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Janne Kaseva

ASSESSING THE CLIMATE RESILIENCE OF CROPPING SYSTEMS THROUGH RESPONSE DIVERSITY

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Abstract

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Northern agriculture faces a rapidly changing climate with increased weather variability. Diversification can reduce the sensitivity of crops to disturbances and foster their capacity to adapt and transform. Increased climate resilience of yields can provide a buffer against climate-related uncertainty and variability. Therefore, it is a key aspect in managing the resilience of the food system, which is increasingly facing fluctuations. Response diversity also enables the evaluation and comparison of the development of diversity in regions over time. This dissertation presents a novel approach to quantifying the diversity of yield responses to weather and outlines its benefits over mere richness of cultivars or crop species. Further, the impact of land-use diversification on economic efficiency is evaluated.

Long-term weather data and yield data for barley and forage crop cultivars were gathered from Finnish regions, and those for wheat were gathered from eight other European countries besides Finland for the period 1980–2014. In addition, Finnish profitability bookkeeping data for land use and economy was utilised. Clustering was based initially on Mahalanobis distances and, later, on principal component scores obtained as a by-product of grouping the agro-climatic variables based on the yield responses. To identify the development in response diversity, the diversity of the clusters cultivated was determined regionally and annually. The most methodologically justified choices were the use of principal component analysis to obtain a more interpretable and meaningful clustering and the use of the exponential of the Shannon index as a measure of true diversity.

Despite ongoing increases in the cultivar diversity of Finnish barley, the diversity in the yield responses to weather conditions decreased in the important regions for cultivation. The yield responses among new cultivars showed greater homogeneity than those among older cultivars. Moreover, in European farmers’ fields, a declining diversity of responses to weather patterns relevant to wheat yield was found. This diversity started to decline in the 2000s, with the decline being the strongest in Czechia. Conversely, the development in response diversity was the most positive in Slovakia. The response diversity of forage crop cultivars clearly depended on the soil type. Unlike clay or organic soils, coarse mineral soils had a reduced response diversity of species and cultivars, indicating a relatively weaker ability to successfully cope with uncertain climate change.

The proposed approach to empirically identify response diversity in order to manage resilience and adaptive capacity enables added value by guiding tailored diversification that allows actors in the food chain to prepare for unexpected fluctuations and changes that are currently very relevant in Europe, thereby securing economic efficiency as well.

Keywords: response diversity, climate resilience, diversity index, crop, cultivar, principal component analysis, cluster analysis

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Janne Kaseva
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Contents

List of publications

This dissertation is based on the following papers. The rights have been granted by publishers to include the papers in dissertation. The publications are referred to in the text by their Roman numerals.

I
Kahiluoto, H., Kaseva, J., Hakala, K., Himanen, S.J., Jauhiainen, L., Rötter, R.P., Salo T. and Trnka, M. 2014. Cultivating resilience by empirically revealing response diversity. Global Environmental Change – Human and Policy Dimensions 25: 186–193. DOI 10.1016/j.gloenvcha.2014.02.002

II
Kahiluoto, Helena; Kaseva, Janne; Balek, Jan; Olesen, Jørgen E.; Ruiz-Ramos, Margarita; Gobin, Anne; Kersebaum, Kurt Christian; Takác, Jozef; Ruget, Francoise; Ferrise, Roberto; Bezak, Pavol; Capellades, Gemma; Dibarik, Camilla; Mäkinen, Hanna; Nendel, Claas; Ventrella, Domenico; Rodríguez, Alfredo; Bindi, Marco; Trnka, Mirek. 2019. Decline in climate resilience of European wheat. Proceedings of the National Academy of Sciences of the United States of America (PNAS) 116 1: 123-128.

III
Mäkinen, Hanna; Kaseva, Janne; Virkajärvi, Perttu; Kahiluoto, Helena. 2017. Shifts in soil–climate combination deserve attention. Agricultural and Forest Meteorology 234-235: 236-246.

IV
Kaseva, Janne; Himanen, Sari J.; Kahiluoto, Helena. 2019. Managing diversity for food system resilience. Advances in Food Security and Sustainability 4: 1-32.

Author's contribution

The author is the corresponding author in publication IV. He led the paper and wrote the first draft and made a significant contribution to all parts of the study. In the publications I to III, the author conducted the experiments and post processed the experimental data. He had also a major role in conceptualizing and planning of the research as well as in the study design, interpretation and presentation of the results, and in the writing process. In the paper I and II, professor Kahiluoto was the corresponding author, and in the paper III, Dr. Mäkinen was the corresponding author.

Nomenclature

Units

ha	hectare
kg	kilogram
kg ha^{-1}	kilogram per hectare
km	kilometre
m	metre
mm	millimetre
N	number of particles
T	temperature
#	number
°C	Celsius

Abbreviations

CAP	Common Agricultural Policy
CO_2	Carbon dioxide
E_H	Shannon’s equitability
EU	European Union
H	Shannon diversity index
KMO	Kaiser–Melkin–Olkin sampling adequacy measure
LMM	Linear mixed model
MI	Multiple imputation
PC	Principal component
PCA	Principal component analysis
S	Number of cultivars or response clusters
SD	Standard deviation
SE	Standard error
UK	United Kingdom

1 Introduction

Food systems are becoming increasingly volatile, and the resilience framework can help in understanding and improving food security. Climate and market volatility have increased, making resilience to change and variability an important component of resource efficiency in building sustainability (Korhonen & Seager, 2008). Therefore, preparing for various changes and intensifying extremes in weather conditions is increasingly important. Climate resilience can be seen as a buffer against climate-related uncertainty and variability (Carpenter et al., 2001), and it is currently an important aspect of managing the resilience of the food system.

One of the most important determinants of resilience is the diversity of responses to disturbances (Folke et al., 2004). According to Gaitán-Cremaschi et al. (2019), system function diversification can enhance the capacity for adaptation and transformation to various future situations and, at the same time, reduce vulnerability to disturbances. The diversity of responses within a functional group, which can be a species or a group of species that provide the same function, can be referred to as response diversity (Elmqvist et al., 2003). This dissertation focuses on the diversity of crop and cultivar yield responses to climatic events that are crucial to the yield. Utilizing response diversity increases the likelihood that at least some cultivars in the group continue to operate in the face of disruptions and changes in weather conditions. However, not all forms of diversity are efficient, and to identify resilience, one must look beyond cultivar, species and genetic diversity. Diversity in functional qualities, rather than type diversity (Page, 2011), is critical for the provision of ecosystem services (Díaz et al., 2007).

Laliberte et al. (2010) presented a few key points that should be considered in response diversity studies. First, a complete effect and response functional trait database must be gathered from a sufficient number of species present in a community. Second, to understand how biodiversity affects the ecosystem function, it is important to recognise the key traits that influence specific ecosystem functions (Naeem & Wright, 2003), although it is not often easy to identify them exactly *a priori* (Petchey & Gaston, 2006). Third, it is important that response traits reflect different responses to specific critical disturbances. Fourth, the classification of species into functional impact groups assumes some degree of functional redundancy (Naeem & Wright, 2003). In ecology, and more specifically in the agri-food system, the response traits of fodder and food supply may vary in shifts for different traits (e.g. climate and pests, demand and price), even at the cultivar level; thus, the response diversity should be directly identified and quantified (Aubin et al., 2009) for each question and case (Petchey & Gaston, 2006). Depending on the perspective of the research, various multivariate methods have been applied to the empirical quantification of response diversity (Laliberté et al., 2010; Mohammadi & Prasanna, 2003; Petchey & Gaston, 2006). Therefore, an empirically quantified response diversity approach could provide a practical tool for assessing and enhancing resilience and developing food security.

Climate change increases uncertainty regarding local weather conditions (Rötter et al., 2013) and intensifies weather variability and extremes (Coumou & Rahmstorf, 2012; Trnka et al., 2014). Agriculture's vulnerability to climate variability and change has been widely documented in the literature (Maracchi et al., 2005; Pachauri et al., 2014), and weather variability – especially in terms of temperature, precipitation and how these two interact – accounts for a significant portion, even a third of the variability in the global yield (Ray et al., 2015). Even with moderate warming, a decrease in the yield level in global and temperate areas (Asseng et al., 2015; Challinor et al., 2014) and an increase in yield variability are projected (Ray et al., 2015). Furthermore, yield variability causes price instability in the globally integrated food market, threatening the stability of food accessibility, especially for the poor, who spend a large proportion of their income on staple foods (Tadesse et al., 2014), which is also the case in Europe. Food security is also a central goal in national emergency supply strategies (FAO, 1996) and in the Common Agricultural Policy of the European Union (CAP; European Commission, 2017), because food insecurity enhances political instability and migration (Maxwell, 2012). Therefore, it is important to investigate the climate resilience of staple food crops, especially wheat, which is the most important source of plant protein in human nutrition (FAOSTAT, 2017) and Europe's most important staple food crop. In northern Europe, rapid shifts can be seen in the agro-ecological zones favouring warm-season crops and the northward extension of cultivation (Fronzek & Carter, 2007; Tuck et al., 2006). As the northernmost country, this affects Finland in particular, and significant changes in agricultural land use are likely (Fronzek & Carter, 2007; Olesen & Bindi, 2002; Peltonen-Sainio, P. et al., 2008).

Soil is becoming an increasingly significant component in modelling the effects of climate change (Constantin et al., 2015; Rötter et al., 2013; Srivastava et al., 2012; Tuck et al., 2006); however, empirical research on the relationship between climatic conditions, soil types and yield responses has been limited. According to Rounsevell et al. (1999), climate-induced changes in land use and management may have the most significant impact on soil. We also have information about climatic drivers associated with soil processes (Rounsevell et al., 1999; Smith et al., 2016), as well as the effects of climate change on the biological, chemical and physical health indicators of soil (Allen et al., 2011). However, some knowledge is available about the connections between soil properties and weather, and although advancements in understanding the impact of human activities on soil function have been made, a complete understanding of how crop–soil systems react to climate change and changes in land use is still inadequate (Nikolaidis, 2011; Rounsevell et al., 1999)

The magnitude of crop responses to climate is known to be sensitive to soil type (Lisson et al., 2016; Rötter et al., 2013), and the agronomic characteristics of soil types vary; thus, the combination of soil and climate plays a key role in agricultural land use projections. According to Mukula and Rantanen (1987), organic soils have low thermal conductivity and high water-holding capacity; clay soils are also characterised by high water-holding capacity. Coarse mineral soils generally have a low water-holding capacity. Therefore, it is highly valuable to investigate the dependence of yield responses to agro-climatic variables on soil type. Due to the variability of soil types, in addition to their regional variability, more information on the combination of soil and climate is needed to enhance the design and assessment of the adaptation of cropping. Therefore, empirical data on the relationship between yield responses to agro-climatic factors and soil type deserve more attention.

1.1 Research gap and motivation for the dissertation

Despite appeals to manage resilience (Chapin et al., 1997; Folke et al., 2004; Scheffer et al., 2001), conceptual and theoretical development has been much faster than empirical application (Laliberté et al., 2010). For instance, a few field studies have found that response diversity can maintain system functions after disturbances in lakes (Schindler, 1990), grasslands (Walker et al., 2012), rice fields (Zhu et al., 2000), coral reefs (Nyström, 2006) and bee communities (Winfree & Kremen, 2009).

The primary motivation for the dissertation came from the fact that there is a gap in the research on the yield effect of agro-climatic conditions and their variability in cropping systems. Specifically, there has been no previous empirical work on the potential of response diversity for climate- or weather-related resilience of cropping systems. The sustainability, resilience and diversity of cropping systems are the main aspects addressed in this dissertation. Sustainability implies two complementary aspects: efficiency (resource use) and resilience. Resilience, identified as the capacity to maintain essential system functions under change, variability and uncertainty, has received increasing attention under accelerated global social–ecological change. Diversity is assumed to reduce sensitivity to disturbances and foster the capacity to adapt to future scenarios. The development of empirical applications has not yet led to a breakthrough, despite appeals to manage resilience. Therefore, methods that empirically reveal the diversity of responses are needed. Further, the essential factors of change in a system need to be recognised, and response diversity should be defined based on the measured and analysed responses to these factors.

The important groundwork and inspiration for developing the approach presented in this dissertation was inspired by Hakala et al. (2012), who showed that different Finnish barley cultivars respond to weather variables differently, with some cultivars being more prone to drought while others being less tolerant to heat stress or flooding. When similar cultivars dominate regional cultivation, benefits accumulate in positive weather conditions and risks in negative ones, thereby increasing annual regional variation. Thus, preparing for varying weather conditions with a versatile cultivar pool may reduce risks and annual variations. Therefore, it can be assumed that the assessment of response diversity using a specific cultivar pool would provide an alternative estimate of regional cultivar diversity compared with the approach based merely on the (type) diversity of individual cultivars. Thus, the response diversity approach provides an opportunity to quantify diversity more effectively by assessing the yield response to climate variability and change. The added value of the response diversity approach can be measured in multiple ways, but the presented approach provides a generic procedure as a practical tool for managing resilience.

1.2 Aims and hypotheses

The aim of these studies (I-IV) was to develop an approach that empirically reveals response diversity and to extend and test its applicability. Potentially, this approach can be utilised in several research areas, but in these studies (I–IV), the approach was applied to yield responses of the cropping systems of barley, wheat and forage crop cultivars to agro-climatic conditions and their variability. The relation between land use diversification and resource-use efficiency on a farm scale was also studied using Finnish profitability bookkeeping data. The use of alternative diversity indices has varied in ecological research, and the benefits of the exponential form of the Shannon index as a true measure of diversity are discussed in Chapter 4.

The studies for the three crops are presented to illustrate how the proposed perspective of resilience can provide new insights and practical means to assist food systems and their actors in preparing for fluctuations and changes that are difficult to predict. The climate resilience of Finnish barley and forage crop cultivars was studied, but in the case of wheat, cultivars from eight other European countries were included. Therefore, the proposed approach was applied to a case of food security when facing climate change, i.e., to barley (I), wheat (II) and forage crop (III) cultivar responses to weather in Finland (I & III) and in Europe (II). In the synthesis article (Study IV), other application areas and a few ways to utilise and evaluate the response diversity approach are presented and discussed, especially in relation to economic efficiency. The cultivar datasets used in the studies were collected from the official variety trials of nine European countries from 1980–2014.

The overarching research question of the dissertation is the following: How can response diversity be quantified, and does it show benefits relative to merely cultivar type diversity as a measure of climate resilience? The utilisation of diverse crop cultivars under varying weather conditions now and in the near future due to the changing climate—measured by the diversity in responses to weather events instead of species richness—was compared as a proxy for resilience. Developments in recent decades related to barley, wheat and forage crops, as well as the application of the approach to various research areas, were studied. The use of statistical methods and diversity indices was evaluated and developed during the process. In addition, the potential trade-off between diversity as a proxy for resilience and economic efficiency was investigated. Table 1.1 shows the contribution of the dissertation articles to answering the overarching research question and to novelty in climate resilience research, as well as the data and methods.

Table 1.1: The structure and contribution of the dissertation articles

ARTICLE	**I BARLEY**	**II WHEAT**	**III FORAGE CROPS**	**IV SYNTHESIS**
MAIN RESEACH QUESTION	Does the assessment of response diversity yield a better estimation of the regional climate resilience of crops compared with that obtained from mere type diversity?	How is climate resilience in European wheat developing, are there differences between countries and are there potential gaps?	Would the combinations of the agro-climatic factors that most influence yield variation vary among soil types?	Is there a trade-off between land-use diversity and economic efficiency?
STUDIED OBJECTIVES	Finnish cultivars 1980-2009	European cultivars 1991-2014	Finnish cultivars 1980-2012	Cultivars, Revenue
STATISTICAL METHODS	LMM and Clustering	LMM, PCA and Clustering	LMM, PCA and Clustering	LMM, PCA, SFA and Clustering
PERSPECTIVE & NOVELTY	The response diversity approach was presented	The approach was widened to nine European countries	The elements of soil and species were included	The development of the approach was presented and discussed with related articles

The first hypothesis (tested by Study I) was that the assessment of response diversity would yield a better estimate of the regional climate resilience of crops compared with that obtained from mere type diversity. This would presumably imply that an approach based on response diversity would allow for a more valid assessment of diversity in terms of the response to climate variability and change, that is, in terms of climate resilience.

The second hypothesis (tested by Study II) expanded the first hypothesis to cover climate resilience in the entirety of Europe to compare climate resilience between countries and to identify potential gaps in the climate resilience of European wheat. Wheat cultivars from nine European countries and a larger research dataset were utilised.

