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Assessing climate resilience of barley cultivars in northern conditions during 1980–2020

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A R T I C L E I N F O

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A B S T R A C T

Northern agriculture faces a rapidly changing climate with increased weather variability. Yield resilience can be assessed through diversity in responses to critical weather patterns, as demonstrated in several European crops. In this study, we extend the work to demonstrate how the response diversity of barley in Finland has developed over time. A total of 257 barley cultivars tested in 18 locations in Finland during 1980–2020 were clustered according to their yield responses to 12 critical agrometeorological variables. Clustering was based on the scores of the principal component analysis used to group the agrometeorological variables based on the yield responses. To identify the development in the response diversity, the diversity of the clusters cultivated was determined annually. The response diversity increased at the beginning of the 21st century but has declined since 2013. Consequently, the Northern barley cultivar selection has become more vulnerable to weather variation despite an increase of cultivars officially tested. The principal component analysis enabled a more interpretable and meaningful clustering than the formerly performed direct clustering of Finnish barley cultivars according to the agrometeorological variables.

1. Introduction

Diversity in crops and cultivars has been demonstrated to improve the resilience of plant production (Kahiluoto et al., 2014, 2019; Mäkinen et al., 2015, 2018; Bowles et al., 2020). The need for diversity and the resilience of production systems will be further emphasised in an increasingly challenging and variable climate with more frequent and severe extreme events (IPCC, 2012; Rummukainen, 2012; Kornhuber et al., 2019). The latter had been explored for barley production in Finland under anticipated future climatic conditions by Rötter et al. (2011). Himanen et al. (2013) showed that an increase in the cultivar diversity of barley resulted in an increase in regional yield and yield stability. The key to this is the notable response diversity of barley cultivars for many weather factors in Finland (Hakala et al., 2012). A high diversity of responses to weather has also been found in Finnish wheat (Mäkinen et al., 2018; Kahiluoto et al., 2019) and grass species (Mäkinen et al., 2015). However, the diversity of cropping fails to increase the resilience of the system if the diversity of crop and cultivar responses to different plausible weather events is not considered. For example, in many countries in Europe, the diversity in responses of wheat cultivars to weather events has decreased (Mäkinen et al., 2018; Kahiluoto et al., 2019). While wheat response diversity has been at a high level in Finland (Kahiluoto et al., 2019), that of barley has not developed at the pace of its cultivar diversity (Kahiluoto et al., 2014).

To improve the resilience of crop production, we need to focus on functional and response diversity rather than on the mere diversity of species or cultivars. Functional diversity, i.e., diversity in functional properties, is crucial for both ecological and economic productivity

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(Tilman et al., 1996, 1997, 2006; Tilman, 2000). Response diversity is an important facet of functional diversity; both are threatened by land use management systems that are too intensive (Tilman, 2000; Laliberté et al., 2010; IPCC, 2019). According to Tondelli et al. (2013), the establishment and progression of breeding programmes during the 20th century contributed to the narrowing of gene pools in cultivated barley. The cultivation of a limited number of crops and only the highest yielding crop cultivars may be an economically judicious choice in the short term. However, changes in the global market, environment, and climatic conditions demand attention to response diversity in agro-ecosystem management to insure the system against external disturbances and secure long-term farm income (Tilman, 2000; Kahiluoto et al., 2014, 2019; Kahiluoto and Kaseva, 2016; Porter et al., 2014; Savary et al., 2020).

In their global exploration of the importance of crop diversity, Jarvis et al. (2008) emphasised two separate aspects: crop diversity can reduce the sensitivity to immediate climate impact and provide a reserve for future adaptive capacity. In the present study, we measure response diversity directly, using yield responses of barley cultivars to weather events as a case, and demonstrate a generic approach to facilitate active adaptive management. We focus on the ways in which an individual farmer or region or country can manage response diversity and thus reduce sensitivity and enhance adaptive capacity. Ensuring capacity to adapt to climate change with its uncertainties, weather variability and extreme events would require increased diversity in response to factors that are, in the first place, related to temperature and precipitation (Rötter et al., 2011; Porter et al., 2014; Trnka et al., 2014).

Methodologically, we introduce an approach to reveal the response diversity of barley using principal component analysis (PCA) for agrometeorological variables as an intermediate step to the clustering of cultivars. The approach previously used for European wheat cultivars (Kahiluoto et al., 2019) and Finnish grass species and cultivars (Mäkinen et al., 2015) is applied and we determine whether structuring weather patterns using PCA before clustering enables a more relevant and interpretable assessment of diversity in terms of yield responses to weather in comparison with direct clustering of yield responses of cultivars to agrometeorological variables. We pose the following research question: How has climate resilience of Northern barley developed in the long term, including recent years?

2. Material and methods

2.1. The approach

This study consisted of five steps, beginning with selecting the critical agrometeorological variables up to the evaluation of the potential added value of selecting a diverse set of cultivars suitable for local climatic conditions. We utilised the grain yield data of 257 barley cultivars from official Finnish variety trials coordinated by Luke for the 1980–2020 period, with weather data from the Finnish Meteorological Institute for the same period.

Twelve agrometeorological variables, which were shown to be the most critical for barley (Trnka et al., 2011; Hakala et al., 2012; Rötter et al., 2013) were selected, and yield responses for all cultivars and for every variable were estimated using linear mixed models (LMM). PCA was used for yield response data to reveal the structure of agrometeorological variables that best represented the diversity of barley yield responses to weather. In addition, cultivars were clustered based on factor scores of the agrometeorological PCs. Annual diversity indices were constructed based on cultivated hectares of cultivar clusters, and the development of the response diversity index was investigated and compared to previous results ending in 2009. Finally, relative differences in diversity indices were compared among regions in Finland.

Table 1
Experimental sites, their latitudes, longitudes, average sowing dates and the number of trials. For an overview of climatic conditions at the different sites, see Fig. 1 in Rötter et al. (2013).

Location	Latitude North	Longitude East	Sowing date	Trials
Inkoo	60°20′	24°00′	12 May	11
Piikkiö	60°23′	22°33′	14 May	19
Pernaja	60°26′	26°02′	15 May	18
Lieto	60°30′	22°27′	15 May	15
Mietoinen	60°38′	21°55′	15 May	55
Anjalankoski	60°41′	26°48′	16 May	27
Jokioinen	60°49′	23°30′	17 May	44
Hauho	61°10′	24°33′	10 May	31
Kokemäki	61°17′	22°15′	16 May	14
Pälkäne	61°20′	24°13′	16 May	36
Mikkeli	61°40′	27°10′	15 May	32
Jyväskylä	62°14′	25°44′	17 May	8
Tohmajärvi	62°14′	30°21′	17 May	28
Laukaa	62°19′	26°19′	18 May	40
Ylistaro	62°57′	22°30′	16 May	137
Maaninka	63°09′	27°19′	18 May	35
Sotkamo	64°01′	28°22′	20 May	33
Ruukki	64°40′	25°06′	20 May	61

2.2. Cultivar yields in variety trials

The official variety trial data included 15,202 yield observations from 18 different locations around Finland (Table 1). The final data consists of a set of 257 cultivars of both Finnish and foreign origin from the early 1980s to the present; the southernmost site was Inkoo (60°2′N, 24°0′E), and the northernmost site was Ruukki (64°40′N, 25°06′E). All the experiments were arranged as randomised complete block designs or incomplete block designs, and the number of replicates ranged between three and four. The set of cultivars varied each year, but long-term check cultivars were used to help in the comparison of cultivars. Depending on location and year, the plot size was 5–10 m x 1.25 m, and fertiliser use depended on soil type and fertility and was comparable with standard practices in Finland (Hakala et al., 2012, 2020).

