	0.0
Unexplained	16.0	22.4	12.6	20.9	16.7	22.9	51.2	18.3	21.5	80.0

environmental subsidies (Peltonen-Sainio and Jauhiainen, 2019) aiming to increase the heterogeneity of agricultural landscapes, reduce the risk of erosion and nutrient leaching, and to enhance biodiversity (Stoate et al., 2009; Herzon et al., 2011; Toivonen et al., 2015). On the other hand, fields with bare fallows may, e.g., be under construction of subsurface drainage systems, which aim for positive long-term impacts on productivity but without instantly realized benefits (e.g., because of use of heavy machinery).

4.2. The pre-crop values varied depending on prevailing conditions

In general, variation in the realized legacy effects seemed to be more dependent on the subsequent crop (21–44%) than the previous crop (11–19%) in rotation (Table 4). Both weather and farming conditions explained variation in the pre-crop values. Not only the growth performance and yield of a crop per se are prone to variation in weather and farming conditions, but also the legacy effects that a crop provides for the following one in rotation (Grange et al., 2022). This was evident in this study, where the data originated from farmers' fields. Elevated temperatures and drought periods often interfere with crop growth and yield determination in high-latitude conditions (Peltonen-Sainio et al., 2016a, 2016b, 2021). For legacy effects, the growing conditions during the growing seasons of both previous and subsequent crop matter. For example, a higher mean temperature and lower number of rainy days during the growing season of a previous crop often reduced the legacy effects for spring cereals (Figs. 3, 6 and S1). The impacts of higher temperatures during the season of a subsequent crop in rotation increased the realization of the legacy effects for barley, spring wheat, and rapeseed (Figs. 4 and 5), as did a higher number of rainy days for annual grasslands and potatoes contrary to barley and rapeseed (Figs. 7 and 8). Prolonged droughts in either of the growing seasons often reduced the legacy effects of crop sequencing (Figs. 9 and S2). This study highlights how challenging it must be for a farmer to identify the impacts of crop sequencing on yields, ecosystem services, and the farm economy (Preissel et al., 2015; Carof et al., 2019; Rämö et al., 2023; Tzemi et al., 2023) due to weather variation (Peltonen-Sainio et al., 2016a, 2016b), but also because of the complexity of the production systems (Kirkegaard et al., 2008). For example, the contribution of previous crops to the variation in pre-crop values varied depending on the farm and field parcel characteristics. Some regional differences were found as well in the realization of pre-crop values (Tables 5 and 6), but also depending on the farming system, farm type, parcel size, and soil type.

Findings of this study highlight the capacity of the novel method (Peltonen-Sainio et al., 2019) to produce comprehensive, nationwide data on pre-crop values for a high number of previous and subsequent crop combinations. Such unique, up-to-date data on pre-crop values can be used to support planning of crop rotations but also to identify variation in legacy effects as well as shortcomings in on-farm realization of experimentally proven pre-crop values. Another strength of this method is that up-to-date data from farmers' fields makes is possible to estimate pre-crop values as soon as the area under a novel crop starts to expand (Peltonen-Sainio and Jauhiainen, 2020). Thereby, farmers can be almost "immediately" supported with novel data. Considering potential limitations, NDVI-value correlates strongly with biomass (Liu et al., 2017; Chapungu et al., 2019), but not necessarily grain yield per se, because both biotic and abiotic stressors at late growth stages may reduce harvest index (Hay, 1995; Peltonen-Sainio et al., 2008).

5. Conclusions

This study was based on realized on-farm legacy effects of ca.

715,000 field parcels, corresponding to >1,818,000 observations in Finland, and it indicated high variation in the pre-crop values depending on the year, region, farm, and weather conditions (and often their interactions). These findings highlight how demanding it is for farmers to recognize the legacy effects provided by crop sequencing. There is an evident need to develop a decision support system that recognizes regional farming systems, available crop choices, crop management, weather conditions, and rationale behind the decision making of farmers. Evidently, better support calls for improved meta-data and this can only be implemented cost-effectively by applying remote sensing combined with large-scale experimental data. Thereby, applying regionally rational crop rotations can be supported to diversify the current cereal-based rotations.

CRediT authorship contribution statement

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

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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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.2023.103850.

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