The third hypothesis (tested by Study III) was that the yield responses and the response diversity of crop species and cultivars to agro-climatic variables, and thus climate resilience, depend on the soil type. We also hypothesise that the combinations of agro-climatic factors most influencing yield variation would vary among soil types. This was tested using forage crops and cultivars.

The fourth hypothesis (tested by a study reported in Synthesis IV) was that diversification as a proxy for resilience would reduce economic efficiency.

The following chapters present the methodology and statistical methods of this empirical approach (Chapter 2), the main results of each study (Chapter 3), a discussion of the main results, including limitations and suggestions for future research (Chapter 4), and the main conclusions of these studies and possible applications (Chapter 5).

2 Methods

2.1 Utilised datasets and the response diversity approach

In all studies, data from domestic official variety trials were used. Long-term yield data for wheat, barley and forage crop cultivars were collected from Finland, and those for wheat were collected from eight other European countries for the period 1980–2014. Thus, the nine countries studied were Belgium, Czechia, Denmark, Finland, France, Germany, Italy, Slovakia and Spain. To evaluate the yield response to weather variables, the annual weather data from 1979 to 2014 from weather stations closest to the experimental sites were used, and weather data from other countries were also gathered in accordance. The actual regional cultivation areas for each cultivar were acquired for Studies I and II. By validating the critical factors of change and cultivar responses in the barley study (I), the generalisability of the findings was examined with comparable data from farmers' fields. The synthesis study (IV) also presents results that utilised completely different data, such as the Finnish profitability bookkeeping data.

A randomised complete block design (RCBD) or an incomplete block design (IBD) was used as the experimental layout of the trials, where the number of replicates of the cultivars varied from two to four. The management of trials was similar to farmers' practices. The set of cultivars varied each year, but long-term standard reference cultivars, also known as checks or controls, were used. Obviously, management practices varied slightly between countries, but overall, they were comparable. For example, Finnish plot sizes were 5–10 m × 1.25 m, depending on the year and location. The forage crop yield was harvested 2–3 times during each growing season. Harvest dates differed between years and trials, depending on weather conditions and the location of the experimental sites.

The proposed response diversity approach was first presented in the barley study (I) and was further developed in the forage crop and wheat studies (III and II). The five steps of this two-stage approach are presented in the following paragraphs and in more detail in subsequent chapters (Figure 2.1).

2.1.1 Stage I: Identification of the responses to change factors

The factors of change that are critical to system performance (Step 1) and the estimated component responses to variations in these factors (Step 2) were determined in Stage I. In the pilot study (I), the generalisability of the results was considered important and was evaluated by validating the chosen critical factors of change and cultivar responses using comparable data from farmers' fields. Due to the limitations and availability of farm data, this step has been omitted from recent studies. However, in certain recent studies (II and III), principal component analysis (PCA) was used to group the chosen factors of change, and this methodological step was found to be so useful that it has since been designated as Step 3.

2.1.2 Stage II: Determination of response diversity

In Stage II, the cultivars were clustered according to the yield responses of agro-climatic variables (I–III), and response diversity indices were formed based on the cluster solutions (I and II). The cultivation area data for the cultivars' shares in different areas from Finland (I) and Europe (II) were utilised in this stage. The calculation of diversity indices was included in Step 4 in the barley study (I) and in Step 5 in the wheat study (II).

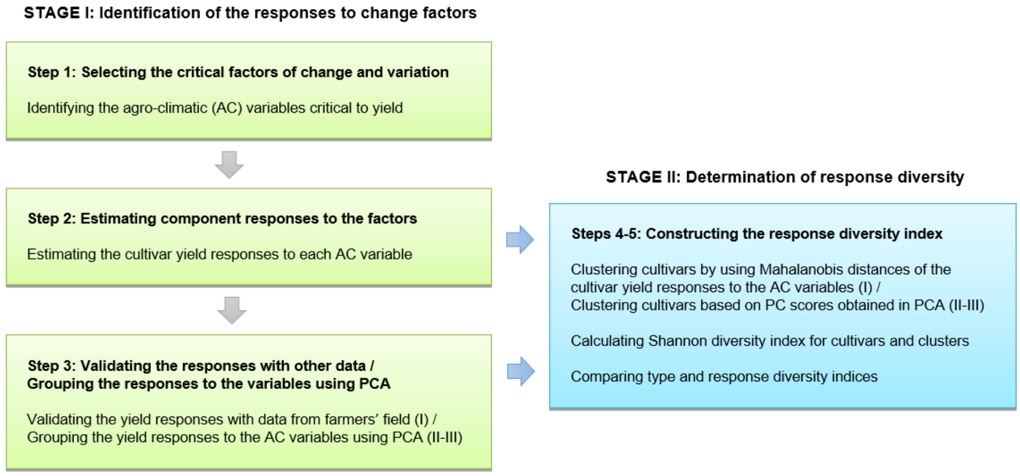

Figure 2.1: The proposed approach for assessing response diversity. The steps of the general procedure are presented in bold, and more detailed descriptions are provided under the heading of each step.

2.2 Methodological steps

The approach is divided into two stages, which consist of five steps overall (Figure 2.1). The structure of the steps was modified slightly during the studies: Step 3 was renewed after the barley study (I), and Steps 4-5 were developed during these studies.

2.2.1 Step 1: Selecting the critical factors of change and variation

In the barley study (I), the agro-climatic variables most critical to barley yield (Hakala et al., 2012; Rötter et al., 2013; Trnka et al., 2011) and the yield response of barley cultivars to variations in these variables in multi-location trials in Finland (Hakala et al., 2012) between 1980 and 2009 were considered. Fourteen experimental sites represented the entirety of Finland, except for the northernmost part of Lapland and the southwestern peninsula of Ahvenanmaa. A minimum of 25 observations were required for each cultivar to be included in the analysis, although a few new cultivars with only 15–20 observations were included. In recent studies (II and III), the limit was lowered to 20 observations per cultivar to take advantage of larger datasets and more cultivars. A few missing values for phenological development dates were replaced by estimates (Hakala et al., 2012). The data consisted of 8430 observations for 112 cultivars of both domestic and foreign origin from the beginning of the 1980s to 2009.

Ten agro-climatic variables that most influenced barley yield were identified using regression analysis for multiple variables, which were initially selected based on existing literature and observations (Hakala et al., 2012). Based on the study by Trnka et al. (2011), two additional variables (#9 and #10) were also added; thus, the 12 most critical agro-climatic variables for barley performance in Finland were selected.

In the forage crop study (III), the agro-climatic variables most critical to forage crop yield were chosen based on the existing literature (Bélanger et al., 2002; Mäkinen et al., 2015; Thorsen & Höglind, 2010; Volenec & Nelson, 2007). The yield responses of 126 cultivars from six species (Festulolium, meadow fescue, tall fescue, Italian ryegrass, red clover and Timothy) were estimated for 35 agro-climatic variables related to fall hardening (FH), the winter (WP) and the growth period (GP). The thirteen most suitable agro-climatic variables were selected in the further analysis based on the criteria mentioned in Study II. A few missing harvesting dates (1%) were replaced by estimates (for details, see Mäkinen et al., 2015). The data consisted of 8361 records from 16 experimental sites in the period 1980–2012. The effect of soil type on crop responses was evaluated by comparing clay, coarse mineral and organic soils, which were classified based on the field information gathered from experimental sites.

In the wheat study (II), the 43 agro-climatic variables most critical to European-wide wheat yield were chosen based on existing literature (Asseng et al., 2015; Porter & Gawith, 1999; Trnka et al., 2011). Weather data were gathered from the nearest stations to the experimental sites during the crop phenological stages (Zadoks et al., 1974). Missing phenological dates were estimated using the matching dates for all cultivars from the same location and year. Trials that did not include a sowing date were excluded from further study. Correlation analysis with overlapping data for cultivars from the same area in the closest growing seasons was used to predict missing heading and maturity dates. In the absence of overlapping data or in the presence of only a few data pairs (five or fewer), the thermal time over 5 °C for that cultivar from nearby sites and previous or subsequent growth seasons was used to estimate those phenological dates. The data consisted of 100985 records from 636 experimental sites in the period 1991–2014.

2.2.2 Step 2: Estimating component responses to the factors

Depending on the study, cultivars with at least 20–25 yield observations were included for further analysis. The values of each agro-climatic variable calculated in the first step were classified into three categories (low, moderate and high) by using different limits depending on the number of observations in each study. This classification can be made, for example, using an equal number of trials (I), the 40th and 60th percentiles (II) or the 45th and 55th percentiles of the distributions of the observations (III). For example, *rain during one month before sowing* was classified according to monthly rainfall up to 24 mm (low), 24–40 mm (moderate) and 40–113 mm (high) precipitation. However, a few variables were classified unequally due to the large number of zero values. For example, 62% values from the observations of the variable *the extreme heat stress days of ≥28 °C one week before through two weeks after heading* were zeros (low), and only 28% values from the observations represented more than one high-stress day (high).

Agro-climatic variables were classified for a few reasons; the assumption of linearity was often violated, as the relationships between yield and agro-climatic variables were nonlinear in most cases. Second, a few weather variables were strongly correlated, which could lead to multi-collinearity problems in further regression analysis. Third, the environmental random effects of year, site and trial were known to account for most of the total variation and had to be therefore accounted for in the model. Hence, linear mixed models (LMMs) were used to estimate the climate-based yield responses separately for each agro-climatic variable. In the barley study (I), the model used was the simplest, whereas in the wheat study (II), the effect of country was added and in the forage crop study (III), the effect of soil type was added. For barley (I), interactions with the cultivars and the categories of each agro-climatic variable were analysed using the following equation:

$$y_{ijklm} = \mu + \text{cultivar}_i + \text{category}_j + \text{cultivar} \times \text{category}_{ij} + \text{site} \times \text{year} \times \text{trial(category)}_{klmj} + \varepsilon_{ijklm}, \qquad (2.1)$$

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 the categorised agro-climatic variable ($j=1,2,3$) and cultivar × category_{ij} is the cultivar-by-environment interaction. All of the abovementioned effects 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.

For wheat (II), the effects of country ($l = 1, \ldots, 9$) and treatment ($k = 0, 1$) were added to the first equation (2.1). Therefore, the following LMM was used:

$$y_{ijklmn} = \mu + \text{cultivar}_i + \text{category}_j + \text{cultivar} \times \text{category}_{ij} + \text{treated}_k + \text{country}_l + \text{site}_m + \text{year}_n + \text{treated} \times \text{country} \times \text{site} \times \text{year(category)}_{jklmn} + \varepsilon_{ijklmn}, \qquad (2.2)$$

where most of the effects and assumptions are the same as those in the previous model. In addition, treated_k refers to the fixed effect of pesticide use. All terms after that were used as random effects. For forage crops (III), the fixed effect of soil type and its two- and three-way interactions with cultivars and the categories of each agro-climatic variable were added to the first model (2.1). Therefore, the following LMM was used:

$$y_{ijklmn} = \mu + \text{cultivar}_i + \text{category}_j + \text{soil type}_k + \text{cultivar} \times \text{category}_{ij} + \text{cultivar} \times \text{soil type}_{ik} + \text{category} \times \text{soil type}_{jk} + \text{cultivar} \times \text{category} \times \text{soil type}_{ijk} + \text{site} \times \text{year} \times \text{trial(category)}_{jlmn} + \varepsilon_{ijklmn} \quad (2.3)$$

At the end of Step 2, the differences in yield estimates between the two extreme categories were calculated for each cultivar; thus, the moderate category was not utilised in further analysis. For example, the estimated yield of each cultivar for *precipitation* rates below 24 mm *one month before sowing* was subtracted from the estimated yield of each cultivar for *precipitation* rates over 40 mm *one month before sowing*. Consequently, a positive yield indicates that a cultivar benefits from precipitation. However, for wheat (II), the relative difference in the estimated yield levels between the two extreme categories was calculated. The purpose was to balance the differences in the cultivar yield levels among countries, although utilizing the simple difference produced similar findings. For forage crops (III), cultivar estimates were calculated for each soil type. Due to the missing yield responses, some cultivars were omitted from the subsequent steps; cultivars with more than two missing yield responses in the 13 agro-climatic variables were excluded (III), and if more than a third of the 43 yield responses were missing, the cultivar was excluded (II). The data sets for multivariate analysis included the yield responses for each cultivar to all agro-climatic variables. For forage crops (III), these data sets were formed for each soil type.

2.2.3 Step 3: Validating the responses with other data / Grouping the responses to the variables using PCA

In the pilot study (I), the generalisability of the results was investigated by validating the critical factors of change and cultivar responses using comparable data from farmers' fields. This was done to ensure the validity of the conclusions in terms of agriculture in practise, since the conditions on the farms differ, at least to some extent, and vary more than those in variety trials. Therefore, 1700 regionally representative farms were chosen and monitored from 1998 to 2005, and to add variation, one-third of the farms were randomly re-selected each year. The farmers recorded their cultivation methods and yields, but the hectolitre weights were measured in a lab using samples provided by the farmers. The agro-climatic variables were adjusted to correspond to the phenological stages by modelling the critical phenological dates based on the recorded sowing dates on farms (Trnka et al., 2011).

The interaction of the cultivars and the categories of each agro-climatic variable was tested in the same way in the farm data as in the trial data. The correlation of cultivar yield responses to the agro-climatic variables from both datasets was evaluated using Pearson's correlation coefficient. Only 15 cultivars with more than 100 observations from farms were chosen for validation because of the possibility of substantial variation in farm conditions. To reduce any potential bias induced by the farmers' yield estimations, a correlation between the trial and farm data for the hectolitre weights that were evaluated in the lab was also determined. Besides the correlations, PCA was performed for both datasets to compare the structures of the agro-climatic variables. However, due to the relatively low number of cultivars available in the farm data (40 cultivars), the results are only tentative.

In recent studies (II and III), the validation step was omitted, and the grouping of the responses of the agro-climatic variables using PCA was raised to a new third step. The purpose of PCA was to reveal the internal structure of the complex data and reduce the dataset to a lower dimension to reveal simplified structures of agro-climatic variables. In PCA, the first principal component (PC) explains most of the variation, the next PC explains the second most and the last PC the least. In general, the first few PCs explain most of the relevant information, and since there is often a noise element in such a dataset, not all variances of the PCs were attempted to be captured. The number of PCs needed can be evaluated from eigenvalues, and the rule of thumb is that eigenvalues greater than one should be retained (Cattell & Jaspers, 1967). In addition, the interpretability of PCs was used as a criterion, especially in the wheat study (II), which consisted of 43 agro-climatic variables. An orthogonal varimax rotation resulted in the most interpretable solution. PCA was also fitted with a few alternative techniques, but the PC structures were found to be stable. The sampling adequacy was tested using the Kaiser–Melkin–Olkin (KMO) measure, which should exceed 0.50 (Kaiser, 1970). It was found middling (KMO=0.77) for wheat (II) and was almost the same (KMO=0.78) in coarse mineral soils for forage crops (III). The sampling adequacies could not be calculated for organic soils and clay soils because the correlation matrices were singular.

PC scores, combining the information of the cultivar yield responses of the agro-climatic variables, were calculated for every PC. The PC scores were obtained using multiple imputation (MI) with 100 imputations for missing data because it required non-sparse data. For MI, the Markov chain Monte Carlo (MCMC) method was utilised in a multivariate normal approach. The effects of using MI on the PC structure were investigated and found to be negligible. This was done by comparing the obtained results to the PCA results obtained from correlation matrices with pairwise exclusion. Consequently, imputations were added to the data, and the PC scores calculated using the regression method were utilised in subsequent analyses (DiStefano et al., 2019). Unstandardised PC scores were utilised to reduce the sensitivity of the clustering results to the number of PCs retained and to weigh a potential noise element in the data less (Mimmack et al., 2000). However, the effect of the standardisation of PCs was found to be minor. Truncated Mahalanobis distances were used in the barley study (I) instead of PCA, but this method has been found to be less interpretative in recent studies (II and III). A few wheat cultivars (n=17) were also omitted as outliers due to their PC scores being over six standard deviations (SD) beyond the mean (Wang et al., 2009).

2.2.4 Steps 4–5: Constructing the response diversity index

In the barley study (I), a cluster analysis was conducted for the data created in Step 2. Thus, the cultivars were clustered based on their yield responses to the agro-climatic variables using the Mahalanobis distance matrix, which utilises complete multivariate information of the yield responses (McLachlan, 1999). Mahalanobis distances weigh less variables with high variance and highly correlated variables (Mimmack et al., 2000). In recent studies (II and III), the cultivars were clustered based on the PC scores created as a by-product of the PCA conducted in Step 3.