2.3. Selection of agrometeorological variables

Based on the literature (e.g., Trnka et al., 2011; Hakala et al., 2012; Kahiluoto et al., 2014), 12 agrometeorological variables expected to have a marked influence on growth and yield formation of barley at different phenological stages were selected. Two variables (9–10) were selected based on the Trnka et al. (2011) and the ten variables that most affected the yield in the variety trials were identified using regression analysis for variables that were selected based on previous literature and observations (for details, see Hakala et al., 2012). The Zadoks scale (Zadoks et al., 1974) was applied to characterise crop phenology, while the daily-based datasets of the Finnish Meteorological Institute were used to calculate weather variables. Missing values for the phenological development dates were substituted by estimates based on a linear model using known dates and latitudes (Hakala et al., 2012, 2020).

The 12 selected agrometeorological variables selected were: (1) precipitation during one month before sowing (mm); (2) deviation from a fixed early sowing date (May 1) (d); (3) precipitation during 3–7 weeks after sowing (mm); (4) heat stress and (5) extreme heat stress at anthesis (number of days with maximum temperatures of 25 °C (heat stress) or 28 °C or higher (extreme heat stress) during a period from 1 week before to 2 weeks after heading); (6) temperature sum (T_{sum} >5 °C) accumulation from 14 days prior to heading until heading (°C); (7) T_{sum} accumulation from heading to yellow ripeness (°C), (8) mean daily T_{sum} accumulation from heading to yellow ripeness (°C); (9) the sum of global radiation (MJ m^{-2}) from sowing to yellow ripeness; (10) the sum of growing days from sowing to yellow ripeness (d); (11) the number of days with rain (>1 mm) from sowing to yellow ripeness (d); and (12) seasonal precipitation from sowing to yellow ripeness (mm).

Among the agrometeorological variables, there were differences in conditions. Variables (1−2) correspond to wet soil that prevents fieldwork, where a delay in sowing may lead to early growth conditions that are too warm and dry for optimal yield formation (Hakala et al., 2012; Peltonen-Sainio et al., 2015). Variable (3) is related to the formation of yield potential; if the growing conditions are too dry during the period of grain number determination, the figure for grain m^{-2} may decrease, leading to yield penalties (Rajala et al., 2009, 2011; Hakala et al., 2012, 2020). Variables (4) and (5) refer to the effects of very high temperatures during anthesis, which may lead to a permanent reduction in the number of flowers and seed, and thereby yield reduction (Hakala et al., 2012, 2020; Ingvordsen et al., 2018). Variable (6) refers to the increased rate of development at high temperatures, which in the period of yield potential formation may result in a decreased number of seeds and yield (Hakala, 1998). Variables (7) and (8) describe warm conditions that may shorten the period of grain filling and thereby result in a decreased yield (Peltonen-Sainio et al., 2011, 2016; Hakala et al., 2012). Variable (9) describes the importance of radiation, which is essential for photosynthesis and crop growth. The number of sunshine hours in June correlated negatively with cereals yields in Estonia (Ingver et al., 2010), while in a recent report on wheat (Mäkinen et al., 2018), there was no correlation between effective global radiation and yield in the highest latitudes. Variable (10) refers to the length of the growing season, which could improve the yield, unless it is related to high precipitation (Hakala et al., 2020). Variable (11) refers to drought and possible high precipitation events that can lead to flooding, to which barley is sensitive (Hakala et al., 2012). Lastly, variable (12) refers to precipitation in general. High precipitation during the growing season has been shown to reduce barley yield (Hakala et al., 2020).

2.4. Responses of cultivars to weather

Cultivars with at least 20 yield observations were included in the previous analysis of response diversity of Finnish barley for a shorter time period and with a direct clustering excluding the intermediary step of PCA (Kahiluoto et al., 2014). Due to changes in the field trial evaluation procedure in the 2010s, often resulting in only 10–15 observations per cultivar, the limit was reduced to ten for new cultivars. However, because we were interested in the success of the newest cultivars and because we wanted to compare the updated approach most effectively with the previous one per se in 1980–2010, a limit of 20 observations was used until 2009, and a limit of 10 observations after 2009. Although this difference in the chosen limit of observations could slightly increase the variability of yield responses in 2010s, we did not want to diminish the previous results just to make the data more consistent without the expected benefit. The 12 agrometeorological variables were classified into three categories of equal numbers of observations, because the relations between yield and the agrometeorological variables were nonlinear in most cases. Even though this caused a loss of information, it enabled the comparison of the yield effects under clearly different weather circumstances. The chosen classification aimed at enough cultivar-wise observations for the extreme categories (low and high) to minimize the number of missing yield differences in the next step. For example, rain during one month before sowing was classified according to monthly rainfall at up to 25 mm (low), 25–40 mm (moderate), and 40–113 mm (high) precipitation in a month. Interactions of agrometeorological variables with cultivars were analysed using the following mixed model:

$$y_{ijklm} = \mu + \text{cultivar}_i + \text{category}_j + \text{cultivar} \times \text{category}_{ij} + \text{site} \times \text{year} \times \text{trial}(\text{category})_{klmj} + \varepsilon_{ijklm}$$

where y_{ijklm} is the observed yield, μ is the intercept, cultivar_i is the average yield level of the ith cultivar, category_j is average yield level at the jth level of categorized environment (j = 1,2,3), and cultivar × category_{ij} is the cultivar-by-environment interaction. All the effects above are fixed in the model. Site × year × $\text{trial(category)}_{klmj}$ is the random effect of the kth site, lth year, and mth trial within the jth category, and ε_{ijk} is the normally distributed residual error.

The difference in estimated yield between the high and the low categories was calculated for each cultivar and agrometeorological variable. For example, if a positive yield response indicated a better yield after a high precipitation season, a negative response indicated better yield in a low precipitation season. If more than a third of the twelve yield responses of a single cultivar was missing, it was excluded. The data for the multivariate analysis in the following steps consisted of the yield responses of 257 cultivars to 12 agrometeorological variables.

2.5. Principal component analysis of cultivar responses

PCA was used to group agrometeorological variables, some of which correlated strongly, leading to multicollinearity in the regression analysis. The purpose of PCA is to reveal the internal structure of the complex, correlated data and to reduce the data set to a lower dimension to reveal simplified structures. Only a few principal components (PCs) are required to contain most of the information, and an attempt is not even made to capture all variances with the PCs, because there is obviously much noise in such a dataset. The first PC always accounts for most of the variation, and the last PC accounts for the least.

To achieve the most interpretable solution, an orthogonal varimax rotation was used. The PCA was also fitted with a few alternative techniques (e.g., promax and the use of correlation matrix), but the structure was very stable, with four interpretable PCs. PC scores, combining the information of agrometeorological variables with PC scores, were calculated for every PC. To obtain the PC scores, multiple imputation (MI) for missing yield responses (8.1%) was used. The effects of MI on the structure of PCs were studied and found to be minor. The SAS procedure MI uses the multivariate normal approach via the Markov Chain Monte Carlo (MCMC) method.

2.6. Classification of cultivars

A cluster analysis using the hierarchical Ward's method (Ward, 1963), which starts with n clusters of size one and continues until all the observations are included in one cluster, was employed for the PC scores created as a by-product of PCA. This data consisted of the yield responses of 257 cultivars to four agrometeorological PCs.

The number of clusters was selected based on the dendrogram, the pseudo t^2-criterion and the variation of r-square (Yeo and Truxillo, 2005), and the squared Euclidean distances between data points were used. PC scores were left unstandardised to give less weight to a potential noise element and to reduce the sensitivity of clustering results to the number of PCs retained (Mimmack et al., 2001). To weight the average yield responses to the agrometeorological variables, PC loadings were used. These PC loadings were squared and divided by the eigenvalue of each PC, and the weighted means and SEs for each combination of PC and cluster were thus calculated according to the following equation:

$$\overline{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}, SE = \sqrt{\frac{\sum_{i=1}^{n} w_i (x_i - \overline{x})^2}{n}},$$

where w_i is the weight and x_i is the average yield response of cultivars to the ith agrometeorological variable.