The hierarchical Ward's method (Ward, 1963) was used for clustering the cultivars. It creates clusters by minimizing the within-cluster variance, starting with n clusters (consisting of one cultivar) and continuing until all cultivars are combined into one cluster. Squared Euclidean distances were used in clustering. The dendrogram, the pseudo t2-criterion and the variation in r-squared values were used to determine the number of clusters (Yeo & Truxillo, 2005). In particular, for forage crops (III), PC scores were also used due to the relatively small sample size. If m equals the number of variables to be clustered, then at least 2^m observations are recommended (Formann, 1984); thus, 4–5 PCs were preferable compared to 13 agro-climatic variables used for the smallest sample size of 72 cultivars from organic soil.

The Shannon–Weaver diversity index, or the abbreviated Shannon index (H), which takes into account the elements of both richness and evenness (Shannon & Weaver, 1949), was calculated for regions based on the cluster solutions. For barley and wheat (I and II), data on the cultivation areas (ha) of the cultivars were utilised in the calculation of the regional type and response diversities. The type diversity index uses every cultivar as a unit, whereas the response diversity index uses clusters as units. Therefore, each cultivar or response cluster was used as a diversity unit; accordingly, the following equation was used to calculate the Shannon diversity indices for each region:

$$H = -\sum_{i=1}^{S} (p_i)(\ln p_i)\ , \tag{2.4}$$

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. However, H is highly nonlinear; 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 and more interpretable measure of diversity (Jost, 2007).

The indices were calculated for the regional and country levels, depending on the study. For example, in the barley study (I), the cultivation areas of the 12 clusters were studied at the regional (16 administrative regions / south and north) and country levels, whereas only the country level was used for wheat (II). In addition to the cultivation areas, the number of cultivars per cluster was also studied similarly for wheat (II). The annual cultivation area for the barley clusters (I) was also computed according to Shannon's equitability to demonstrate the evenness element of the diversity index independently (Mulder et al., 2004). These equitabilities enabled the comparison of changes in type diversity and response diversity on a consistent scale [0,1]. The equitabilities (E_H) were calculated by dividing each H by its theoretical maximum (H_{max}), which is the same as ln(S). Therefore, equitabilities ranged between 0 and 1, with the latter indicating complete evenness and zero indicating the dominance of one cultivar or cluster.

PC loadings were also used to weigh the average yield responses to the agro-climatic variables (II). PC loadings were squared and divided by the eigenvalue of each PC, and the weighted means and SEs for each combination of PCs and clusters were calculated according to the following equations:

$$\bar{x} = \frac{\sum_{i=1}^{n} w_i x_i}{\sum_{i=1}^{n} w_i}\ , \qquad SE = \sqrt{\frac{\sum_{i=1}^{n} w_i (x_i - \bar{x})^2}{n}}\ , \tag{2.5}$$

where w_i is the weight and x_i is the average yield response of cultivars to the *i*th agro-climatic variable. Therefore, the sum of the weights of the agroclimatic variables is one for each PC. The relationship between the interannual stability of the yield and response diversity was demonstrated by calculating the relationship between the yield response variability in each PC and the accumulated number of clusters. The weighted means of the cluster SDs were calculated for each PC and the number of combined clusters in order from one to nine, based on the dendrogram (Figures 2 and S1 in Study II). When comparing the three-cluster solution to the four-cluster solution, for instance, one of the former clusters was split, while all others remained the same. Therefore, the pooled SD for each cluster solution was calculated as follows:

$$SD_{pooled} = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2 + \cdots + (n_k - 1)s_k^2}{n_1 + n_2 + \cdots + n_k - k}}\ , k = 1, \ldots, 9\ , \tag{2.6}$$

where *s* is the SD of the k^{th} cluster and *n* is the number of cultivars in the k^{th} cluster. Statistical analyses were performed using the GLIMMIX, MIXED, HPMIXED, PRINCOMP, FACTOR, DISTANCE, CLUSTER, MI, CORR and REG procedures in SAS (version 9.3) or SAS Enterprise Guide 7.15 (SAS Institute Inc., Cary, NC, USA).

3 Results

The results from the first three studies (I–III) are reported in this chapter, and the results of the synthesis study (IV) are discussed in the next chapter.

3.1 Diversity of Finnish barley cultivars

Twelve cultivar clusters were formed for barley (I) based on the yield responses to 12 agro-climatic variables. The selection of the number of clusters was based on the aforementioned statistical criteria (see Section 2.2.4), and it can be seen as somewhat coincidental that the number of clusters and agro-climatic variables were the same. The variance explained by these 12 clusters was 43%. The cultivar-wise yield responses for each agro-climatic variable were calculated as the difference between the yield estimates of the highest and the lowest thirds of weather conditions for each of the 12 variables. The median differences ranged between 130 and 580 kg ha^{-1} (330 kg ha^{-1} on average), depending on the weather variable, with the largest being 1000–1500 kg ha^{-1}.

Correlation analysis and PCA were conducted in the validation step to ensure that cultivar-wise yield responses were similar across the trials and farmers' fields. The correlation between the cultivar-wise responses in the trial data and the farm data was 0.58 [0.48, 0.67] for the yield and 0.70 [0.61, 0.76] for the hectolitre weight. In addition, PCA for the yield responses resulted in a similar PC structure for both datasets, confirming the stability of the weather factor structure.

Both diversity indices were calculated for each year, and their slopes were statistically compared for each of the 16 regions (Figure 2 and Table 2 in Study I). The overall level of diversity indices for cultivars (type) was higher than that for clusters (response) due to the presence of a larger number of cultivars compared to clusters. Both indices increased evenly in 1998–2009 in the southern regions, but in the central and northern regions, the differences increased in the early 2000s and again in the mid-2000s, meaning that the response diversity index decreased even as the type diversity index increased.

Equitabilities of response diversity decreased significantly in the central and northern regions, indicating that barley cultivation was concentrated in fewer agro-climatic response clusters. In Central and Northern Finland, the decline in response diversity was accompanied by an increase in the area under cultivation for the 3rd cluster, which replaced the area under the previously cultivated 1st cluster (Figure 3 in Study I). The older cluster was found to be relatively stable for weather fluctuations and had a moderate yield level, whereas the yield level of the newer cluster was higher, increasing due to relatively early sowing and decreasing due to drought.

3.2 Diversity of European wheat cultivars

In most European countries examined herein, farmers' fields showed a decreased diversity of wheat yield response to weather patterns crucial to wheat production. Overall, the diversity of yield responses to weather conditions started to decline in the 2000s, with the clearest decline occurring in Czechia since 2002 (Figure 1 in Study II). In Czechia, the response diversity was the highest in the first few years of the period, but since then, it has declined. The decline started in Germany in 2003, in Spain in 2005 or even earlier, in Slovakia in 2006 and in Denmark in 2009, resulting in the lowest response diversity at the end of the studied period. A recent increase in response diversity, as well as the greatest response diversity, was found in Finland. However, Finland is a relatively minor wheat producer, and the number of cultivars in cultivation is also relatively small in Finland. During the entire period, the response diversity increased in Belgium, Finland and France ($P<0.001$), whereas since 2006, the development in Belgium has varied much without an increasing trend ($P=0.35$). In France, no clear evidence of an increase after 2008 was found ($P=0.13$).

The trend of response diversity in variety trials showed a similar pattern as that in farmer's fields. In the trials, however, the decline was smaller and not as consistent, which indicates an unexploited potential to utilise cultivars tested in different countries. The yield responses of the nine clusters calculated for the nine critical weather patterns, also called agro-climatic PCs (Table S1 in Study II), ranged from +12% to −56% (Figure 2 in Study II), showing rather high yield effects for different weather patterns. The total number of clusters increased until 1999, remained constant until 2004 and declined thereafter. Correspondingly, the number of cultivars increased until 2001 and began to decline in 2009.

A response diversity desert, meaning a low diversity of weather response clusters, was found in the Czech variety trials (Figure 3 in Study I). Smaller diversity deserts were observed in Germany and Spain and in the case of durum wheat in Italy. Almost all durum wheat cultivars were found in a single cluster (8th), whereas only four of them were grouped into other clusters (7th and 3rd). In contrast, the highest diversity of weather response clusters, identified as a response diversity hotspot, was discovered in Slovakia. Of particular interest were the promising unique cluster (6th) and currently the nearly unique cluster (7th). Cultivars in the 6th cluster benefited from high radiation, drought avoidance and warm fall and winter temperatures, whereas cultivars in the 7th cluster benefited from higher precipitation. All of these features represented positive responses to weather conditions in which most clusters suffered more or less (Figure S1 in Study II).

The interannual yield variability depending on the accumulated number of clusters is presented in Figure 2 in Study II. In the main figure, the yield variance declined when the number of clusters increased. The effect is especially accentuated when moving from one cluster to two, especially with the first PC. The yield sums for the seven-year period did not differ much when the cultivated area was divided equally among three cultivars compared to when only one cultivar was used, although there was obvious variation during the years (the box in Figure 2 in Study II). However, the total yield variation among the years declined considerably, as much as 16%–32%.

3.3 Diversity of Finnish forage crop cultivars

Most clay soils in Finland are found in the south and southwest, whereas the proportion of organic soils is highest in the northernmost part of the country. Central and eastern Finland had the highest amounts of coarse mineral soils (Figure 1 in Study III). However, all cultivars presented in the results were tested in each soil type in the experimental sites throughout Finland.

Compared to previous studies (I and II), the impact of soil type on the diversity of the responses of species and cultivars was added in the LMMs. Therefore, the three-way interaction of soil type, cultivar (or species) and each agro-climatic variable was also included in the models. A statistically significant interaction was found for almost every agro-climatic variable (Table 1 in Study III). In clay and organic soils, the average absolute yield response of forage crops to the weather was 10%, whereas in coarse mineral soil, it was 8%. The differences in yield responses of forage crops depending on the soil type were significant on the agro-climatic variable level; for example, the yield responses to *high precipitation during the regrowth stage* (Figure 3 in Study III) or *during fall hardening* (Figure 5 in Study III), *high temperatures during the regrowth stage* (Figure 4 in Study III) and *high mean daily accumulation of temperature above 0°C during the winter period* (Fig. 6 in Study III) indicated clear differences among species and cultivars. Abundant precipitation during the regrowth stage was clearly beneficial for Timothy in organic soils, whereas the yield effect of soil type was negligible for Meadow fescue. Similarly, red clover and Festulolium showed significantly more positive yield effects on clay soils than on coarse mineral soils. However, there was clearly significant variation in the yield effects of cultivars within forage crops (Figure 3 in Study III).

The principal component (PC) structure of each soil type was compared to the overall PC structure, including four agro-climatic PCs, formed in the previous forage crop study (Mäkinen et al., 2015). Most of the total variation in clay and organic soils could be explained by the temperature accumulation rate and the number of days when the maximum temperature was at least 25 °C in the regrowth stage (Table 3 in Study III). Agro-climatic factors related to winter (PC3) and the number of days when the maximum temperature was at least 25 °C at the primary growth phase, as well as the length of fall hardening and the amount of precipitation (PC2), explained most of the variation in coarse mineral soils.

The dependence of the response diversity of species and cultivars on soil type was studied using cluster analysis. Depending on the soil type, the species and cultivars formed several clusters based on how their yields responded to agro-climatic variables. Four clusters were found in coarse mineral soils, eight in organic soils and nine in clay soils

(Figure 7 in Study III). Most Timothy cultivars were clustered in one cluster in coarse mineral soils, whereas they were divided into two clusters in clay soil and four clusters in organic soil. Red clover showed a similar trend, with the majority of the cultivars clustered together in coarse mineral soils but divided into two clusters in clay soils. In the reactions of cultivars to agro-climatic variables, uniformity within forage crops was the strongest in organic soils, whereas most cultivars that reacted differently were found the most in coarse mineral soils.

3.4 Summary of the results

The barley study (I) answered the question of whether response diversity yields a better estimate of the regional climate resilience of crops than that obtained from mere type diversity. The results confirmed that it was possible to form similar, meaningful agro-climatic factors for the trials and farmers' fields, confirming the stability of the weather factor structure. Therefore, the response and type diversity indices based on the cultivation areas of each cultivar were calculated for each region. The slopes of the type and response diversity indices were statistically compared for each region for each year. The difference between the indices in the central and northern regions tended to widen in the early 2000s and again in the middle of the decade, which meant that the response diversity index decreased while the cultivar type diversity index increased. However, both indices increased steadily in the southern regions from 1998 to 2009. In the central and northern regions, the equitabilities of response diversity decreased, which indicates that barley cultivation was concentrated in fewer agro-climatic response clusters. The growth in the cultivation area of a new cluster, which replaced the area under the previously farmed old cluster, correlated with a decline in response diversity in Central and Northern Finland. The yield level of the older cluster was found to be moderately stable for weather variations, whereas the younger cluster's yield level was higher, increasing due to relatively early sowing and reducing due to drought.

The wheat study (II) answered the question of whether the diversity of yield responses varied between European countries and whether European wheat generally has sufficient climate resilience. In most of the European countries that were studied, farmers' fields showed a declining diversity of wheat yield responses to the weather patterns relevant to wheat yield. Generally, diversity started to decline in the 2000s, being strongest in Czechia since 2002. In addition to Czechia, diversity gaps were observed in Germany and Spain and in Italy in the case of durum wheat. For example, almost all durum wheat cultivars reacted similarly to weather patterns. In contrast, diversity was the most positive in Slovakia. The decline in variety trials was slightly smaller and less consistent; the number of clusters increased until 1999 and decreased after 2004, whereas the number of individual cultivars increased until 2001 and decreased from 2009 onwards. Therefore, the unexploited potential of utilising cultivars tested and used in other countries was noticed.

The forage crop study (III) answered the question of whether the diversity of yield responses and the most influencing agro-climatic factors depend on the soil type. It was shown that the PC structures of each soil type differed from each other and from the overall structure of the four agro-climatic factors formed in the previous forage crop study (Mäkinen et al., 2015). Therefore, the response diversity of the forage crop cultivars was clearly dependent on the soil type. In contrast to clay or organic soils, coarse mineral soils displayed a reduced diversity of species and cultivar responses, indicating a relatively weaker capacity to successfully cope with uncertain climate change. Based on how their yields responded to agro-climatic variables, the species and cultivars formed various clusters according to the type of soil. For example, most Timothy cultivars were clustered in one cluster in coarse mineral soils, in two clusters in clay soils and in four clusters in organic soils. The uniformity within forage crops was the strongest in organic soils, whereas most cultivars that reacted differently were found in coarse mineral soils.

The synthesis study (IV) deepened the understanding of the connection between diversity and resource efficiency as well as the possibilities of expanding the approach in other sectors. Thus, the methodological development of the approach was also evaluated in greater detail in this context, as was the case with the interpretation of the diversity measure. The use of the exponential form of the Shannon index as a more appropriate measure of true diversity was discussed in more detail in this context. Therefore, these studies demonstrated and confirmed the utility of response diversity in different contexts. It can provide a better tool to assess the developments in specific areas compared with merely type diversity.

4 Discussion

The uncertainty in climate change is strongest at the farmers' level (Howden et al., 2007; Rötter et al., 2013), where crop diversity is managed on an annual basis. The proposed cluster-based response diversity measure for barley, wheat and forage crop cultivars is applicable to Finnish farms and can be used to evaluate and compare all areas or farms. In the barley study (I), it was shown that the results could be utilised at a practical level in agriculture, even if the variation in conditions was increased. However, more work is needed to facilitate this approach so that the utilisation of variety selection is more practical on a single farm (IV).

Instead of cultivating a single genotype, a set of cultivars with different yield responses to various climatic conditions and environments should be used, as this would increase yield stability under environmental fluctuations. Selecting cultivars based on the empirical information of yield responses to climatic conditions that are crucial to the yield and maintaining a sufficient level of response diversity could secure higher total yields and financial returns for farmers. This importance of response diversity in yield variation is discussed in Chapter 4.2 by comparing the total yields over a seven-year period from one site in Czechia. More information and perhaps more practical tools are needed to help and enable farmers to choose from a set of cultivars having both sufficient response diversity and high production potential. These issues are discussed in the following chapters.

4.1 Assessing response diversity

4.1.1 Value added by the empirical assessment of response diversity

The resilience approach focuses on dealing with uncertainty, complexity and unpredictable variability, thereby facilitating tools for a shift to adaptive management. The proposed approach facilitates adaptive management by empirically evaluating the critical factors of change and identifying the most effective diversity that reduces sensitivity to variation and increases the capacity to adapt to realistic ranges of such critical factors. Additionally, it can direct adaptive management and governance in reaction to climate variability and change as well as in the economy of agricultural activity or in the sales of retail suppliers in response to price volatility (Howden et al., 2007; Kahiluoto et al., 2020), for example. In the latter case, food suppliers were clustered according to how their sales reacted to global price fluctuations or strikes. It was shown that higher diversity indicated more stable access to affordable food for Finnish consumers.