2.7. Assessing response diversity

The differences between the cultivar type diversity index and response diversity index were studied at regional and country levels. While the type diversity index uses every cultivar as a unit, the response

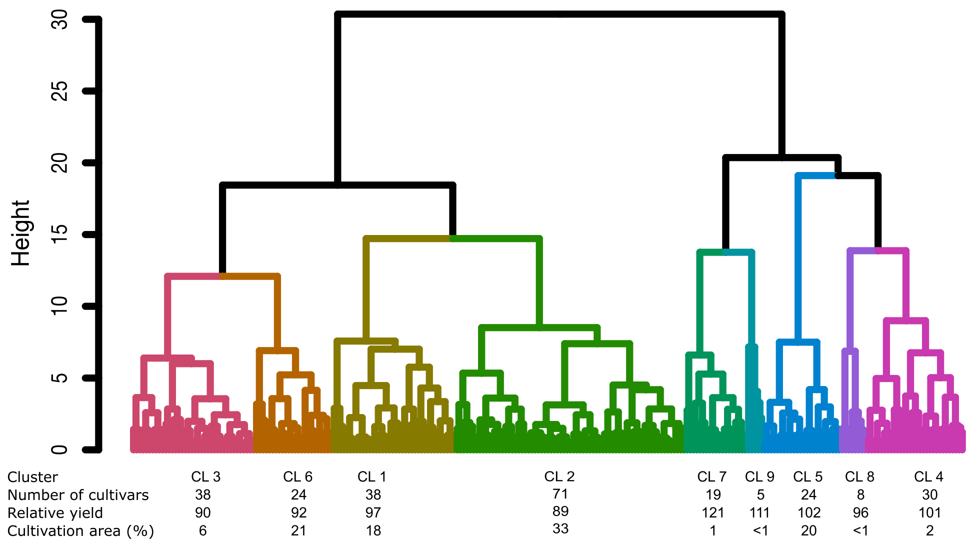

Fig. 1. Cultivar clusters. Division of cultivars in clusters according to their yield responses to the weather patterns based on PCs (Table 2). Nine clusters were selected based on this dendrogram, the pseudo t^2-criterion and the variation of r-square. Details about the clusters are shown at the bottom of the figure. Cultivation areas for the clusters are given as a percentage of the total barley area from 1996 to 2020.

diversity index uses clusters as units. The scale of indices differs based on the maximum number of units, and therefore only the shapes and trends of indices during a period were compared. To calculate the Shannon-Weaver indices (H) for two regions and for the whole country in 1996–2020, the following equation was used:

$$H = -\sum_{i=1}^{S}(p_i)(\ln p_i),$$

where p_i is the proportion of cultivar or response cluster i from a sample and S is the number of cultivars or response clusters of a sample. However, H is known to be highly nonlinear, and thus the effective number of cultivars or response clusters was interpreted based on the exponential of the Shannon index, which is known to be the correct measure of true diversity (Jost, 2007). All statistical analyses were performed using the GLIMMIX, MIXED, HPMIXED, FACTOR, MI, and REG procedures in the SAS Enterprise Guide 7.15 (SAS Institute Inc., Cary, NC, USA). The dendrogram of Fig. 1 was produced in R (R Core Team, 2021) using the package dendextend (Galili, 2015).

3. Results

3.1. Weather patterns critical to yield

Four agrometeorological PCs critical to yield were formed according to the sensitivity of cultivars to the twelve chosen agrometeorological variables: a high T_{sum} around heading and rapid accumulation of T_{sum} after heading (PC1); precipitation or drought (PC2); effective T_{sum} (>5 °C) and radiation (PC3); and precipitation before sowing (PC4, Table 2). These four PCs explained 71% of the total variation of the yield responses. Strong loadings of agrometeorological variables in the same PC indicate a similar effect on yield level.

At PC1, the loadings were strongest for the variables (4) and (5) (heat stress and extreme heat stress at anthesis) and (8) (mean daily T_{sum} accumulation from heading to yellow ripeness). The strongest variables for PC2 were (11) (the number of days with rain (>1 mm) from sowing to yellow ripeness) and (12) (seasonal precipitation from sowing to yellow ripeness). T_{sum} accumulation from 14 days prior to heading until yellow ripeness (6) and the sum of global radiation from sowing to yellow ripeness (9) were the strongest indicators for PC3, and precipitation during one month before sowing (1) was the strongest indicator for PC4 (Table 2).

3.2. Yield responses to weather patterns by cultivar clusters

Cultivars were grouped in nine clusters according to their yield responses to the weather patterns based on the PCs (Fig. 1). The structure of the nine clusters explained 64% of the total variation in yield responses measured in PC scores, and the clusters consisted of 5–71 cultivars with an average of 29 cultivars each. On average, the newest cultivars were found in the 7th cluster (regarding the launch year, $\bar{x}$=2014) and the oldest ones in the 2nd cluster ($\bar{x}$=1991). In addition, the highest yield level, 21% above average, was found in the 7th cluster, and the lowest, 11% below average, in the 2nd cluster (Fig. 1). Clusters 2, 4, and 7 consisted mainly of two-row cultivars, whereas six-row cultivars were dominant in the 5th and 6th cluster.

To determine which clusters benefited, and which suffered, from specific weather patterns, the means of yield responses were estimated for all combinations of PCs and clusters (Fig. 2). The differences between the clusters were detected based on the average yield responses to PCs. For example, the 2nd and 3rd clusters were quite similar, but their average yield response to PC1 differed most as the 2nd cluster clearly benefitted from a low T_{sum} around heading. Whereas the 2nd, 3rd, and 6th clusters were more stable irrespective of the weather patterns, the yield response of the last three clusters showed much more variation among the weather patterns. A quarter of yield responses were bigger than 500 kg ha^{-1}, and these were mainly due to the T_{sum} around heading. PC4 had a negative effect on all clusters but was most negative on the modern and unstable cluster (9th). The best ability to benefit from photosynthetically effective radiation (PC3) was found in the modern clusters (9th and 7th), with a positive yield response of 250–300 kg ha^{-1}, which suggests a profitable return of inputs in conditions that are especially favourable. However, if temperatures are too high for optimal grain number or grain filling (PC1), or the growing time is shorter than optimal, e.g., because of abundant precipitation before sowing (PC4), the yield loss of cultivars in the 7th cluster can be 500–900 kg ha^{-1}. Although this would be a significant yield loss for a cultivar with a modest yield level, it only brings yields of this cluster to an average level or higher than that in the oldest cluster (2nd), which explains the recent increase in the cultivation area of the most recent cluster (7th). All clusters suffered from a high T_{sum} around heading (PC1), but the 3rd and 6th clusters suffered least (about 100 kg ha^{-1}),

Table 2
Principal component (PC) loadings of the Varimax-rotated pattern of 12 agrometeorological variables, based on principal component analysis (PCA). Highly loaded variables (>|0.50|) are in bold. The total variance explained (71%) by the PCs are presented for each PC in the bottom row.

Agrometeorological variable	T_{sum} around heading	Precipitation or drought	Effective T_{sum} and radiation	Precipitation before sowing
(4) Heat stress at anthesis (d)	**0.92**	-0.20	0.00	0.08
(8) Mean daily T_{sum} accumulation from heading to yellow ripeness (°C)	**0.89**	-0.25	-0.06	0.08
(5) Extreme heat stress at anthesis (d)	**0.85**	0.29	0.19	-0.01
(11) The number of days with rain from sowing to yellow ripeness (d)	-0.14	**0.85**	-0.03	0.05
(12) Seasonal precipitation from sowing to yellow ripeness (mm)	0.01	**0.83**	-0.09	0.16
(3) Precipitation during 3–7 weeks after sowing (mm)	-0.08	**0.67**	-0.08	-0.41
(6) T_{sum} accumulation from 14 days prior to heading until heading (°C)	0.22	-0.19	**0.67**	0.16
(9) Sum of global radiation from sowing to yellow ripeness (MJ m^{-2})	-0.27	-0.35	**0.63**	-0.36
(2) Deviation from a fixed early sowing date (d)	-0.09	0.25	**0.62**	0.18
(7) T_{sum} accumulation rate from heading to yellow ripeness (°C)	0.27	-0.26	**0.60**	-0.14
(10) Sum of growing days from sowing to yellow ripeness (d)	-0.38	0.40	**0.56**	-0.32
(1) Precipitation during one month before sowing (mm)	0.06	0.03	0.02	**0.89**
Variance explained (%)	22.8	20.7	16.4	10.9

while the 4th, 8th, and 9th clusters suffered about 1000 kg ha^{-1}.

While the four most unpopular clusters accounted for only 0–2% of the cultivation area during the study period, cultivation of the modern cluster (7th) with the highest yielding and newest cultivars has been increasing for the last 5–6 years (Fig. 3b). These cultivars benefit from long and warm growing seasons with high radiation (Fig. 2). The growing cluster (5th) was cultivated throughout Finland, with seven brand new cultivars entering the market. Of the other popular clusters, the first also had seven new cultivars, while the 6th cluster had only one new cultivar. The old popular (2nd) cluster with the earliest launch year on average also had a few potential two-row cultivars, indicating that all clusters have some potential new cultivars for the near future (Fig. 3).

3.3. Development of the dominance of the clusters

The cultivars from the oldest cluster (2nd) representing rather stable yield responses to weather patterns dominated the cultivation area in Finland until 2000, after which the cluster gradually faded away (Fig. 4). The cultivation areas of the most popular clusters (6th, 5th, and 1st) representing low T_{sum} around heading and resistance to precipitation have grown rapidly, in that order. Together, they had covered about 80% of the total field area under barley cultivation by 2020. While cultivars in the 6th cluster are older and yield less, the newest cultivars in both clusters (5th and 6th) yielded up to 20–30% more than the present average, which may explain their increasing cultivation areas. The most stable cluster (3rd) emerged after 2009 but has decreased since 2014. In 2002–2010, the 6th cluster lost its position but grew again in area thereafter and is now the second most cultivated cluster, and is especially dominant in the north of Finland (Fig. A1b). The most cultivated cluster (5th) has grown in area annually throughout the country, while the development of the 1st cluster was fastest between 2004 and 2010 (Fig. 4b). Although the first cluster is still popular in southern Finland (Fig. A1a), it has almost faded away in the north. Overall, there seems to be a transition from one dominant cluster to a few new ones in southern Finland, while the variation is more complex in northern Finland (Fig. A1b).

3.4. Value added of response diversity

Diversity indices for cultivation areas of cultivars were calculated for 1996–2020 (Fig. 5). The type diversity index refers to the diversity of individual cultivars, whereas the response diversity index refers to the diversity of the cultivar clusters. Both indices increased until 2000, after which the increase was moderate until the mid-2010s. The division of the cultivated area into new cultivars then continued, stabilising at the current level in 2013. True diversity, which is the exponential of the Shannon diversity index, for cluster responses in 2000–2013 increased by 56% but has decreased slightly since, being 36% higher in 2020 than in 2000 due to the dominance of the three clusters (Fig. 5). At the same time, true diversity for individual cultivars has grown 120% since 2000. Consequently, cultivar use is 2.2 times as diverse in 2020 as in 2000, while the true response diversity of clusters is only 1.4 times higher in 2020 than in 2000.

The annual diversity indices were also studied regionally by dividing Finland into two parts (Fig. A2). Both indices increased in southern Finland until 2016, but in the north, the decline had already started in 2013. The country-level indices approximately reflect the average of the two regions, as the cultivation areas of both regions are quite similar in size.

4. Discussion

4.1. Identifying cultivar clusters

The results indicated more diverse barley cultivation after 2009 compared to Kahiluoto et al. (2014). A cluster dominant in the earlier study was now divided into three clusters, which the previous method could not identify (Fig. 4a), thus reflecting the value added of including PCA. Although the cultivar type diversity and the number of cultivars to select from increased steadily throughout the study period, the response diversity started to decrease after 2013, indicating increased vulnerability and decreased resilience, which was not revealed merely by the cultivar diversity. This demonstrates that the response diversity is a more targeted measure for resilience to weather variability whereas the type diversity does not recognize the similarity of individual cultivars.

In accordance with the conclusions of Hakala et al. (2012), the PCA model constructed in this present study showed more diversity in response to the variables related to temperature than to precipitation. A high diversity of barley cultivars in their responses to high temperatures around heading and to a high rate of T_{sum} accumulation prior to grain filling was also revealed by the PCA model in the present study. The correlation between yield responses to weather revealed by the trial-based data and those assessed on farmers' fields was also studied with PCA and found satisfactory already in our previous study, although it was not reported then. However, we hypothesized and evaluated the new method to be more stable and to have more interpretable results for the response diversity using unstandardised PC scores in clustering. This appears to reduce noise in data, although the previously used

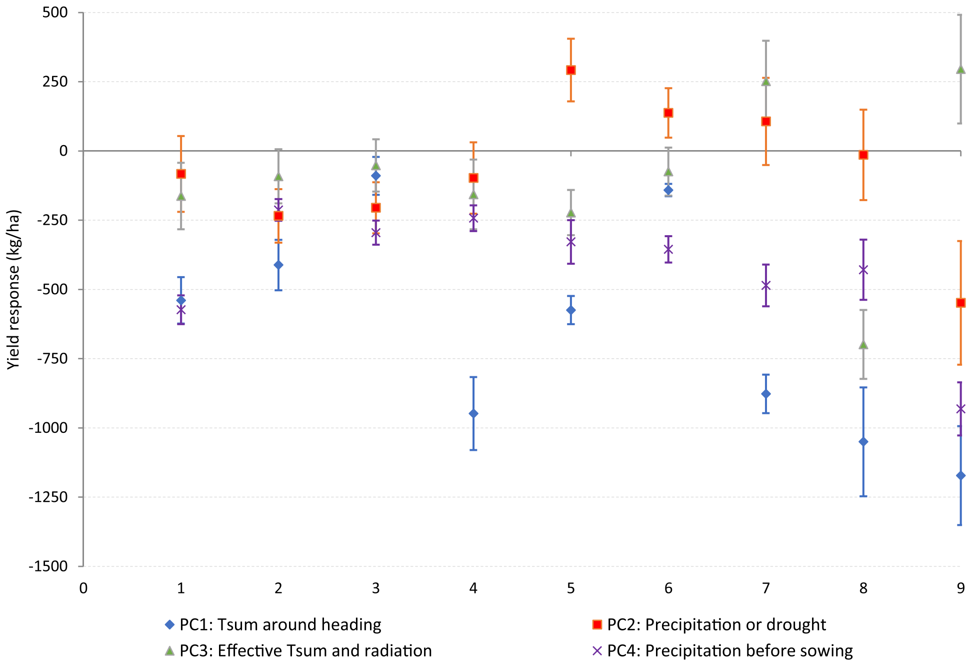

Fig. 2. Yield responses of the cultivar clusters to the weather patterns. The yield effects of four weather patterns (PCs) critical to the barley yield for the nine identified cultivar clusters (in the x-axis) are shown in the y-axis. The effects of each PC on the weighted mean yields are marked with a symbol, and the standard error is shown by vertical bars. The yield effects are presented for a large amount of mentioned weather patterns; for example, a high accumulation of T_{sum} around heading (PC1) will lead to yield loss in every cluster. In the second PC, positive values indicate the benefit of precipitation and negative values the benefit of drought.