The aim of the barley study (I) was to present a new approach to studying response diversity in different areas and circumstances. Therefore, this approach can be used to quantify response diversity generally, and it could be applicable to any system that provides empirical information about the responses associated with a phenomenon whose variability and changes can be measured. One proposed way to evaluate the added value of this approach is to compare the diversity indices (type and response) in each case. In many cases, data availability may be a limiting factor because the proposed approach requires relatively large datasets depending on the studied area. For example, in cultivar studies, thousands of observations might be needed, whereas in supplier studies, fewer observations might be sufficient. In cultivar studies, long-term trials or observatories that provide reliable multi-year datasets are needed. Alternative data sources have been discussed in more detail in the context of the barley study (I). The increase in the availability of open data will also facilitate the use of the proposed approach in the near future.

The same approach was utilised for the European wheat (Study II) and for Finnish forage crops (partly in Study III). However, some methodological modifications can be made depending on the studied area. For example, PCA was utilised for forage crops (Study III) instead of direct clustering based on a distance matrix (Study I). This new method was found to be useful and provided more stable and interpretable results. The use of PC scores can be recommended, especially in situations where the sample size is relatively small (Study III). As a rule of thumb, a sample size of at least 2^m, where m equals the number of clustering variables, is recommended (Formann, 1984). Therefore, 4–10 factors (or PCs) are preferable to 10–40 variables for small sample sizes. Many of the selected agro-climatic variables tended to be relatively strongly correlated; thus, the factors captured a large amount of total variation. To ensure that different combinations of soil types with species and cultivars from various areas were represented in the dataset, comprehensive data on species and varieties and their soil types from different locations were collected (Study III). Fewer observations were available for organic soils, which is partly because not all species thrive there.

Another methodological choice was to use unstandardised PC scores formed as a by-product of PCA, which should give less weight to the potential noise element and reduce the sensitivity of the clustering, especially to the number of PCs retained (Studies II-III). The results of standardizing PC scores appeared to be relatively comparable, but the method used seems more meaningful as it takes into account the eigenvalues of PCs. Although the previously employed clustering technique using Mahalanobis distances between yield responses may theoretically be a more straightforward technique for clustering yield responses, the use of PC scores appears to reduce data noise. PCA was already utilised in the barley study (I) for data validation when modelling and comparing the weather factor structure of datasets from trials and farmers’ fields. Therefore, based on our experience, we recommend the use of PCA in the clustering step as well, although some criticism of factor-based clustering has been presented in the past.

In the wheat study (II), the approach was extended to nine European countries, which substantially increased variation in the data. Due to a large yield variation between countries, the relative yield difference was used to account for and balance the differences between the yield levels of cultivars. This was done on a theoretical basis but was found to be relatively insignificant, indicating the stability of the clustering. Although the problems associated with increased yield variability compared with data from one country were not overwhelming, this might become a problem in studies in other areas.

4.1.2 The use of the exponential of the Shannon index as a true diversity measure

Various diversity indices are widely used in different research areas, including ecology. Diversity indices have unique properties that are useful for different areas, but entropies such as Shannon and Gini–Simpson are the most known indices. However, it is important to note that entropy is not the same as diversity. Similar to how the diameter of a sphere is an indicator of its volume but not the volume itself, it is merely an index of diversity. Thus, using the diameter as volume in equations would lead to misleading results. Jost (2006) mentioned that most diversity indices are actually entropies, not diversities, and that their mathematical behaviour does not usually correspond to ecologists' theoretical or intuitive concept of diversity. However, all diversity indices can be transformed into true diversities that accurately capture the concept of diversity. More importantly, the conversion to true diversities enables the comparison of diversities among different communities and facilitates the accurate interpretation of the results.

In the ecological context, true diversity can be measured as the effective number of species, which means that a community with 12 equally common species is twice as diverse as a community with six equally common species. The indices that have this 'doubling' property, first presented by Hill (1973), provide intuitive and interpretable results about diversity, but most raw indices do not obey this property, although their numbers equivalents do. All 'Hill numbers' are functions of

$$D \equiv \left(\sum_{i=1}^{S} p_i^q \right)^{\frac{1}{1-q}}, \tag{4.1}$$

which means that diversity depends on the value of q; thus, the diversity of a single community can be calculated through any of these measures. The order of a diversity measure q represents its sensitivity to common and rare species. Thus, species richness (q=0) is totally insensitive to species frequencies and weighs rare species more, whereas the Simpson concentration (q=2) gives more weight to common species. Only the Shannon entropy (q=1) weighs all species by their frequency without favouring. Therefore, it is one of the most widely used diversity indices among ecologists for a good reason.

When indices are not shown in the original scale, it is very difficult to compare them. Because the Shannon and Gini–Simpson indices are highly non-linear, it is easy to come to incorrect conclusions. For example, the difference of 0.99 and 0.97 in the Gini–Simpson values appears minor, but the drop in diversity is 66% because the actual true diversity measures in the original scale are 100 and 33. Due to the 'doubling' property, any of those three indices can be used to compare two communities, but there are several reasons to favour Shannon entropy. One of the most important reasons is that it can only be consistently decomposed into meaningful independent alpha and beta components. Therefore, according to Jost (2006), the exponential of Shannon entropy is the only true diversity measure that can be divided into alpha (diversity of community), beta (diversity between communities) and gamma diversities (diversity of a region). In addition, Jost (2007) presented five properties that intuitive alpha and beta should have for the exclusion of other diversity indices.

Jost, (2007) also disputed the frequent criticism of Shannon measures that they do not have a clear biological interpretation. Due to this misunderstanding, the Gini–Simpson index has been widely recommended over Shannon entropy (Lande, 1996; Magurran, 2004); however, as shown in previous studies (Jost, 2006; Jost, 2007), the Gini–Simpson index emphasises dominant species and is not suitable for studies involving landscape alpha or beta. Species richness has been suggested by some authors as an alternative to Shannon entropy, but it is a poor choice for separating communities or comparing changes in diversity over time because it is utterly insensitive to differences in species frequency. It is also easy to question its ecological realism, as species frequencies are often more interesting than mere presence or absence. Obviously, frequencies provide an additional aspect that should be used when they are available. For these reasons, the Shannon index was used throughout this dissertation. Both the Shannon index and true diversity measure were used depending on the purpose. For barley, the statistical significance of the slopes of the diversity indices (response and type) was compared for each region, whereas for the wheat and Finnish farm efficiency studies (Kahiluoto & Kaseva, 2016; Figure 8 in Study IV), true diversities were presented and interpreted.

4.2 Value added by the assessment of the response diversity of barley, wheat and forage crop cultivars

4.2.1 Response diversity of barley, wheat and forage crop cultivars

Barley was an obvious choice for the pilot study because large amounts of data were needed, and it is the most cultivated cereal and fodder crop in Finland. Therefore, maintaining barley diversity is crucial to secure animal production as well. A more diverse response to critical and unpredictable changes and fluctuations could ensure that greater variability can be endured before the critical threshold of the barley production system and, thus, food security can be exceeded. It was found that the response diversity of barley decreased in central and northern Finland, indicating increased vulnerability and decreased resilience (Elmqvist et al., 2003; Folke et al., 2004; Laliberté et al., 2010), which could not have been revealed from cultivar-type diversity alone. The cultivation area concentrated on fewer agro-climatic clusters in Finland’s central and northern regions during the 2000s, especially in the latter half of the decade, although cultivar-type diversity rose at the same time. In particular, the cluster sensitive to drought and benefitting from early sowing was increasingly dominant. This shift to concentrated cultivation appears to be due to the yield potential of new cultivars that represented the same agro-climatic cluster and were released to the market at the time. As reported by Himanen et al. (2013a; 2013b) there occurred no shift in precipitation or temperature during the period between the regions, which may explain the observed concentration as farmers adjusting to the shift in weather. About half of all barley cultivars that entered the market in 1998–2009, with their accumulated cultivation area being 65% and even 89% since 2005, were included in that single agro-climatic cluster. On the contrary, in the first year of the period, the cultivated area was roughly divided into 2–3 agro-climatic clusters. Therefore, the increase in competition in the market may have influenced breeders, leading them to introduce new varieties that are similar in terms of the weather. The suggested method can be applied to choose a tailored set of cultivars that reflects a larger diversity of responses to critical weather variability and lowers the annual variability.

According to the correlation between the accumulated number of clusters and the inter-annual yield variability, cultivar diversity in response to weather can be used as a proxy for climate resilience. The decline in yield variance due to increasing response diversity, for example, using more diverse cultivars, can be observed for different agro-climatic PCs from the main figure (Figure 2 in Study II). Through a seven-year field experiment example from Caslav in Czechia, the idea of response diversity as a yield-stabilising tool was also demonstrated by combining cultivars from different clusters to show increased yield stability under weather variability. Three example cultivars from the 1st, 3rd and 5th clusters were selected based on the number of available observations and similar mean yields. In our calculation example, the area under cultivation was divided equally between cultivars between 2001 and 2007 and then compared to the cultivation of each cultivar separately. Compared to the cultivar Apache with the highest total yield, only a 2% loss in total yield was observed; however, the standard deviation among the years declined by 16%–32%. It highlights the importance of using the cultivars of several clusters by sharing the risk with respect to weather conditions.

The country-wise trends of response diversity in the cultivar trials did not show a particularly promising development (Figure 3 in Study II). For example, in Denmark, the number of mainly UK-originating cultivars declined from 80 after a strong increase in the 2000s to a third of mainly Danish cultivars in 2014. The loss in wheat production, presumably caused by the unusually warm winter of 2007 with late frost occurrences (Kristensen et al., 2010) led to the substitution of foreign cultivars with local ones, which likely contributed to the decline in response diversity. In Finland, the low number of cultivars remained constant throughout the whole period.

The diversity in responses observed within forage crop species and cultivars for various soil types, especially the difference between coarse mineral soil relative to organic or clay soils, is essential for agriculture's ability to adapt and be resilient to at least moderate but hopefully also to more extreme climate variation. For example, Timothy cultivars in organic soils displayed a significant degree of variation in their responses. The so-called safe space for adaptive actions may be expanded by the diversity of responses to critical change, and farmers could implement these strategies in practice to improve production resilience by choosing cultivars from various clusters within each soil type. To enable such choices by farmers, it is crucial in breeding to provide and ensure a diverse cultivar pool by taking into account the functions of different soil types. However, because yield losses due to soil-dependent extreme weather are not currently recorded in variety trials, much information is lacking, especially from the diversity of responses to extreme weather conditions. Documenting yield losses as a result of extreme weather occurrences and possibly including them in a separate analysis would thus be an immediate improvement.

Clay soils are usually considered drought-prone; however, this was not supported by the results, which may be because forage crops have reasonably well-developed root systems, and clay soils have a high water-retention capacity. Forage crops in clay soils typically suffer from abundant precipitation during fall hardening or the regrowth stage, which may be explained by the clay soils' significant compaction (Mukula & Rantanen, 1987). The warm growing season was also the most crucial factor for organic soils, which typically have limited thermal conductivity, especially during drying (Mukula & Rantanen, 1987). Forage crops in organic soils seemed to benefit most from extremely hot temperatures and low precipitation throughout the regrowth phase, which can be explained by organic soils' high water-holding capacity and possibly a high ground water table.

In contrast to clay and organic soils, abundant precipitation during fall hardening, high temperatures prior to the first harvest and low accumulation of thaw days during winter, along with an accumulation of cold stress days having a temperature of at least −15 °C during winter, strongly affected the agro-climatic PCs, which explained the highest yield variation in coarse mineral soils. The occurrence of thaw days throughout winter was harmful for coarse mineral soils, indicating the potential negative consequences of anticipated warmer winters in the future (Jylhä et al., 2008). However, the projected increase in precipitation in fall and a shortened hardening phase (Ruosteenoja et al., 2011) may be advantageous for yield performance in coarse mineral soils. Breeding should take into account the ability to withstand severe temperature stress, especially when considering cultivation on coarse mineral soils, which are widespread in Northern Central Europe.

4.2.2 Adaptation to shifts in climate

Projected climate change is expected to increase temperatures by 3–4 °C in summer and 8–9 °C in winter by the end of this century (Ruosteenoja et al., 2011). This will also extend the growing season and likely affect crop production (Peltonen-Sainio et al., 2009a; Rötter et al., 2013). However, the potential of agriculture in boreal conditions is projected to remain relatively modest even in the scenario of a 5 °C global temperature change (Trnka et al., 2011). Precipitation is also projected to increase, especially in winter. Although precipitation in June could have a positive effect on the yield (Peltonen-Sainio et al., 2009a), in particular, the increase in precipitation during fall may have a negative impact on yields (Ylhäisi et al., 2010).

The spatial heterogeneity of soil types may cause noticeable shifts in the relationships between agro-climatic factors and soil types as a result of climate change-induced shifts and the northward extension of agricultural zones (Audsley et al., 2006; Carter & Saarikko, 1996; Peltonen-Sainio et al., 2008). Although most of the forage production occurs on coarse mineral soils nowadays, which are mostly located in central and eastern Finland, organic soils may become more significant if production shifts northwards. As hypothesised and demonstrated, soil type has a significant impact on how forage species and cultivar yields respond to the agro-climatic factors that affect the yield. However, future land-use scenarios are unclear and variable, making it extremely difficult to predict which crops will actually shift. In the USA, significant changes in maize output have been predicted (Newman, 1980), and significant changes in numerous crops are projected in Canada. In Finland, the region suitable for wheat production may move quickly, from 110 km in the east to 290 km in the west to the north, due to a 1 °C increase in mean temperature (Carter & Saarikko, 1996). In this light, the findings highlight the importance of the relationship between climate, soil and the underlying processes in planning for successful agricultural adaptation, such as planting new species or expanding existing species into new lands. However, there is no guarantee that crops will successfully adapt to new regional distributions of agricultural land use.

For wheat (II), temporal development of weather response clusters was found. As a result of breeders' response to the increase in average temperatures in the late growing seasons of the 2000s (Peltonen-Sainio et al., 2009b), there was a shift towards yield stability and benefit from late solar radiation, as well as lower yield loss due to late heat and precipitation (the 3rd cluster replacing the 1st and 5th clusters). After 2000, in southern countries, the 5th cluster suffered more from early drought, high minimum temperatures in summer and heat at heading compared to the previously dominant clusters, and by coming more popular in cultivation, it aggravated the risk of yield loss (Semenov & Shewry, 2011). This development could be an unintentional side effect of the selection for other traits. Overall, the response to precipitation appeared to be a risk for the entire continent because none of the clusters responded positively to abundant precipitation (Figure S1 in Study II). This is problematic because these circumstances favour diseases and result in low yield (Kristensen et al., 2010), and wheat is generally sensitive to even a few days of exposure to water logging (Malik et al., 2002). The yields of individual cultivars more than doubled in some cases with scarce precipitation compared to abundant precipitation (PC1 in Figure S1 in Study II). These empirical findings, which show doubled yields in scarce precipitation compared to abundant precipitation, are consistent with simulations that show heat stress, not drought sensitivity, is what prevents wheat in Europe from adapting to climate change (Semenov & Shewry, 2011).

While one-fifth of the world's wheat is produced in Europe (FAOSTAT, 2017), the lack of diversity exposes production to greater volatility, thereby increasing the risk of food insecurity. Most wheat is cultivated for either bread or pasta flour, and each uses a different cultivar; however, most wheat used as feed does not fulfil the standards for those uses. In particular, the durum wheat cultivars used for pasta seemed to lack response diversity to weather events. Because the Italian durum germplasm needs low temperatures for vernalisation (Motzo & Giunta, 2007), it was not surprising that durum suffered from heat at heading and warm winters. Higher cultivar diversity was found in the trials at the European level than at the country level, but significant differences in climatic conditions and environments made it difficult to utilise cultivars directly across Europe. However, the cultivars used in national trials could be made more diverse by utilising additional cultivars from the European list of approved cultivars, but this may require more funding for targeted research and financial incentives for companies. Wider utilisation of developed cultivars could also be a cost factor for breeders, as breeding a selection of genuinely unique cultivars is likely to be more expensive than breeding a relatively homogeneous group. Although there may be indirect benefits due to decreased risks and reduced contract area requirements, wider selection also imposes more expenses on traders. The countries that have traditions in private–public breeding partnerships, such as Belgium and Finland, showed better development in response diversity than, for example, Germany, where private breeders have dominated thus far. The public actor responsible for food security may benefit the most from sufficient response diversity, but it may also benefit the weakest actors in the wheat supply chain, such as farmers and low-income customers, by increasing yield and price stability. Although breeders might be encouraged by farmers' demand to diversify wheat cultivars' responses to the weather, farmers understandably prioritise yield potential and quality. However, the cultivation of multiple cultivars may not only temporarily equalise labour demand but also reduce costs for farmers. Therefore, yield stability should be seen as a complementary breeding goal because there is not an inherent trade-off between long-term average yield or yield potential with diversity in weather responses. For example, in regions of Finland with a high diversity of barley cultivars, where yield fluctuations between years were minimal, the average yield was also higher than in regions with low cultivar diversity (Himanen et al., 2016).