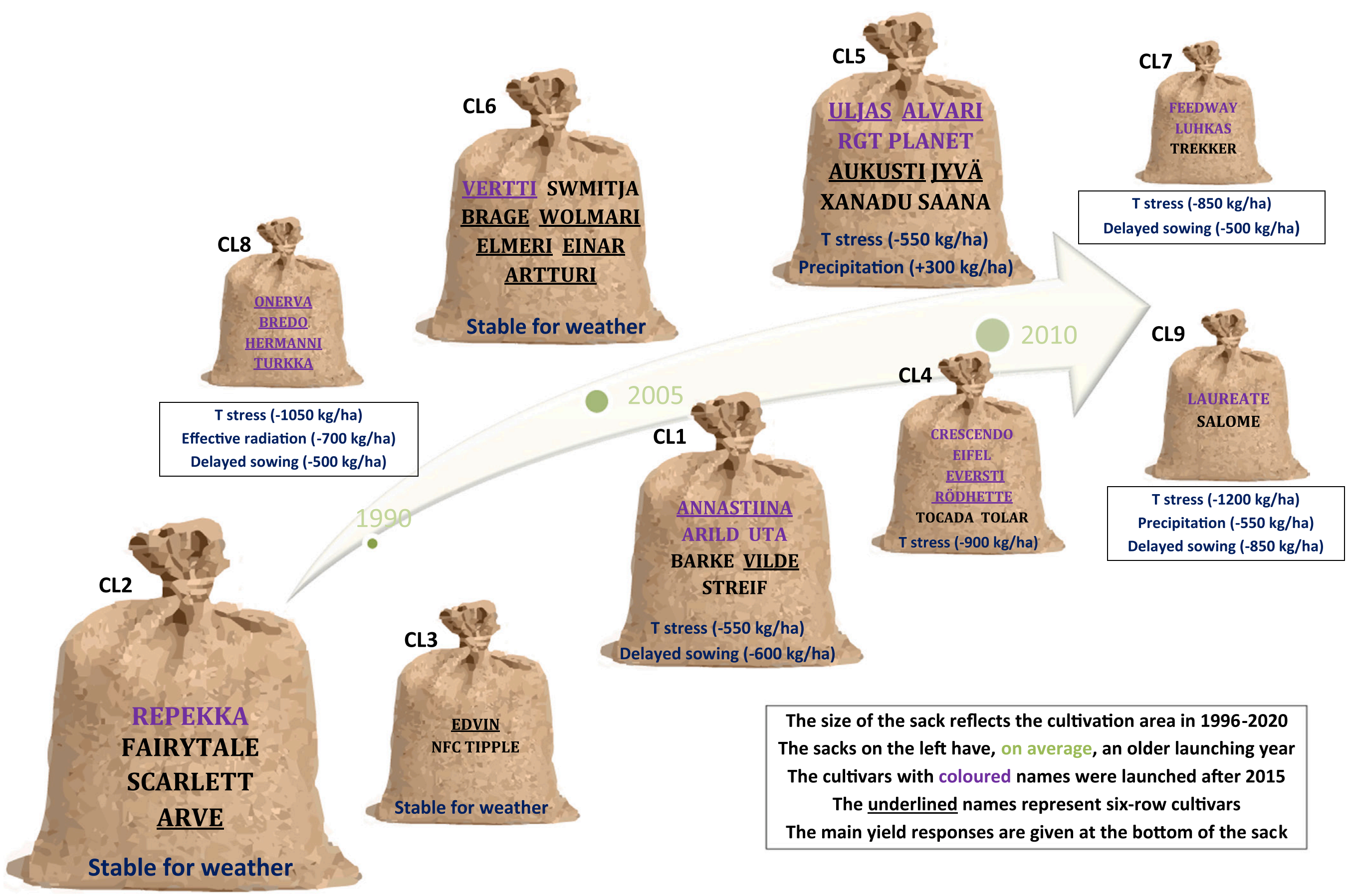

Fig. 3. Cultivars according to popularity or future potential. Each sack contains modern cultivars even when the average age (presented by the arrow) of the cultivars is high. Choosing cultivars from different sacks would diversify barley cultivation in Finland in terms of resilience to weather variability. T stress refers to temperature stress.

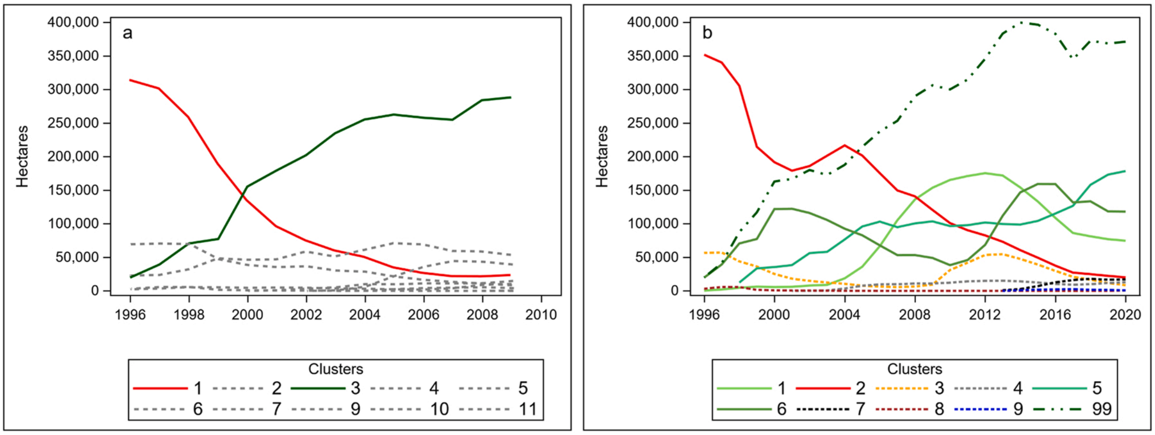

Fig. 4. Development of the cultivated area of the cultivar clusters in Finland in the years 1996–2010 (a) and 1996–2020 (b). Cluster numbers regarding the advanced approach with PCA for 1996–2020 of the current analysis (b) cannot be compared directly with the previous analysis excluding PCA for 1996–2009 (a), where only two main clusters are coloured. The same main colours in (a) and (b) illustrate that the 3rd cluster in the previous analysis excluding PCA (a) is in the current analysis (b) divided into three clusters (1, 5, and 6). An artificial cluster (named as 99) summarises the hectares of these three clusters to facilitate the comparison.

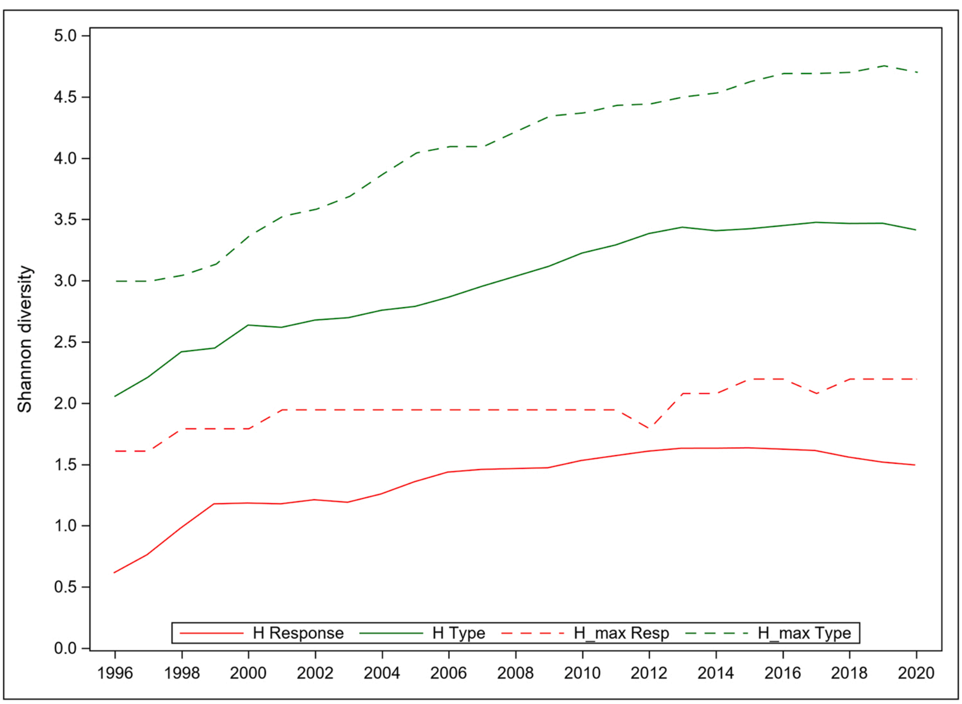

Fig. 5. Development of cultivar diversity. The cultivar (Type) and the weather response (Response) based diversity indices for barley in Finland are measured by the Shannon diversity index (H). Dashed lines show the theoretical maximum of both indices, which are a logarithm of the maximum numbers (max) of cultivars or clusters, respectively. Although the amount and equitability of the cultivar use increased up until 2013, these cultivars mainly represented only a few clusters, especially after 2013.

Mahalanobis distances between yield responses are theoretically a more straightforward way to cluster yield responses. The standardisation of PC scores seems to lead to quite similar results, but we have found this a more sophisticated method to also take into account the eigenvalues of PCs.

Modern cultivars are usually tested with only 10–15 trials each, so we had to reduce the limit of observations per cultivar required. This may reduce the reliability of estimated yield responses for each agrometeorological variable when cultivar-specific estimates are based on fewer observations, and the limit was thus reduced only for the new data. We controlled this issue of reliability by requiring that each added cultivar have estimated yield responses at least for two thirds of the agrometeorological variables. The structure of PCs changed little after the addition of new data, which also suggests that the datasets were consistent. Overall, the benefits of adding 60 modern cultivars with a lower observation limit were considered more important than the potential disadvantages.

Although, the use of best linear unbiased predictions (BLUP) is common in genotypic modelling, the use of best linear unbiased estimates (BLUE) allowed us to compare the most recent decade with the previous study and to use kilograms throughout the analysis and report the actual yield effects in kilograms per hectare for factors and clusters also. Also due to the inherent variation in cultivars yields, e.g. for growth time and type of spikelet (two- and six-row cultivars), the use of random effects has previously been found to underestimate the differences between cultivars in our studies. In this study, we were most interested in the genotype by agrometeorological variable interaction, which makes the interpretation of that random GxE interaction more complex than using it as a fixed effect.

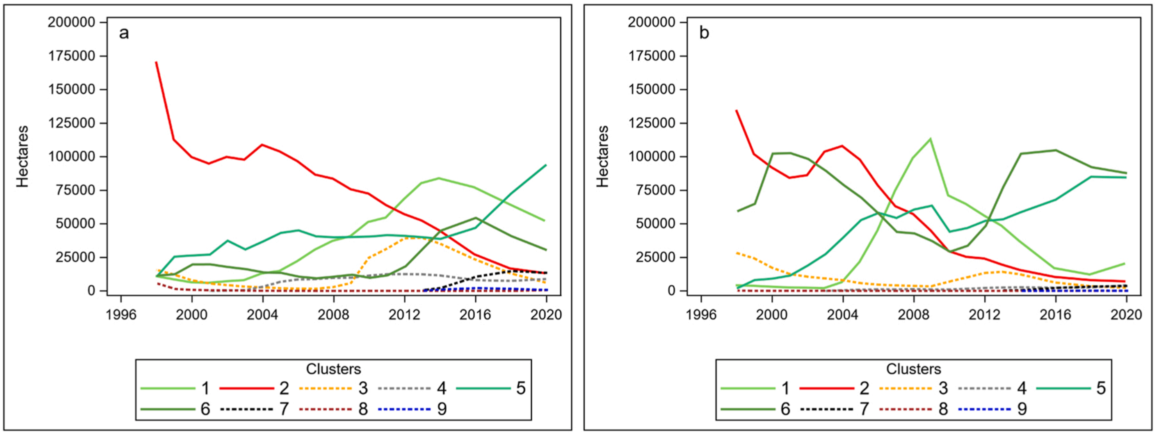

Fig. A1. Annual cultivated hectares in a) southern and b) northern Finland by each cultivar cluster for 1998–2020, respectively. Data for 2017 and 2019 were not available, so estimates have been used. In southern Finland, the transition has been from one cluster to a few new ones, while in northern Finland the variation is more complex.

4.2. Farmers' practices

As found in the previous study, the decline in the cultivation area of the dominant cluster in the 2000s is probably due to the modest yields of the rather old cultivars in this cluster, despite their yield reliability and stability in most weather conditions. The lack of reactions to weather indicates not only reliability, but also an inability to benefit from exceptionally favourable conditions. Farmers' income is often based on area-based subsidies rather than profits from grain sales. Therefore, modern full-time farmers may prefer to take at least some risk at the cost of yield reliability. The fact that the number of farms in Finland is decreasing, while the size of farms is increasing (www.luke.fi/economydoctor), also suggests a trend of farming becoming more professional. In accordance with this, a recent study in Finland showed that the intention of farmers to try new crops and cultivars is higher the bigger the farm is (Peltonen-Sainio et al., 2020). The yields of the new cultivars in the oldest (2nd) cluster are developing favourably, which may help to increase the area of cultivation of this weather-stable cluster in the future, especially if the extreme events brought by climate change and cultivation risks thereby increase (IPCC, 2012), as assessed for Finland by Rötter et al. (2013).

While farmers are tempted to cultivate high-yielding cultivars, they also tend to sow cultivars with different growing times, both to secure their maturation in the short Finnish growing season and to diversify harvesting times in the autumn (Palosuo et al., 2015). In Europe as a whole, farmers have also been shown to react to the changing climate by changing the time window of cultivation and choosing a more diverse selection of crops and crop cultivars (Olesen et al., 2011), taking into account the perceived shifts in favourable weather for the pre- and post-anthesis periods of the growing cycle. Most cultivars in the most popular clusters (5th and 6th) are cultivars with a short growing time, which secures their maturation before the autumn rains. In addition, the 6th cluster, in particular, was shown to be about as tolerant to different weather events as the old popular cluster (2nd), which would increase its yield stability in less favourable conditions. The tolerable yield levels with the short growing time and the reliability of cultivation may be the reasons for the significant share of this cluster in the cultivation area of barley in Finland. Another reason is that the short growing time of the cultivars in this cluster means some of them can also be grown in the north of Finland, where the growing season is extremely short. Moreover, the cultivars are mainly used for fodder and are cultivated for that purpose in all areas in Finland, both in the south and in the north. The number of promising newcomers with yield levels exceeding 6000 kg ha^{-1} suggests that the most popular clusters (5th and 6th) will continue to be among the dominant clusters in the near future.

Barley, which is the most cultivated crop in Finland, is more sensitive to high than to low precipitation (Hakala et al., 2020). However, drought in early growth phases, when the amount of grain per area is determined also, significantly decreases barley yields (Hakala et al., 2012). In the present study, all the clusters with large cultivation areas had low sensitivity or even benefited from abundant precipitation (PC2). Tolerating at least some excess moisture is a beneficial trait in barley cultivation especially with the increased occurrence of extreme rain events during the growing season in the future climate (Ruosteenoja et al., 2016).

The most modern clusters (7th and 9th) were the only ones clearly benefiting from effective T_{sum} and radiation (PC3). At the same time, they suffered from high precipitation before sowing (PC4). These qualities suggest that these clusters would succeed best in future warmer conditions with long growing seasons and high temperature sums, allowing the realisation of a high yield potential. Accordingly, the cultivation area of the most modern cluster (7th) has started to increase recently, mainly in southern Finland. The potential of this cluster in the market is likely to increase further if climate warming with higher T_{sums} and longer growing seasons continues in Finland in the 21st century (Ruosteenoja et al., 2016). The fact that the same increase is not shown for the other modern but unstable cluster (9th), found extremely sensitive to precipitation during growing season, suggests that tolerance of or even benefiting from increased precipitation is one of the crucial qualities for future conditions with an increased risk of heavy rain events and interannual weather variability (IPCC, 2012; Rummukainen, 2012).