Farmers' levels of risk-taking vary, but the significant proportion of yield-independent subsidies in farm income in Europe (46%; European Commission, 2017) serves as a disincentive to innovations for yield security. For example, in Czechia, the level of subsidies is lower than that in most EU members, but the costs are further increased by the fact that most of the farmland is rented. Therefore, farmers have an obvious need for cultivars that can withstand droughts. From a management perspective, a cultivar portfolio with a diversity of responses to the weather could be a requirement for farmer subsidies or loss compensation as well as for a lower cost of insurance. Overall, the main challenge for enhancing response diversity lies in the required change of perspective, as participants in wheat supply chains must shift their focus from individual cultivars and their potential production under ideal conditions to a portfolio of cultivars (Figure 4.1). By choosing cultivars from different sacks, i.e., response clusters, a farmer or a region could better prepare for fluctuating environmental conditions, securing a more consistent total yield each year. The lack of knowledge and experience in the diversity approach maintains the focus on individual cultivars rather than on a portfolio of cultivars, which have better potential for yield stability. Therefore, practical tools to illustrate and communicate the diversity in cultivar responses among farmers, breeders and traders are needed for the shift in perspectives towards resilience (Paavola et al., 2016). More generally, the resilience of wheat supply chains and food systems could be improved by accelerating a dialogue within wheat value chains and involving researchers and policymakers (Himanen et al., 2016).

Figure 4.1. The idea of diversification of cultivation on farms by choosing cultivars from different response clusters. Each sack represents characteristics that define the response of each cultivar cluster to weather conditions.

4.3 Next steps to utilise the presented response diversity approach

Due to the increased amount of environmental variation in the wheat and forage crop studies (II and III), questions arise about the absence of potential and relevant predictors. Adding soil information for barley and wheat, as done in the forage crop study (III), would be very interesting and is actually the subject of another wheat article in progress. It was shown that yield responses related to agro-climatic variables are highly dependent on soil type (III); thus, adding a country level to the proposed approach would be highly interesting and novel. Another article under development uses widened data on Finnish barley and utilises the updated approach presented for wheat (II). A comparison of the new and the old approaches provides new insights into not only the evolution of response diversity but also the stability of weather-based clustering of cultivar yields. The proposed approach has not been updated previously on the same subject, so it will be important to examine how it changes over time and any potential weaknesses that may arise.

The idea of response diversity was introduced and tested for Finnish barley and then expanded to forage crops and European-wide wheat. Testing possible impacts at the farm level, similar to the idea behind the calculation example from Czechia, could be possible with sufficient parcel-scale data collected from farmers' fields instead of variety trials. These data were gathered for Finnish barley in the 2010s and may enable the identification of potential regional gaps, hotspots and deserts from a resilience perspective. Farm- and region-specific factors for resilience-based cultivation could be studied in addition to the efficiency and yield stability of a farm or a region. This novel knowledge may be valuable for optimizing and planning adaptation measures in a changing climate and could provide the next step towards developing a practical decision-making tool and support system to improve regional guidance. Making the benefits of response diversity known, at least at the regional level, is extremely important, but it would be even more convincing for farmers if the economic benefits of diversification could be demonstrated more concretely at the farm level as well.

As mentioned in the beginning, response diversity has not yet been thoroughly quantified, probably because it is difficult to be quantified, and even when it has, the methods have varied a lot. This research on measuring response diversity will continue, and there are some interesting new articles on the topic (Loreau et al., 2021; Ross et al., 2022).

5 Conclusions

Long-term monitoring systems enable the empirical investigation of response diversity. The concept of resilience, which has already opened up a new perspective, can be employed as a practical advancement tool by presenting the possibilities of practical tools based on available empirical data. The proposed approach for empirically identifying response diversity in order to manage the resilience and adaptive capacity of crops to climate change adds value by guiding targeted diversification. The resilience perspective brings added value to the food chain by helping actors prepare for unforeseen fluctuations and changes, which are also particularly visible nowadays in Europe. Diversification can be an effective and practical strategy for managing resilience in multiple sections of food systems. Even less diversity can lead to increased resilience if the essential diversity that promotes resilience is successfully identified. Increasing the efficiency of diversification would thus aid in combining the complementary components of sustainability, i.e., resilience and efficiency.

Our findings support the hypothesis that yield responses, and thus the response diversity, of forage crop species and cultivars to agro-climatic variables depend on the soil type. Furthermore, the weather patterns that have the greatest influence on forage crop yield variations differ depending on the soil type. Climate–soil–crop combinations were identified as important for adaptation, underlining the need to address alterations in climate–soil–crop combinations rather than climate alone. Finland served as an example of a northern agricultural country with long days, busy growing seasons and a significant amount of organic land, but the approach can be applied for adapting agricultural practices in general, regardless of geographical location, and for other systems as well. In this study, management practices and breeding remained unchanged, whereas only climatic conditions changed. More research that takes into account the impact of rising atmospheric CO_2 and how climate, soil and agricultural systems react to changes in the carbon and nutrient cycles is needed.

The trend of European wheat towards the same dominating weather response clusters between northern and central European countries, as well as between southern European countries, was discovered and interpreted as concerning. Since the declining diversity of yield responses to weather patterns critical to yields was also found in farmers' fields in most European countries, cultivar selection practices and current breeding programs seem to fall short in their efforts to prepare for climatic unpredictability and variability. The removal of current disincentives and the introduction of new and fresh incentives and regulations for diversity in yield responses to climatic uncertainties can and deserve to be enabled by national action plans and the European Union's Common Agricultural Policy (CAP). However, regulations must be flexible enough to support continuous collective learning and adaptive management. To gain deeper knowledge of the genetic basis of yield and quality responses to weather, more research and collaboration between all operators in the field are needed. Furthermore, this approach provides ways to communicate across science, policy and actor interfaces and facilitates public–private partnerships.

Although agricultural policy has been based on a presumptive trade-off relationship for decades, it appears that the dependence between resource-use efficiency and production diversity is either scarce or non-existent and could be avoided through system management. However, the operational implementation of the response diversity approach and its application to resilience management requires re-tooling through collaborative processes involving key actors from different sectors of society; however, the fear of losing economic efficiency is not a good reason to avoid diversification in promoting resilience, and especially response diversity that represents a more effective form of resilience.

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Cultivating resilience by empirically revealing response diversity

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ABSTRACT

Intensified climate and market turbulence requires resilience to a multitude of changes. Diversity reduces the sensitivity to disturbance and fosters the capacity to adapt to various future scenarios. What really matters is diversity of responses. Despite appeals to manage resilience, conceptual developments have not yet yielded a break-through in empirical applications. Here, we present an approach to empirically reveal the 'response diversity': the factors of change that are critical to a system are identified, and the response diversity is determined based on the documented component responses to these factors. We illustrate this approach and its added value using an example of securing food supply in the face of climate variability and change. This example demonstrates that quantifying response diversity allows for a new perspective: despite continued increase in cultivar diversity of barley, the diversity in responses to weather declined during the last decade in the regions where most of the barley is grown in Finland. This was due to greater homogeneity in responses among new cultivars than among older ones. Such a decline in the response diversity indicates increased vulnerability and reduced resilience. The assessment serves adaptive management in the face of both ecological and socio-economic drivers. Supplier diversity in the food retail industry in order to secure affordable food in spite of global price volatility could represent another application. The approach is, indeed, applicable to any system for which it is possible to adopt empirical information regarding the response by its components to the critical factors of variability and change. Targeting diversification in response to critical change brings efficiency into diversity. We propose the generic procedure that is demonstrated in this study as a means to efficiently enhance resilience at multiple levels of agrifood systems and beyond.

1. Introduction

Intensified climate and market turbulence has brought considerable uncertainty to human activities (Coumou and Rahmstorf, 2012; Dessai et al., 2007). The volatility of the food and financial markets has reintroduced food security on to the world agenda. Resilience and adaptive capacity, robustness and multi-stability are required to complement the 'predict and adapt' approach of preparing for projected long-term changes (Dessai et al., 2007; Scheffer et al., 2001). Diversification is the strategy with highest expectations, with response diversity being the key (Folke et al., 2004; Elmqvist et al., 2003). Response diversity, if empirically assessed, could lay the groundwork for adaptive management and facilitate, at the interfaces of science, policy and private actors, adaptive governance for a resilient society.

To recognise resilience, we must move beyond species, cultivar and genetic diversity. Diversity in functional properties rather than diversity of types per se (Page, 2010) is crucial for the provision of ecosystem services (Diaz et al., 2007). Response diversity refers to the diversity of responses within a functional group (e.g. within a species, or group of species providing the same function) (Elmqvist et al., 2003; Nyström, 2006). While providing diversity of responses to disturbances, response diversity within a functional group ensures that at least some members of the group maintain their function when facing such disturbances. Consequently, response diversity enables the continuous provision of the same function in turbulent and changing environments also (Folke et al., 2004; Nyström, 2006). In addition, response diversity, by providing material for selection in new conditions or for new targets, builds

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the capacity for successful transformations (Chapin et al., 1997). Therefore, theoretically, diversity does not per se enhance resilience, whereas diversity in responses to critical variability and change produces such enhancement.

Despite appeals to manage for resilience (Folke et al., 2004; Chapin et al., 1997; Scheffer et al., 2001), the conceptual and theoretical development of this approach has generated few empirical applications to date (Laliberte et al., 2010). A limited number of field studies have observed that response diversity serves to sustain system functions following disturbances in coral reefs (Nyström, 2006), lakes (Schindler, 1990), bee communities (Winfree and Kremen, 2009), rice fields (Zhu et al., 2000) and grasslands (Walker et al., 1999). Indirect assessments of the impact of management on response diversity, which depend on the generic and hypothetical division of plant function and response traits, have also been reported (Laliberte et al., 2010). However, the adequate classification of responses should be based on the function of interest (Aubin et al., 2009) and reflect differential responses to roughly specified critical disturbances (Naeem and Wright, 2003). In an agrifood system, the response traits of fodder and food supply may be different for shifts in, for example, climate and pests, demand and price, even at the cultivar level. Therefore, the response diversity must be identified and quantified directly (Aubin et al., 2009) for each given question and case (Petchey and Gaston, 2006). Multivariate statistical methods, including clustering and ordination methods that are applied to assess genetic or species diversity (Laliberte et al., 2010; Petchey and Gaston, 2006; Mohammadi and Prasanna, 2003), provide examples of methodological solutions for the direct empirical quantification of response diversity.

Here, we introduce an empirical approach for directly revealing response diversity and apply this approach to a case of food security when facing climate change, i.e. to barley cultivar responses to weather in Finland. Barley cultivars vary in response to weather parameters (Hakala et al., 2012). For example, particular cultivars are drought susceptible, whereas others do not tolerate flooding or heat stress. We hypothesised that the assessment of the response diversity would yield a different estimate of the regional cultivar diversity than that obtained from mere type diversity. If so, then the approach based on response diversity would allow a more valid assessment of diversity in terms of the response to climate variability and change. In the case of added value by response diversity, this approach could provide a generic procedure as a practical tool to manage resilience.

2. Materials and methods

Our analysis involved two stages that were composed of five steps (Fig. 1).

2.1. Stage I: Identification of the responses to change factors

Stage I determines the factors of change that are critical to the system performance and the component responses to variations in these factors. In our example, we considered the agro-climatic parameters most critical to barley grain yield (Hakala et al., 2012; Rötter et al., 2013; Trnka et al., 2011) and the grain yield response of barley cultivars to variations in these parameters in multi-location trials (Hakala et al., 2012), which spanned three decades, in Finland. The generality of the results can be tested by validating the critical change factors and responses using other data. We determined the correlation in cultivar responses between the trial data and data from farms to test, whether the cultivars respond to the agro-climatic parameters under farm conditions similarly as in the trials, i.e. whether the response diversity model that was created using the trial data is valid in practical farming conditions, and thus applicable to guide the adaptive management of farmers and decision-making in, for example, breeding or agricultural policy.

2.1.1. Step 1: selecting the critical factors of change and variation

Data from the MTT Agrifood Research Finland Official Variety Trials (Hakala et al., 2012) from 14 locations from Mietoinen in the south (60°23′ N, 22°33′ E) to Ruukki in the north (64°40′ N, 25°06′ E) and to Tohmajärvi in the east (62°14′ N, 30°21′ E) were used. Consequently, the cultivar trials represented all of Finland except for the northernmost part of Lapland, i.e. of region I, and the southwestern peninsula of Ahvenanmaa, i.e. region XVI (Table 2, Fig. 2). Six trials were in regions II to VIII and eight trials were in regions IX to XV (Fig. 2). The trials were of a randomised complete block design or an incomplete block design. The number of replicates was 3 or 4. Cultivars in the experiments differed in the long term; however, standard reference cultivars were used across the trials. Fertilizer use depended on the cropping history, soil type and soil fertility and was consistent with the farmer practices (Hakala et al., 2012). Cultivars for which there were more than 25 observations were included in the analysis. Estimates were substituted for a few missing values for the phenological development dates (Hakala et al., 2012). The data consisted of a set of 112 modern cultivars of both Finnish and foreign origin from the early 1980s to the present (8.430 records) (Table 1).

The agro-climatic data of the Finnish Meteorological Institute for the trial locations were used. Ten agro-climatic parameters that most affected barley grain yield in the trials were identified using a regression analysis for parameters, which were selected based on previous literature and observations (for details, see Hakala et al., 2012). The correlating parameters were excluded to avoid multicollinearity. Two additional parameters (parameters 9 and 10 below) were selected based on the recent European study by Trnka et al. (2011). Consequently, the following twelve phenology-related agro-climatic parameters, which are the most critical for barley performance in Finland, were selected.

(1) Precipitation during one month before sowing (mm).
(2) Deviation from a fixed early sowing date (d).
(3) Drought 3–7 weeks after sowing indicated by accumulated precipitation (mm).
(4) Heat stress days of $\geq$25 °C one week before through two weeks after heading (d).

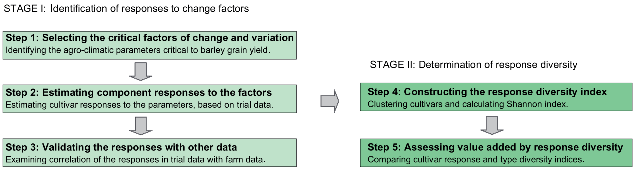

Fig. 1. The proposed approach to response diversity assessment. The steps of the generic procedure are presented in bold. The procedure that is applied to the case is specified for each step.

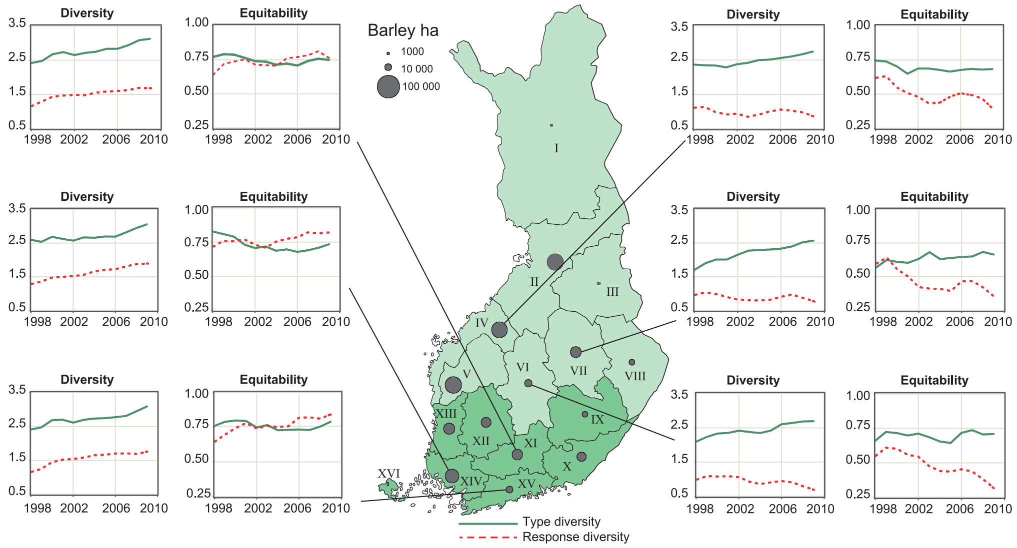

Fig. 2. Disparity between the Shannon indices and the equitabilities for the barley cultivar type diversity (continuous line) and response diversity (dashed line). Equitability represents the evenness component of the diversity indices which also include the component of richness. Equitability was calculated by dividing each value of the Shannon diversity index by the theoretical maximum for that value. The development in the regions with the smallest and greatest disparity between the indices since 2005 is shown. Dark green indicates the regions for which the disparity values were in the lower half of all regional values (the charts to the left). The size of the circles illustrates the barley cultivation area in 2005–2009. The Roman numerals refer to the regions that are presented in Table 1.

(5) Extreme heat stress days of ≥28 °C one week before through two weeks after heading (d).
(6) Temperature sum ($T_{sum} > 5$ °C) accumulation from 14 d before heading until heading (°C) ($T_{sum} > 5$ °C is the sum of degrees above 5 °C for all days, for which $T_{mean} > 5$ °C).
(7) $T_{sum} > 5$ °C accumulation rate from heading until yellow ripeness (°C).
(8) $T_{sum} > 5$ °C accumulation rate per day from heading until yellow ripeness (°C).
(9) Sum of effective global radiation from sowing until yellow ripeness (MJ m^{-2} for days with $T_{mean} > 5$ °C).
(10) Sum of effective growing days from sowing until yellow ripeness (d) (number of days with $T_{mean} > 5$ °C).
(11) Number of days with rain (>1 mm) from sowing until yellow ripeness (d).
(12) Seasonal precipitation from sowing until yellow ripeness (mm).

2.1.2. Step 2: estimating component responses to the factors

Each agro-climatic parameter was classified into three categories because the relations between the grain yield and the agro-climatic parameters were nonlinear in most cases. The 33rd and the 66th percentiles were used to form equal-sized categories. For example, the grain yield observations for each barley cultivar were divided into groups based on precipitation rates of 0–24 mm, between 24 and 40 mm and above 40 mm one month before

Table 1
Characteristics of the cultivar data. The 15 barley cultivars that were used in the validation are shown as examples.

Cultivar	First trial	Last trial	Number of trials	Mean yield (kg ha^{-1})	STD of yield	Mean hectolitre weight (kg)	STD of hectolitre weight	Heading DAS[a]	Yellow ripeness DAS[a]
Artturi	1989	2008	133	4911	1316	64.0	4.3	53.8	95.1
Arve	1987	2003	274	4727	1389	62.9	5.2	53.4	93.6
Barke	1997	2009	28	4702	1318	68.7	4.2	53.8	91.7
Erkki	1992	2008	99	5386	1366	65.6	4.2	55.3	96.0
Inari	1991	2006	67	4898	1586	69.4	3.8	53.1	93.6
Jyvä	1997	2008	69	4729	1483	66.5	4.0	54.5	91.4
Kunnari	1997	2009	144	5089	1510	65.6	4.6	54.8	91.4
Kustaa	1981	2001	290	4221	1474	67.3	5.6	52.3	92.9
Kymppi	1981	1999	249	4507	1592	66.0	5.5	52.9	93.3
Loviisa	1985	1996	173	4709	1530	64.1	6.7	52.2	94.4
Mette	1982	1997	122	4589	1450	66.6	6.5	52.7	94.0
Rolfi	1990	2009	179	4880	1380	62.7	4.6	54.8	95.0
Saana	1992	2008	124	4696	1327	67.3	4.5	55.1	92.2
Scarlett	1995	2009	120	4690	1665	69.3	3.7	55.0	91.8
Thule	1991	1999	85	5050	1380	65.0	4.7	53.9	95.9

[a] DAS, days after sowing.

sowing. However, the extreme heat stress days of ≥28 °C one week before through two weeks after heading (the agro-climatic parameter (5) above), were distributed among the 62nd (0 days) and the 72nd (1 day or less) percentiles, while the rest of the cases represented more than 1 heat stress day of ≥28 °C. The interaction of these categories with the cultivar grain yield of each of the 112 modern cultivars (see Section 2.1.1) was analysed using the following mixed model:

$$\begin{aligned} y_{ijklm} &= \mu + \text{cultivar}_i + \text{category}_j + \text{cultivar} \times \text{category}_{ij} \\ &\quad + \text{experimental site} \times \text{year} \times \text{trial(category)}_{klmj} + \epsilon_{ijklm} \end{aligned}$$

where y_{ijklm} is the observed yield, μ is the intercept, cultivar$_i$ is the average yield level of ith cultivar, category$_j$ is the average yield level at jth level of categorised environment (j = 1, 2, 3) and cultivar × category$_{ij}$ is the cultivar-by-environment interaction. All the above effects are fixed in the model. Experimental site × year × trial(category)$_{klmj}$ is the random effect of kth experimental site, lth year and mth trial within jth category, and ε_{ijklm} is a normally distributed residual error. The cultivar-by-environment interaction was statistically significant ($P < 0.05$) for every agro-climatic parameter included.

For each cultivar and agro-climatic parameter, the difference in yield between the extreme categories 1 and 3 was calculated. These data consisted of the grain yield responses of 112 cultivars to 12 agro-climatic parameters. For example, the mean yield of each cultivar for precipitation rates over 40 mm one month before sowing (agro-climatic parameter 1, category 3) were subtracted from the mean yield of each cultivar for precipitation rates below 24 mm one month before sowing (agro-climatic parameter 1, category 1). Consequently, a positive grain yield response meant that the grain yield was better when the precipitation rate one month before sowing was low.

2.1.3. Step 3: validating the responses with other data

The validity of the estimated yield responses in the trials was tested under the conditions occurring on farms, to ensure the validity of the conclusions for practical agriculture. Data on the cultivar grain yield on farms, which were collected by the Cereal Inspection Unit of the Finnish Food Safety Authority since 1966, and the grid-based weather data at a 10 km × 10 km resolution of the Finnish Meteorological Institute, which originated from the proximate weather stations, were used. In total, 1700 regionally representative farms were monitored, and approximately one-third of these farms were re-selected annually at random. The cultivation practices and yields were documented by the farmers, and the hectolitre grain weights were assessed in the laboratory from samples that were provided by the farmers. The agro-climatic parameters were adjusted to the phenological stages by modelling the critical phenological dates (Trnka et al., 2011), which were based on the sowing dates that were documented on each farm. The interaction of the grain yield of each cultivar and each agro-climatic parameter was tested in the farm data in a similar manner to that for the trial data. Pearson's correlation coefficient was calculated to compare the trial and farm data for the cultivar grain yield responses to the agro-climatic parameters.

To control the possible bias that might have been introduced by the farmers' yield assessments, the correlation for the trial versus farm data for the hectolitre weights that were assessed in the laboratory was also calculated. The hectoliter weights were only used for this purpose. Due to the potentially high variation in farm conditions, which may affect cultivar responses to the agro-climatic parameters, only the cultivars for which there were more than 100 farm observations (15 cultivars) were selected for validation. The data from 1998 to 2005 were used for validation, the period being limited by the availability of grid-based agro-climatic parameters (radiation). In addition to the correlations, also a principal component analysis for both the trial and the farm data was performed, to compare the trial and farm results for validation. The results are tentative due to the relatively low number of analysed units relative to the requirements of a robust principal component analysis: 40 cultivars in the farm data were used.

2.2. Stage II: estimation of response diversity

Stage II classifies the components according to the responses and creates a diversity index, which is based on the classification.

2.2.1. Step 4: constructing the response diversity index

A cluster analysis using Ward's method (Ward, 1963) was employed for the data that were created in Step 2 to cluster the cultivars according to grain yield responses to the agro-climatic parameters. The clustering was based on a Mahalanobis distance matrix, which uses the full multivariate information of the grain yield responses (McLachlan, 1999). The data contained the grain yield responses of the 112 cultivars (rows) to the 12 agro-climatic variables (columns). The Mahalanobis distance gives less weight to variables with a high variance and to highly correlated variables, such that all the characteristics are treated as being equally important (Mimmack et al., 2001). The cluster number was selected based on the dendrogram, the pseudo t^2-criterion and the r-square (Yeo and Truxillo, 2005) variation.

The Shannon diversity index (H), which implies both richness and evenness of distribution (Shannon and Weaver, 1949), was calculated for the cultivation areas of the 12 clusters of barley cultivars, which resulted from clustering (see above) in the 16 administrative regions of Finland. The 'response diversity' index thus had each of the 12 clusters as a diversity unit. The Shannon diversity index was calculated according to the following equation:

$$H_i = -\sum_{k=1}^{K} \frac{w_{ik}}{W_i} \ln \frac{w_{ik}}{W_i}, \quad \text{for } i = 1, \ldots, n \quad \text{regions}$$

where k = 1, . . ., K refers to the number of clusters; w_{ik} is the sum of cultivation area (ha) by cluster k of region i, W_i represents the total sum of cultivation area (ha) of region i, and (w_{ik}/W_i) is the proportion of the cultivation area (ha) that is covered by cluster k.

Shannon's equitability of the annual cultivation area for the clusters was also calculated to illustrate independently the evenness component of the diversity index (Mulder et al., 2004). The equitabilities also allow a direct comparison of the shifts in type diversity versus in response diversity because the scale of each is the same for equitability. Shannon's equitability (E_H) was calculated by dividing each H value by its theoretical maximum ($H_{\max}$): ($H_{\max} = \ln(K)$). The possible equitability values range between 0 and 1, with 1 indicating complete evenness. The cultivation areas of the barley cultivars for 1998–2009 were used to calculate the diversity indices and equitabilities. This information was collected annually from all farms in Finland by the Information Centre of the Ministry of Agriculture and Forestry.

2.2.2. Step 5: assessing the value added by response diversity

The annual Shannon diversity index and the equitability for each of the 16 regions were calculated using each individual cultivar as a diversity unit ('type diversity') (Himanen et al., 2013a) for comparison with the 'response diversity' index that was constructed (Section 2.2.1, Step 4). Differences between the slopes, which illustrated the development of the diversity indices and equitabilities (for 'response diversity' and 'type diversity') over time, were tested for both indices and equitabilities. The slopes of the variable year for the indices and the equitabilities were calculated for each region using a linear regression model. The models consisted of the intercept term in addition to the year.

The equality of the slopes within each region was tested for the indices and equitabilities using Student's two-tailed *t*-test. For the equitabilities and indices, the difference of the annual means of the two indices was also tested using the following mixed model:

$$y_{ijk} = \mu + \text{index}_i + \text{region}_j + \text{index} \times \text{region}_{ij} + \text{year} \times \text{region}_{kj} + \epsilon_{ijk}$$

where y_{ijk} is the observed value of index, μ is the intercept, index_i is the average level of ith index, region_j is the average level at the jth level of index ($i = 1, 2$) and index × region_{ij} is the interaction of the ith index within the jth region. The index refers to both H and E_H. All the above effects are fixed in the model. Year × region_{kj} is the random effect of the kth year within the jth region, and ε_{ijk} is the normally distributed residual error.

All of the statistical analyses were performed using PROC MIXED, CORR, FACTOR, PRINCOMP, DISTANCE, CLUSTER and REG of SAS (version 9.3, SAS Institute Inc., Cary, NC, USA). PROC PRINCOMP and DISTANCE were used to calculate the Mahalanobis matrix in Step 4 (Section 2.2.1).

3. Results

A generic procedure is proposed and the value-added of the response diversity approach is demonstrated by exemplifying the procedure using the case of barley cultivars (Fig. 1).

The practical significance of the yield response to the agro-climatic parameters is illustrated by the difference in cultivar yield between the highest and lowest third of the values for the 12 parameters. The median for the cultivars in such differences ranged between 134 and 579 kg ha^{-1} (332 kg ha^{-1} on average) depending on the parameter. Yield responses of up to 1500 kg ha^{-1} to some parameters were demonstrated, and a response of more than 1000 kg ha^{-1} was not rare. A cluster number of 12 for the grain yield responses by the cultivars to the 12 agro-climatic parameters was identified as best corresponding to the statistical criteria (for the criteria, see Section 2.2.1). The proportion of variation in yield responses to weather explained by the 12 clusters was 0.43.

The correlation between the cultivar responses in the trial data and farm data was 0.58 [CI 95% 0.48, 0.67] for yield and 0.70 [CI 95% 0.61, 0.76] for hectolitre weight. The principal component analysis for the grain yields resulted in a similar principal component structure for both the trial data and the farm data.

There were several cultivars in cultivation for most of the agro-climatic response clusters represented in the regions. Therefore, the means for the cultivar type diversity indices were higher than response diversity indices for the sown areas of barley cultivars ($P < 0.0001$) (Fig. 2). In the southern regions, both of the indices increased evenly in value from 1998 to 2009 (Fig. 2 and Table 2). However, in more than half of the 16 regions of the country, i.e. in the central and northern regions, the slope for the response diversity index differed from that for the type diversity index (Table 2). In the central and northern regions, the response diversity index decreased, although the cultivar type diversity index continuously increased. The discrepancy between the two indices in the central and northern regions tended to increase slightly at the start of the 2000s and increased again in the middle of the decade (Fig. 2). The decrease for the equitabilities (evenness) of response diversity was higher than for the response diversity index as a whole (Fig. 2) showing the barley cultivation concentrating in fewer agro-climatic response clusters, while the number of response clusters represented (richness) increased little relative to the increase in the number of cultivars.

The decrease in the equitability of barley cultivar response diversity in the Central and Northern Finland coincided with the increase in the cultivation area of a single response cluster, the grain yield of which is reduced by drought and which benefits from a relatively early sowing. This cluster (Cluster 3) replaced cultivars from another, previously equally extensively cultivated response cluster (Cluster 1) (Fig. 3), which shows little response to the weather parameters but with only a moderate yield level.

4. Discussion

4.1. Value-added by empirical assessment of response diversity

The resilience approach is a perspective for orientation in uncertainty, complexity and unpredictable variation, suggesting adaptive management. The proposed procedure assists adaptive

Table 2
Differences between cultivar type and response diversity indices and their equitabilities.

Region[a]	Diversity indices		Equitabilities[b]			
	Difference in slopes[c]	*p* value[d]	Difference in slopes[c]	*p* value[d]	Difference in means[c]	*p* value[d]
I	0.07 ± 0.02	<0.001	0.02 ± 0.01	0.024	−0.13 ± 0.02	<0.001
II	0.12 ± 0.01	<0.001	0.04 ± 0.00	<0.001	0.17 ± 0.02	<0.001
III	0.11 ± 0.01	<0.001	0.04 ± 0.01	<0.001	0.03 ± 0.02	0.207
IV	0.05 ± 0.01	<0.001	0.01 ± 0.00	0.029	0.19 ± 0.02	<0.001
V	0.03 ± 0.01	<0.001	0.00 ± 0.00	0.524	0.15 ± 0.02	<0.001
VI	0.08 ± 0.01	<0.001	0.02 ± 0.00	<0.001	0.21 ± 0.02	<0.001
VII	0.08 ± 0.01	<0.001	0.03 ± 0.01	<0.001	0.17 ± 0.02	<0.001
VIII	0.08 ± 0.01	<0.001	0.03 ± 0.00	<0.001	0.20 ± 0.02	<0.001
IX	0.01 ± 0.01	0.204	0.00 ± 0.00	0.641	0.11 ± 0.02	<0.001
X	0.01 ± 0.01	0.339	−0.01 ± 0.01	0.069	0.08 ± 0.02	0.002
XI	0.02 ± 0.01	0.048	−0.01 ± 0.00	<0.001	0.01 ± 0.02	0.725
XII	0.02 ± 0.01	0.065	−0.01 ± 0.00	0.264	0.07 ± 0.02	0.005
XIII	0.01 ± 0.01	0.058	−0.01 ± 0.00	0.129	0.07 ± 0.02	0.006
XIV	−0.02 ± 0.01	0.028	−0.02 ± 0.00	<0.001	−0.04 ± 0.02	0.150
XV	0.00 ± 0.01	0.904	−0.02 ± 0.00	<0.001	−0.00 ± 0.02	0.875
XVI	−0.02 ± 0.01	0.115	−0.01 ± 0.01	0.351	−0.05 ± 0.02	0.038

[a] The roman numbers refer to the regions in Fig. 2.

[b] Each value of Shannon diversity index divided by the theoretical maximum of that value, representing evenness.

[c] The difference between the indices ($\text{index}_{\text{type}} - \text{index}_{\text{response}}$) ± standard error of difference. The slope refers to the average annual change in the value of the index and the mean refers to the average value of the index 1998–2009.

[d] Student's two-tailed *t*-test, $\alpha = 0.05$, $n = 24$.