5. Conclusions

The significant increase in the number of barley cultivars during the first decade of the 21st century in Finland has now stagnated. Furthermore, response diversity as the most critical factor for the resilience of barley cultivation to weather variability levelled off earlier has begun a decline since the mid-2010s. Attention therefore needs to be paid to ensure that this recent decline does not continue. The identification of response diversity critically enhances the understanding of resilience and adaptive capacity of cropping. Moreover, the demonstrated approach including PCA to structure the weather patterns based on yield responses provides a generic method to promote resilience in practice. A practical tool based on the method is directly applicable to farms and regions in Finland and can be adjusted to serve other regions and countries. The approach presented in the present study for barley can be used to identify the most critical gaps and the highest gains by diversification, and underpin and demonstrate the value of response diversity for enhancing resilience. Generally, this applies more for the response of

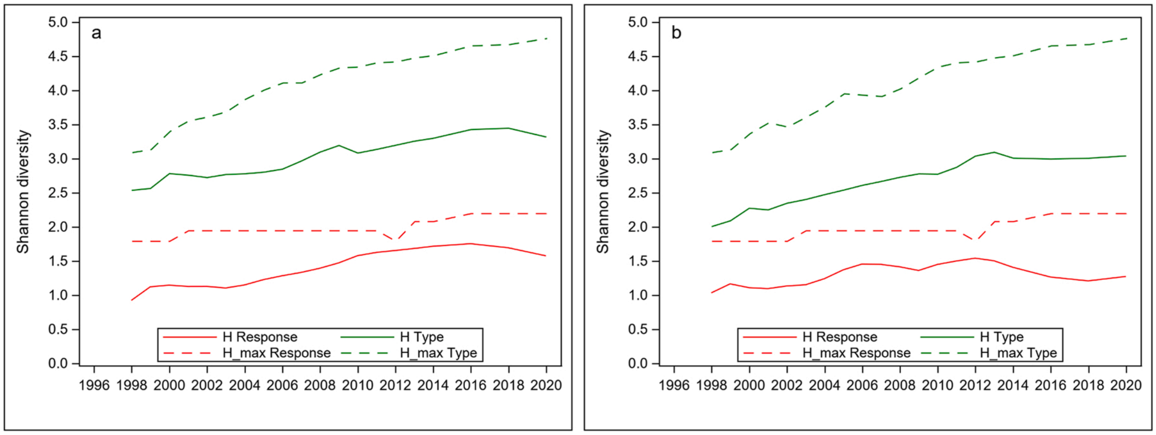

Fig. A2. Annual type and response diversity indices measured by the Shannon diversity index (H) in a) southern and b) northern Finland by each cultivar cluster for 1998–2020, respectively. Data for 2017 and 2019 were not available, so estimates have been used. Dashed lines show the theoretical maximums (max) of both indices, which are a logarithm of the numbers of cultivars or clusters, respectively. Both indices increased in southern Finland during 2016, but in northern Finland the decline had already started in 2013.

crop diversity to weather, production line or farm activity to price fluctuations, and even for supplier diversity to plausible supply disturbances or changes in demand (Kahiluoto et al., 2020).

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

See Figs. A1 and A2 here.

References

Bowles, T., Mooshammer, M., Socolar, Y., Calderón, F., Cavigelli, M., Culman, S., Deen, W., Drury, C., Garcia y Garcia, A., Gaudin, A., Harkcom, W., Lehman, R., Osborne, S., Robertson, G., Salerno, J., Schmer, M., Strock, J., Grandy, A., 2020. Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. One Earth 2, 284–293. https://doi.org/10.1016/j.oneear.2020.02.007.

Galili, T., 2015. Dendextend: An R package for visualizing, adjusting, and comparing trees of hierarchical clustering. Bioinformatics. https://doi.org/10.1093/bioinformatics/btv428.

Hakala, K., 1998. Growth and yield potential of spring wheat in a simulated changed climate with increased CO_2 and higher temperature. Eur. J. Agron. 9, 41–52. https://doi.org/10.1016/S1161-0301(98)00025-2.

Hakala, K., Jauhiainen, L., Himanen, S.J., Rötter, R.P., Salo, T., Kahiluoto, H., 2012. Sensitivity of barley varieties to weather in Finland. J. Agric. Sci. 150, 145–160. https://doi.org/10.1017/S0021859611000694.

Hakala, K., Jauhiainen, L., Rajala, A.A., Jalli, M., Kujala, M., Laine, A., 2020. Different responses to weather events may change the cultivation balance of spring barley and oats in the future. Field Crops Res. 259, 107956 https://doi.org/10.1016/j.fcr.2020.107956.

Himanen, S.J., Ketoja, E., Hakala, K., Rötter, R., Salo, T., Kahiluoto, H., 2013. Cultivar diversity has great potential to increase yield of feed barley. Agron. Sustain. Dev. 33, 519–530. https://doi.org/10.1007/s13593-012-0120-y.

Ingver, A., Tamm, I., Tamm, Ü., Kangor, T., Koppel, R., 2010. The characteristics of spring cereals in changing weather in Estonia. Agron. Res. 8 (Special Issue III), 553–562.

Ingvordsen, C.H., Lyngkjær, M.F., Peltonen-Sainio, P., Mikkelsen, T.N., Stockmarr, A., Jørgensen, R.B., 2018. How a 10-day heatwave impacts barley grain yield when superimposed onto future levels of temperature and CO_2 as single and combined factors. Agric. Ecosyst. Environ. 259, 45–52. https://doi.org/10.1016/j.agee.2018.01.025.

IPCC, 2012. In: Field, C.B., Barros, V., Stocker, T.F., Qin, D., Dokken, D.J., Ebi, K.L., Mastrandrea, M.D., Mach, K.J., Plattner, G.-K., Allen, S.K., Tignor, M., Midgley, P.M. (Eds.), Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, and New York, NY, USA, p. 582. 〈https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf〉.

IPCC, 2019, Climate change and land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. 〈https://www.ipcc.ch/site/assets/uploads/2019/08/4.-SPM_Approved_Microsite_FINAL.pdf〉.

Jarvis, D.I., Brown, A.H.D., Cuong, P.H., Collado-Panduro, L., Latournerie-Moreno, L., Gyawali, S., Tanto, T., Sawadogo, M., Mar, I., Sadiki, M., Hue, N.T.-H., Arias-Reyes, L., Balma, D., Bajracharya, J., Castillo, F., Rijal, D., Belqadi, L., Rana, R., Saidi, S., Ouedraogo, J., Zangre, R., Rhrib, K., Chavez, J.L., Schoen, D., Sthapit, B., De Santis, P., Fadda, C., Hodgkin, T., 2008. A global perspective of the richness and evenness of traditional crop-variety diversity maintained by farming communities. PNAS 105, 5326–5331. https://doi.org/10.1073/pnas.0800607105.

Jost, L., 2007. Partitioning diversity into independent alpha and beta components. Ecology 88, 2427–2439. https://doi.org/10.1890/06-1736.1.

Kahiluoto, H., Kaseva, J., 2016. No evidence of trade-off between farm efficiency and resilience - dependence of resource-use efficiency on land-use diversity. PLOS One 11 (9), e0162736.

Kahiluoto, H., Kaseva, J., Hakala, K., Himanen, S.J., Jauhiainen, L., Rötter, R.P., Salo, T., Trnka, M., 2014. Cultivating resilience by empirically revealing response diversity. Glob. Environ. Change 25, 186–193. https://doi.org/10.1016/j.gloenvcha.2014.02.002.

Kahiluoto, H., Kaseva, J., Balek, J., Olesen, J.E., Ruiz-Ramos, M., Gobin, A., Kersebaum, K.C., Takáč, J., Ruget, F., Ferrise, R., Bezak, P., Capellades, G., Dibari, C., Mäkinen, H., Nendel, C., Ventrella, D., Rodríguez, A., Bindi, M., Trnka, M., 2019. Decline in climate resilience of European wheat. PNAS 116, 123–128. https://doi.org/10.1073/pnas.1804387115.

Kahiluoto, H., Mäkinen, H., Kaseva, J., 2020. Supplying resilience through assessing diversity of responses to disruption. IJOPM 40, 271–292. https://doi.org/10.1108/ijopm-01-2019-0006.

Kornhuber, K., Osprey, S., Coumou, D., Petri, S., Petoukhov, V., Rahmstorf, S., Gray, L., 2019. Extreme weather events in early summer 2018 connected by a recurrent hemispheric wave-7 pattern. Environ. Res. Lett. 14, 054002 https://doi.org/10.1088/1748-9326/ab13bf.