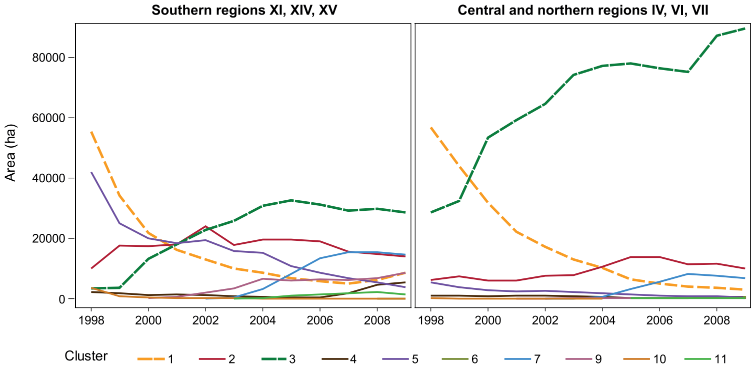

Fig. 3. Development of the cultivation area of the barley cultivar response clusters (1998–2009) in the Southern regions (left) and in the Central and Northern regions (right) of Finland. Cluster 3 represents cultivars, the grain yield of which is clearly reduced by drought and benefits from relatively early sowing. Cluster 1 represents cultivars with a stable but only moderate yield.

management through the empirical assessment of the critical factors of change, and through identification of the diversity most effective for reducing sensitivity to variation and increasing the capacity to adapt to plausible ranges of such critical factors. Therefore, the procedure has relevant implications for public policies and private enterprise strategies. The procedure provides means to communicate at the interfaces of science, policy and practitioners, and to facilitate public-private partnerships. The generic approach proposed here can guide adaptive management and governance not only in the case of climate variability and change such as demonstrated here but also in the response by the economy of farm activities or by sales of retail suppliers to price volatility (Howden et al., 2007), for example. In the latter case, which exemplifies the on-going work of part of the authors, food suppliers could be clustered according to the differential responses of their sales to global price variability. High cluster diversity would indicate stability regarding consumer access to affordable food.

The decrease in response diversity of barley cultivars in the central and northern regions of Finland shown here, indicates increased vulnerability and decreased resilience (Folke et al., 2004; Elmqvist et al., 2003; Laliberte et al., 2010), which was not revealed merely by the cultivar diversity ('type diversity'). The developments that are deleterious for resilience, as revealed by the empirical assessment of the response diversity, can then be addressed through adaptive management informed by the assessment. Similar models, as here for barley, can be constructed for other crops and conditions based on documented pluri-annual yields and associated weather. Such models would facilitate targeted crop diversification beyond maintaining biodiversity, to serve as a tool for farmers to enhance resilience and adaptive capacity (Jarvis et al., 2008). Similar models can be used to quantify response diversity generally. The demonstrated approach is applicable to any system in which empirical information for the response of components can be related to documented changes and variations with relevance. The added value of the use of this proposed approach can be investigated in each case by comparing the diversity index for the responses with the index for the mere types.

The limiting factor for the application of the proposed approach could in many cases be set by the availability of data. Concerning natural and managed ecosystems, the data requirements are met by creating long-term observatories and well-planned monitoring infrastructures that provide reliable multi-year datasets. Examples of such can be found in Europe through the ANAEE networking initiative (www.anaee.com) or, more specifically for grasslands and forests, through the Ecofinders project (www.ecofinders.eu). Chronosequences may also be sources of data for these response diversity assessments. However, many more types of data sets can be utilised in applying the proposed procedure in various contexts. Examples of such data sets include the European Farm Accountancy Data Network (http://ec.europa.eu/agriculture/rica/definitions_en.cfm), numerous other data sets that have been compiled by authorities, and data sets by retailers and other private actors. In addition to those methods applied in this study, there are other methods that can also be applied, depending on the context of the application. Principal component analysis would be an alternative, in addition to direct clustering, to model the response structure and in validation to ensure applicability in the context where the model could serve decision-making.

4.2. Value-added by the assessment of response diversity of barley cultivars in Finland

The uncertainty in climate change is greatest at the local level where individual farmers operate (Howden et al., 2007; Rötter et al., 2013). The farmers manage crop cultivar diversity annually. The particular cluster-based response diversity index for barley cultivars to weather is directly applicable to farms in Finland. The statistically significant and relatively high positive correlations between the cultivar responses to the agro-climatic parameters in the trial data versus in the data from farms show the validity of the response diversity index for practical agriculture, despite potentially more variation in conditions and less precise weather estimates on farms than in the trials. The fact that the correlation coefficient for hectolitre weights for the trial data versus farm data did not essentially differ from the corresponding correlation coefficient for grain yields indicates that the farmer assessments of the grain yields were reliable enough. The similar principal component structure found for both the trial and the farm data provides an additional evidence for the conclusion that the response diversity model that was constructed is applicable under farm conditions.

The decrease in the response diversity of barley cultivars in central and northern Finland during the last decade, despite the continuous increase in cultivar (type) diversity, was due to the cultivation area concentrating on fewer weather response clusters of barley cultivars especially at the latter half of the decade. One weather response cluster, with cultivars sensitive to drought and benefitting from early sowing, increasingly dominated. There occurred no shift, neither a difference between southern vs. central and northern Finnish regions, in precipitation or temperature during the growing seasons of 1998–2009 (Himanen et al., 2013a,b), nor in the other agro-climatic parameters that could explain the observed concentration as a farmers' coping to a shift in weather. Rather, it seems that farmers' cultivation concentrated, because all the barley cultivars performing well in these regions introduced to the market during the period represented the same weather response cluster. Nearly half of all the barley cultivars introduced to the market in Finland during that period (1998–2009), and 65% of their accumulated cultivation area, 89% since 2005, represented that single weather response cluster from all the 12 weather response clusters of barley cultivars in trials during the last decades. On the contrary, until 1998, barley cultivation area was mainly divided among two to three weather response clusters with a dominant one different from that during 1998–2009.

The increased competition in the cultivar market may have led breeders to release new cultivars of increasing similarity. In central and northern Finland barley cultivation (even if barley represents a comparative advantage in cereal cultivation in northern Finland) occurs at the northernmost margin of global agriculture, with a relatively narrow genetic basis for useful breeding material. Therefore profit-oriented breeding efforts in a competitive market where new cultivars always catch attention, easily concentrate on a small cultivar group offering high yield. Farmer experimentation may then lead to an increasing similarity among sown cultivars, unless special attention is given and tools and incentives to increase response diversity are provided for preparing to a climate with high uncertainty (Rötter et al., 2013) and increased variability (Field et al., 2012).

The assessment that was proposed here can be used to select a tailored set of cultivars that represents a wider range of responses to critical weather variation, to reduce the inter-annual variation and probability of yield losses on farm, in a particular region and over the entire country. Therefore, the model was validated under farmer field conditions, where management (e.g. fertilisation, crop protection) and soil types vary to a greater extent and therefore potentially elicit differences in response to weather in comparison with the case at official trial sites. The specific model could be used in the communication among farmers, advisors and breeders, and other actors such as industry and trade while making cultivation contracts. The use of such models could be promoted by administrators and policy-makers and, for instance, through the Common Agricultural Policy of the European Union. The empirical assessment of response diversity could also serve the maintenance of a sufficiently broad range of responses to critical weather in breeding, to secure the adaptive capacity for the long term requirements. The assessment can be used in communicating among private breeding companies, authorities and policy-makers in order to share the costs of such a public good. Practical tools applying the results are under development to assist the actors in communication and decision-making.

Barley is the most widely grown cereal and fodder crop in Finland, and it is difficult to find suitable substitutes for this crop. Thus, the decreasing resilience of barley cultivation could lead to a decline in animal production as well. Such a development would endanger food processing (dairy, meat and brewing industries), which relies on domestic primary production. Reduced resilience and the consequent decline in barley cultivation when facing anomalies in critical weather could put many activities that support Finnish agriculture at risk, such as breeding, education, extension, seed and fodder trade and quality control services. If critical thresholds, in terms of the extent of the currently relatively small market for such products and services, were reached, a domino effect in the domestic food supply chain could result that would endanger Finland's food security. Such a threshold could be crossed due to one or several years of lost harvest and the consequent need to rely solely on expensive imported fodder. Correspondingly, more diversity in responses to critical, unpredictable change and variation could ensure that a higher degree of variation in weather is required before a critical threshold in the barley production system and food security would be crossed. This example illustrates the potential of revealing response diversity in distancing critical thresholds. Resilience can, such as shown here, only be enhanced through diversification if the very aspect of response diversity is directly assessed and if the practical management of resilience is understood and facilitated through such assessments.

5. Conclusions

Practical tools, such as the assessments suggested by this study, could promote the robust rooting of the resilience discourse on empirical grounds, an on-going concern in the resilience community (Folke et al., 2004) and in adaptation science (Howden et al., 2007). For the required transformations and adaptive responses, a desired adaptive process rather than a precisely planned outcome is sought (e.g. Milly et al., 2008) that sets specific demands on the assessment approaches and long-term monitoring systems, which are exemplified here by the particular case of Finnish barley. Such practical tools and available data could prevent the concept of resilience, which has potential to open new perspectives, from simply becoming another buzzword among many. The proposed generic approach for the empirical identification of response diversity to manage resilience and adaptive capacity to global environmental change creates added value by guiding tailored diversification. If the key diversity that fosters resilience is identified, more resilience can be achieved with less diversity. An increase in the efficiency of diversification would help to successfully combine the complementary dimensions of sustainability, i.e. resilience and efficiency.

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Publication II

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Decline in climate resilience of European wheat

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Decline in climate resilience of European wheat

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Food security relies on the resilience of staple food crops to climatic variability and extremes, but the climate resilience of European wheat is unknown. A diversity of responses to disturbance is considered a key determinant of resilience. The capacity of a sole crop genotype to perform well under climatic variability is limited; therefore, a set of cultivars with diverse responses to weather conditions critical to crop yield is required. Here, we show a decline in the response diversity of wheat in farmers' fields in most European countries after 2002–2009 based on 101,000 cultivar yield observations. Similar responses to weather were identified in cultivar trials among central European countries and southern European countries. A response diversity hotspot appeared in the trials in Slovakia, while response diversity "deserts" were identified in Czechia and Germany and for durum wheat in southern Europe. Positive responses to abundant precipitation were lacking. This assessment suggests that current breeding programs and cultivar selection practices do not sufficiently prepare for climatic uncertainty and variability. Consequently, the demand for climate resilience of staple food crops such as wheat must be better articulated. Assessments and communication of response diversity enable collective learning across supply chains. Increased awareness could foster governance of resilience through research and breeding programs, incentives, and regulation.

wheat | cultivar | Europe | climate resilience | response diversity

Food security relies on the resilience of staple food crops to climatic variability. Climate change increases the uncertainty regarding local weather (1) and intensifies weather variability and extremes (2, 3). Reductions in wheat yield in global and temperate areas (4, 5) and an increase in yield variability are projected even with moderate warming (6). While food availability is endangered in the long term (4, 5), yield variability induces price volatility and speculation (7). Price volatility in the globally integrated food market threatens the stability of access to food by the poor, who spend a great proportion of their income on staple foods (7) also in Europe. Food insecurity enhances political instability and migration (8), which aggravate national and regional food security concerns. Consequently, food security (9) is an important goal of both national emergency supply strategies and the Common Agricultural Policy of the European Union (10). While the impact of trade on food availability is negligible in Europe, which produces one-fifth of world's wheat (11), the region is more prone to instability than net exporters of food or countries in chronic states of food stress (12). Wheat is the leading source of plant protein in the human diet (11) and the most important staple food crop in Europe, but climate resilience of European wheat is unknown.

Resilience refers to the capacity to maintain core functions of, for example, food supply chains, under disturbance, and ability to adapt to change (13), while climate resilience specifically buffers against climate-related uncertainty and variability (14). A diversity of responses to disturbance is considered a key determinant of resilience (15, 16). "Response diversity" implies diversity within a function in response to change or variability critical to the function (16), for example diversity within the wheat yield supply in response to climatic events that are critical to the yield. Not any diversity of cultivars ("type diversity") is effective, but the diversity in the responses to critical weather events can effectively enhance climate resilience (17). Resilience is an important complement to the currently dominant goal of crop improvement (i.e., yield potential), which remains important. Response diversity provides the actors and governance of crop supply chains with a practical tool to assess and enhance the climate resilience of crops and thus food security.

Climatic variability and extremes are responsible for one-third of the global variability in crop yields (6). Climatic variability

Significance

Food security under climate change depends on the yield performance of staple food crops. We found a decline in the climate resilience of European wheat in most countries during the last 5 to 15 y, depending on the country. The yield responses of all the cultivars to different weather events were relatively similar within northern and central Europe, within southern European countries, and specifically regarding durum wheat. We also found serious Europe-wide gaps in wheat resilience, especially regarding yield performance under abundant rain. Climate resilience is currently not receiving the attention it deserves by breeders, seed and wheat traders, and farmers. Consequently, the results provide insights into the required learning tools, economic incentives, and role of public actors.

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explains 31–51% of the variability in wheat yield in western Europe and 23–66% of the wheat yield variability in eastern Europe, while in southern Europe climatic variability is responsible for 15–45% of the yield variability in Italy and Greece and more than 75% in southern Spain (6). Consequently, the dominant approach of adapting crops to climate change by tailoring the genotypes to the most likely long-term change remains insufficient. The climate resilience (14) of crops has become critical to stabilizing food supply (1, 17, 18) and avoiding price spikes (19, 20), especially for rain-fed European wheat (21). The climate resilience of crop yield performance has a strong genetic basis, but the phenotypic outcome exhibits an interplay with the environment. The capacity of a single crop genotype to maintain a good yield performance under climatic variability and extremes is limited; therefore, a set of cultivars with diverse responses to critical weather conditions is required to promote the climate resilience of crops.

Seed traders and farmers manage the climate resilience of crops annually by selecting sets of cultivars for sale and cultivation, while breeders contribute to the resilience in the long term by providing the diversity in responses among cultivars. We previously demonstrated a decline in the diversity of barley responses to weather despite an increase in the number of cultivars over the last decade in the main cultivation area in Finland (17). Here, we quantified the response diversity of wheat in nine European countries. We identified the variation in response diversity on farmers' fields (Fig. 1) and demonstrated the relation to climate resilience (Fig. 2). We further revealed the variation of weather responses among countries (Fig. 3) and among weather patterns in trials (*SI Appendix*, Fig. S1). We used yield and weather data from cultivar trials from 1991 to 2014 at 636 locations for 991 cultivars of winter wheat, spring wheat, and durum wheat in nine countries, as well as their cultivation areas in eight countries. First, we determined the responses of wheat yield to weather by identifying the agroclimatic variables critical to yield (step 1) (17), estimating the cultivar yield responses to the variables (step 2) (17), and grouping the weather variables based on the responses using principal component analysis (PCA, for R^2 values see *SI Appendix*, Tables S1 and S2) (step 3) (18). Second, we estimated the response diversity by clustering the cultivars based on the component scores (step 4) (18) and assessed the annual diversity indices for the clusters (response diversity) and individual cultivars (type diversity) in farmers' fields and trials by country (step 5) (17).

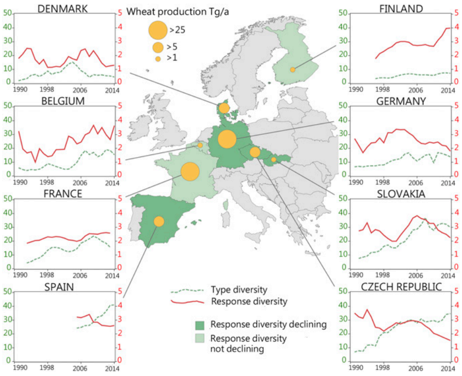

Fig. 1. Decline in climate resilience of wheat on farmers' fields after 2002–2009 in most European countries. The long-term trends of the diversity of the responses to critical weather patterns (response diversity), illustrating the climate resilience and the diversity of cultivars (type diversity). True diversities are shown representing the exponential of the Shannon index [exp(H)] (36, 37). All of the cultivar yield data were utilized (n = 100,985).