Laliberté, E., Wells, J.A., Declerck, F., Metcalfe, D.J., Catterall, C.P., Queiroz, C., Aubin, I., Bonser, S.P., Ding, Y., Fraterrigo, J.M., McNamara, S., Morgan, J.W., Merlos, D.S., Vesk, P.A., Mayfield, M.M., 2010. Land-use intensification reduces functional redundancy and response diversity in plant communities. Ecol. Lett. 13, 76–86. https://doi.org/10.1111/j.1461-0248.2009.01403.x.
Mäkinen, H., Kaseva, J., Virkajärvi, P., Kahiluoto, H., 2015. Managing resilience of forage crops to climate change through response diversity. Field Crops Res 183, 23–30. https://doi.org/10.1016/j.fcr.2015.07.006.
Mäkinen, H., Kaseva, J., Trnka, M., Balek, J., Kersebaum, K.C., Nendel, C., Gobin, A., Olesen, J.E., Bindi, M., Ferrise, R., Moriondo, M., Rodríguez, A., Ruiz-Ramos, M., Takáč, J., Bezák, P., Ventrella, D., Ruget, F., Capellades, G., Kahiluoto, H., 2018. Sensitivity of European wheat to extreme weather. ISSN 0378-4290 Field Crops Res. 222, 209–217. https://doi.org/10.1016/j.fcr.2017.11.008.
Mimmack, G.M., Mason, S.J., Galpin, J.S., 2001. Choice of distance matrices in cluster analysis: Defining regions. J. Clim. 14, 2790–2797. https://doi.org/10.1175/1520-0442(2001)014<2790:CODMIC>2.0.CO;2.
Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Rossi, F., Kozyra, J., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34, 96–112. https://doi.org/10.1016/j.eja.2010.11.003.
Palosuo, T., Rötter, R.P., Salo, T., Peltonen-Sainio, P., Tao, F., Lehtonen, H., 2015. Effects of climate and historical adaptation measures on barley yield trends in Finland. Clim. Res. 65, 221–236. https://doi.org/10.3354/cr01317.
Peltonen-Sainio, P., Jauhiainen, L., Hakala, K., 2011. Crop responses to temperature and precipitation according to long-term multi-location trials at high-latitude conditions. J. Agric. Sci. 149, 49–62. https://doi.org/10.1017/S0021859610000791.
Peltonen-Sainio, P., Rajala, A., Känkänen, H., Hakala, K., 2015. Improving farming systems in northern Europe. In: Sadras, V.O., Calderini, D. (Eds.), Crop Physiology (2nd edition) - Applications for Genetic Improvement and Agronomy. Acad. Press, Oxford, pp. 65–91. https://doi.org/10.1016/B978-0-12-417104-6.00004-2.
Peltonen-Sainio, P., Venäläinen, A., Mäkelä, H.M., Pirinen, P., Laapas, M., Jauhiainen, L., Kaseva, J., Ojanen, H., Korhonen, P., Huusela-Veistola, E., Jalli, M., Hakala, K., Kaukoranta, T., Virkajärvi, P., 2016. Harmfulness of weather events and the adaptive capacity of farmers at high latitudes of Europe. Clim. Res. 67, 221–240. https://doi.org/10.3354/cr01378.
Peltonen-Sainio, P., Sorvali, J., Kaseva, J., 2020. Winds of change for farmers: Matches and mismatches between experiences, views and the intention to act. Clim. Risk Manag. 27, 100205 https://doi.org/10.1016/j.crm.2019.100205.
Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D. B., Travasso, M.I., 2014. Food security and food production systems. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 485–533.
R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing,, Vienna, Austria (URL). ⟨https://www.R-project.org/⟩.
Rajala, A., Hakala, K., Mäkelä, P., Muurinen, S., Peltonen-Sainio, P., 2009. Spring wheat response to timing of water deficit through sink and grain filling capacity. Field Crops Res 114, 263–271. https://doi.org/10.1016/j.fcr.2009.08.007.
Rajala, A., Hakala, K., Mäkelä, P., Peltonen-Sainio, P., 2011. Drought effect on grain number and grain weight at spike and spikelet level in six-row spring barley. J. Agron. Crop Sci. 197, 103–112. https://doi.org/10.1111/j.1439-037X.2010.00449.x.
Rötter, R.P., Palosuo, T., Pirttioja, N.K., Dubrovsky, M., Salo, T., Fronzek, S., Aikasalo, R., Ristolainen, A., Carter, T.R., 2011. What would happen to barley production in Finland if global warming exceeded 4°C? A model-based assessment. Eur. J. Agron. 35, 205–214. https://doi.org/10.1016/j.eja.2011.06.003.
Rötter, R.P., Höhn, J., Trnka, M., Fronzek, S., Carter, T.R., Kahiluoto, H., 2013. Modelling shifts in agroclimate and crop cultivar response under climate change. Ecol. Evolut. 3, 4197–4214. https://doi.org/10.1002/ece3.782.
Rummukainen, M., 2012. Changes in climate and weather extremes in the 21st century. Clim. Change 3, 115–129. https://doi.org/10.1002/wcc.160.
Ruosteenoja, K., Jylhä, K., Kämäräinen, M., 2016. Climate projections for Finland under the RCP forcing scenarios. Geophysica 51, 17–50. ⟨http://www.geophysica.fi/pdf/geophysica_2016_51_1-2_017_ruosteenoja.pdf⟩.
Savary, S., Akter, S., Almekinders, C., Harris, J., Korsten, L., Rötter, R., Waddington, S., Watson, D., 2020. Mapping disruption and resilience mechanisms in food systems. Food Secur 12, 695–717. https://doi.org/10.1007/s12571-020-01093-0.
Tilman, D., 2000. Causes, consequences and ethics of biodiversity. Nature 405, 208–211. https://doi.org/10.1038/35012217.
Tilman, D., Wedin, D., Knops, J., 1996. Productivity and sustainability influenced by biodiversity in grassland ecosystems. Nature 379, 718–720. https://doi.org/10.1038/379718a0.
Tilman, D., Knops, J., Wedin, D., Reich, P., Ritchie, M., Siemann, E., 1997. The influence of functional diversity and composition on ecosystem processes. Science 277, 1300–1302. https://doi.org/10.1126/science.277.5330.1300.
Tilman, D., Reich, P., Knops, J., 2006. Biodiversity and ecosystem stability in a decade-long grassland experiment. Nature 441, 629–632. https://doi.org/10.1038/nature04742.
Tondelli, A., Xu, X., Moragues, M., Sharma, R., Schnaithmann, F., Ingvardsen, C., Manninen, O., Comadran, J., Russell, J., Waugh, R., Schulman, A.H., Pillen, K., Rasmussen, S.K., Kilian, B., Cattivelli, L., Thomas, W.T.B., Flavell, A.J., 2013. Structural and temporal variation in genetic diversity of European spring two-row barley cultivars and association mapping of quantitative traits. Plant Genome 6, 1–14. https://doi.org/10.3835/plantgenome2013.03.0007.
Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvåg, A.O., Eitzinger, J., Seguin, B., Peltonen-Sainio, P., Rötter, R.P., Iglesias, A., Orlandini, S., Dubrovský, M., Hlavinka, P., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Gobin, A., Vucetic, V., Nejedlik, P., Kumar, S., Lalic, B., Mestre, A., Rossi, F., Kozyra, J., Alexandrov, V., Semerádová, D., Zalud, Z., 2011. Agroclimatic conditions in Europe under climate change. Glob. Change Biol. 17 (7), 2415–2427.
Trnka, M., Rötter, R.P., Ruiz-Ramos, M., Kersebaum, K.-C., Olesen, J.E., Semenov, M.A., 2014. Adverse weather conditions for wheat production in Europe will become more frequent with climate change. Nat. Clim. Change 4, 637–643. https://doi.org/10.1038/nclimate2242.
Ward, J.H., 1963. Hierarchical grouping to optimize an objective function. J. Am. Stat. Assoc. 58, 236–244.
Yeo, D., Truxillo, C., 2005. Applied Clustering Techniques Course Notes. SAS Institute Inc,, Cary, NC27513, USA.
Zadoks, J.C., Chang, T.T., Konzak, C.F., 1974. A decimal code for the growth stages of cereals. Weed Res. 14, 415–421.