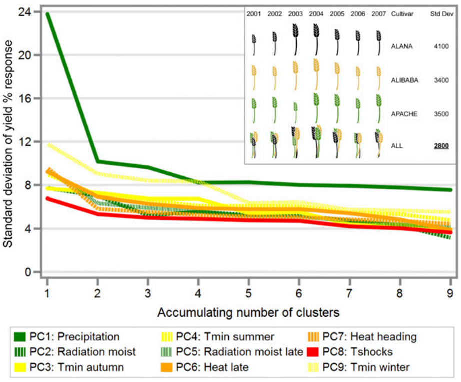

Fig. 2. Increase in the climate resilience of European wheat with increasing response diversity. The main figure shows the decrease in the variation in the percentage yield response to the weather patterns (agroclimatic PCs) critical to yield due to the increase in the number of weather response clusters considered. All of the cultivar yield data were utilized (n = 100,985). The box shows how combining cultivars from different clusters increases the yield stability under weather variability. The three exemplary cultivars (dark, yellow and green heads) represent clusters 1, 3 and 5, respectively, from Caslav, Czechia and were selected based on the largest number of observations and similar average yields (n = 78). If the cultivation area was evenly divided among the three cultivars from 2001 to 2007 in comparison with the cultivation of only the cultivar with the highest total yield (Apache), a 2% loss in total yield appeared, but the SD among the years declined by 16–32%. The relative size of the heads refers to the relative annual yields of the three cultivars.

Materials and Methods

Data. Long-term data series of cultivar trials between latitudes 37.21° and 61.34° and longitudes −6.02° and 26.24° in nine countries across Europe (Finland, Denmark, Germany, Belgium, Czechia, France, Slovakia, Italy, and Spain) were used. In some countries (Fig. 1), the period was limited by data availability. The trials had a randomized complete block design or an incomplete block design with two to four replicates, and their management was similar to farmer practices. The cultivars in the experiments differed over time, but standard reference cultivars were used over long periods and across several countries. Cultivars with at least 20 yield observations were included in the assessment. The total number of clustered cultivars (minimum number of observations was 20) was 36 for Finland, 90 for Italy, 113 for Belgium, 139 for France, 140 for Germany, 169 for Czechia, 186 for Spain, 188 for Slovakia, and 265 for Denmark. Annual grain yield (kilograms per hectare) was used as the response variable. The entire cultivar yield data set comprised 100,985 observations.

Step 1: Identifying Agroclimatic Variables Critical to Wheat Yield. The agroclimatic variables that were potentially critical to yield (*SI Appendix*, Table S1) were selected based on responses reported in the literature (5, 22, 23). Data on these agroclimatic variables during crop phenological stages (24) were obtained from the stations closest to the cultivar trial sites. Missing data on sowing, heading, or maturity dates were estimated based on the corresponding dates for all of the cultivars from the same site and year. If a sowing date was missing, then it was assumed that the sowing dates of all cultivars did not differ (unless stated otherwise in the metadata). If no sowing date was available for a given site and year, then all data were discarded from further analysis. If the heading and maturity dates were missing, then the missing values were estimated using correlation analysis

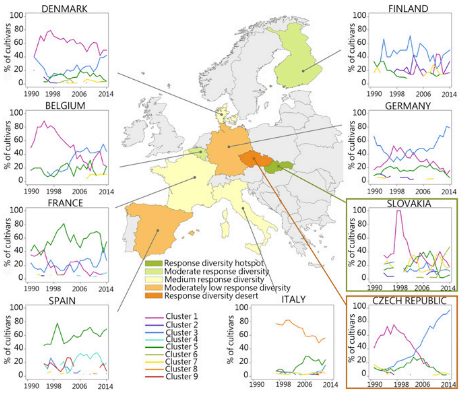

Fig. 3. Climate resilience hotspots and deserts of European wheat. The country charts show the percentages of cultivars in each weather response cluster with different responses to weather patterns (agroclimatic PCs) critical to yield in cultivar trials. The colored (green to orange) areas on the map illustrate the response diversity classes based on the proportion of the dominant cluster (>90 to <50%), the number of other simultaneously important clusters (0–4), and the trends. All of the cultivar yield data were utilized ($n = 100{,}985$).

with overlapping data for the cultivars from the same site across the other seasons. If no overlapping data or limited (five or fewer) data pairs were available, then the heading and/or maturity dates were estimated using the thermal time above 5 °C obtained for the given cultivar from nearby sites and preceding/subsequent seasons. The analysis described below in more detail was based on a previously suggested procedure (25, 26).

Step 2: Estimating Cultivar Yield Responses to the Agroclimatic Variables. The observations for each agroclimatic variable were classified into three categories because the relations between grain yield and the agroclimatic variables were nonlinear in most cases. Some variables were also strongly correlated, leading to multicollinearity in the regression analysis. The random effects of country, site, and year were known to contain most of the variation and thus had to be taken into account. The 40th and 60th percentiles of the distributions of the agroclimatic variables were used to form categories of low, moderate, and high values for each variable. For example, the grain yield observations were divided into groups based on the number of rainy days experienced from sowing to maturity: fewer than 56, between 56 and 68, and above 68. The interaction of these categories with the grain yield of each of the 991 cultivars was analyzed using the following mixed model:

$$\begin{aligned} \mathrm{y}_{ijklmn} = {} & \mu + \mathrm{cultivar}_i + \mathrm{category}_j + \mathrm{cultivar} \times \mathrm{category}_{ij} + \mathrm{treated}_k + \mathrm{country}_l \\ & + \mathrm{site}_m + \mathrm{year}_n + \mathrm{treated} \times \mathrm{country} \times \mathrm{site} \times \mathrm{year}(\mathrm{category})_{jklmn} + \varepsilon_{ijklmn}, \end{aligned}$$

where y_{ijklm} is the observed yield (annual yield), μ is the intercept, cultivar$_i$ is the average yield level of the ith cultivar, category$_j$ is the average yield level at the jth level of the categorized environment, cultivar × category$_{ij}$ is the cultivar-by-environment interaction, and treated$_k$ refers to the use of pesticides. All of the above effects are fixed in the model. Country$_l$, site$_m$, year$_n$, and the interaction of treated × country × site × year (category)$_{jklmn}$ are random effects of the lth country, mth experimental site, and nth year within the jth category.

For each cultivar and agroclimatic variable, the relative difference in yield between the extreme categories (high–low) was calculated. The relative difference was used to balance the differences between the yield levels of cultivars, although using the simple difference led to similar results. These data consisted of the grain yield responses of 991 cultivars to 43 agroclimatic variables. For example, the relative difference of the estimated yields of each cultivar that experienced fewer than 56 rainy days from sowing to maturity and the estimated yields of each cultivar that experienced more than 68 rainy days from sowing to maturity was calculated. Consequently, a positive grain yield response implied a positive effect of numerous rainy days.

Step 3: Grouping the Responses to the Agroclimatic Variables Using PCA. PCA was used to identify a simplified structure that best explained the variance in the data on the yield responses of the cultivars to agroclimatic variables. We also established the agroclimatic variables that behaved in similar ways. The first PC (i.e., agroclimatic factor) always accounts for most of the variability, and the last PC accounts for the least variability; therefore, only a few PCs are needed to contain most of the information. PCs with eigenvalues above one were retained, and the last PC was deleted based on interpretation and cross validation (27, 28). Nine PCs explained 70% of the total variation (varied from 15 to 5%). An orthogonal varimax rotation was used to achieve a more meaningful and interpretable solution. An oblique promax rotation was also tested but was found unnecessary based on relatively low correlations between PCs. The sampling adequacy, tested with the Kaiser–Melkin–Olkin (KMO) measure, was middling, with a KMO value of 0.77 (29).

We excluded 149 cultivars that were missing more than one-third of the yield response observations to the 43 agroclimatic variables to reduce the number of imputations and thus to improve reliability. A small number of cultivars ($n = 17$) were excluded as outliers because their score for one of the significant PCs was more than six SDs beyond the sample mean score (30). Multiple imputations (MI) with 100 replicates for missing data (10%) were used to obtain the PC scores, which were used to further analyze each cultivar. A multivariate normal approach via the Markov chain Monte Carlo method was used for the MI. The effects of the imputations on the PCA structure were studied by basing the PCA on a correlation matrix without imputations and were found to be negligible. Therefore, the imputations were retained in the data, and the PC scores calculated using the regression method were used in further analyses (31). PC scores were left unstandardized to give less weight to a possible noise element and decrease the sensitivity of the clustering results to the number of PCs retained (32). The effects of standardization and the use of truncated Mahalanobis distances were also examined but were found less interpretative.

Step 4: Clustering Cultivars Based on the Agroclimatic PC Scores. We clustered the cultivars based on their yield responses to agroclimatic variables (step 2). Clustering was based on the PC scores, calculated as a byproduct of PCA (step 3). The cultivars were clustered with Ward's (33) method, which starts with n clusters of size one and continues until all of the observations are included in one cluster. The squared Euclidean distances between data points were used. The number of clusters (nine) was selected based on the dendrogram, the pseudo t^2 criterion,′ and the variation in R^2 values (34). PC loadings (obtained in step 3) were used to weight the average yield responses to the agroclimatic variables (18). The PC loadings were squared and divided by the eigenvalue of each PC. Therefore, $\sum_{i=1}^{n} w_i = 1$, where n is the number of agroclimatic variables and component loadings. The weighted means and SEs were calculated according to the following equation:

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

where w_i is the weight and x_i is the average yield response to the ith agroclimatic variable.

The connection between the interannual stability of the yield and response diversity was investigated by calculating the relationship between the variation in the yield response to each of the nine PCs and the accumulated number of clusters. The pooled SDs, which are weighted averages of the SDs for several clusters, were calculated for the number of accumulated clusters from one to nine based on the dendrogram. For example, when eight clusters were compared with nine, only one of the former clusters was divided, and all others remained unchanged. The pooled SD was calculated as follows:

$$\mathrm{SD}_{pooled} = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2 + \ldots + (n_k - 1)s_k^2}{n_1 + n_2 + \ldots + n_k - k}}, k = 1, \ldots, 9,$$

where s is the SD of the kth cluster and n is the number of cultivars of the kth cluster.

Step 5: Assessing Response Diversity. The annual Shannon diversity index (H), which reflects the richness and evenness (35) of the distribution (36), was calculated for the cultivated area of cultivars (cultivar diversity) and for the clusters (response diversity) in every country, because the weather extremes relative to the phenological stages of wheat appear nationally rather than throughout Europe. The statistics on the national cultivation areas for cultivars in Finland, Denmark, Belgium, France, Germany, Czechia, and Spain apart from Andalusia during the period from 1991 to 2014 were utilized. In addition, the annual response diversities were calculated based on the relative number of cultivars in each cluster in the trials by country. A Shannon index equal to zero indicates that only one cultivar (or cluster) was cultivated in the country; the Shannon index increases as the number of cultivars or clusters (richness) and/or the evenness of the distribution of hectares or trials among them increases. The Shannon index gives an equal weight to each observation and is comparable among cases with different compositions (35, 36). The Shannon index was calculated according to the following equation:

$$H_i = -\sum_{k=1}^{K} \frac{w_{ik}}{W_i} \ln \frac{w_{ik}}{W_i}, \; i = 1, \ldots, n,$$

where n refers to the number of countries, $k = 1, \ldots, K$ refers to the number of clusters; w_{ik} is the area cultivated by cluster k in country i; W_i represents the total area cultivated in country i; and w_{ik}/W_i is the proportion of area cultivated by cluster k. Indices were interpreted based on the exponent of the Shannon index, which is the true diversity (i.e., the effective number of cultivars or response clusters). On this scale, a community with a true diversity four times larger than that of another community is four times as diverse as the other community (37).

All statistical analyses applied the procedures MIXED, FACTOR, MI, SCORE, DISTANCE, and CLUSTER in SAS (version 9.4; SAS Institute Inc.).

Results and Discussion

Temporal Development of Response Diversity in Farmers' Fields. We found that the diversity of yield responses to weather patterns that are critical to yield (i.e., the proxy for the climate resilience of crops) is declining in farmers' wheat fields in most European countries. A rapid remedy is not expected because the trend of response diversity in the cultivar trials was not much better. In farmers' fields, the overall diversity of responses to weather began to decline in the first decade of the millennium (country-level P values <0.001 if not specified), with the sharpest decline occurring in Czechia since 2002 (Fig. 1). The decline in Germany began in 2003, in Spain in 2005 or earlier (data not available), in Slovakia in 2006, and in Denmark in 2009 ($P = 0.023$), leading to the lowest response diversity among the countries. The response diversity also showed a continuous declining trend from 1991 to 2014 in Czechia. This development may have contributed to the stagnation and increased variability in wheat yields in most of Europe during the same period, which has been mainly attributed to climate change (38–40). The only country with a recent increase in response diversity was Finland, which also exhibited the greatest response diversity (Fig. 1) and no observed increase in yield variability (40) despite the lowest number of cultivars (*Materials and Methods*) among the countries. Through the entire period from 1991 to 2014, the response diversity slightly increased in Finland, Belgium, and France ($P < 0.001$), but since 2006 Belgium was characterized by sharp variations and no increase ($P = 0.35$), and there was no clear evidence of an increase after 2008 in France ($P = 0.13$).

The diversity of crops in response to weather represents climate resilience, as confirmed by our data on the relation between the accumulated number of weather response clusters of cultivars and the interannual yield variability, as shown in Fig. 2. The decline in yield variance due to response diversity depended on cultivar, location, and year. Even if the response diversity of wheat generally declined, the diversity of wheat cultivars grown (i.e., type diversity) tended to slightly increase in the farmers' fields in most countries (Fig. 1). For the R^2 values associated with the weather patterns (PCs) see *SI Appendix*, Fig. S1, and for the critical agroclimatic variables see *SI Appendix*, Table S2.

Temporal Development of Response Diversity in Cultivar Trials. We identified a general declining trend in the response diversity of wheat cultivars not only in the farmers' fields but also in the cultivar trials. The decline was smaller and less consistent in the trials than that in farmland, indicating an unexploited potential to draw upon the cultivars tested in the countries. The yield responses of the nine weather response clusters of cultivars identified (*SI Appendix*, Table S1) to the nine critical weather patterns determined as the agroclimatic principal components (PCs) (*SI Appendix*, Table S2) varied from +12 to −56% (*SI Appendix*, Fig. S1). The total number of weather response clusters of wheat cultivars in European trials increased until 1999, remained constant until 2004, and thereafter gradually declined. The total number of cultivars increased until 2001 and began to decline in 2009. As exceptions to this trend, the low number of cultivars in Finland has remained constant, and the strong increase with mainly United Kingdom-originating cultivars in Denmark abruptly and sharply declined from 80 cultivars in 2000 to ∼25 mainly Danish cultivars in 2014. The sharp decline in Denmark was promoted by wheat yield losses due to an exceptionally warm winter of 2007 with late incidents of frost (41). This event led to replacement of the foreign cultivars with local ones, likely contributing to the decline in response diversity.

Temporal Development of Weather Response Clusters. In the available sets of cultivars in northern and central Europe, a shift toward yield stability and benefit from late high solar radiation and less penalty from late heat and precipitation (cluster 3 replacing clusters 1 and 5) occurred as a response from breeders to the increased average temperatures during the late growing seasons of the 2000s (40). In contrast, in southern countries after 2000, a cluster that suffers from high minimum temperatures in summer, early drought, and heat at heading (cluster 5) more than the previously dominant clusters took over, aggravating the risk to yield loss (42). This development cannot be explained as a response of cultivar selection to climate change but may rather represent unintentional adverse side effects to selection for other traits. The response to rain appears to be a sneaking risk for the entire continent: No single wheat cultivar cluster responded positively to abundant precipitation (*SI Appendix*, Fig. S1). Wheat yield is generally sensitive to even a few days of exposure to water logging (43) and to wet weather that favors diseases and thus results in low yield (41). The yields of individual cultivars under scarce precipitation were even doubled compared with those under abundant precipitation (PC1 in *SI Appendix*, Fig. S1). These empirical findings are in line with simulations that suggested that heat stress rather than drought sensitivity is the limiting factor to the adaptation of wheat to climate change in Europe (42).

Resilience Deserts and Hotspots. We found a low diversity of weather response clusters—a response diversity "desert"—in trials of Czechia; smaller deserts were detected in Germany and Spain, and a durum wheat desert was found in Italy (Fig. 3 and *SI Appendix*, Fig. S1), which is the main durum producer in the world and is where most (1.6 million ha) of European durum wheat is cultivated. A single cluster (cluster 8) with all 44 durum wheat cultivars with >20 observations (apart from three durum cultivars in cluster 7 and one cultivar in cluster 3) dominated Italy. Durum suffers from heat at heading and high winter temperatures because cold temperatures are required for vernalization in the Italian durum germplasm (44). There is also an alarming similarity among northern and central European countries (apart from Slovakia), as well as among the southern European countries, in the development of the dominant weather response clusters of wheat cultivars (Fig. 3).

A response diversity hotspot was found in Slovakian cultivar trials, including one promising unique cluster (cluster 6) and a cluster currently nearly unique (cluster 7) to Slovakia.

In particular, the members of the currently most common cluster 6 benefited from high radiation, avoidance of drought, and warm autumn and winter, and a single cultivar in cluster 7 benefitted from above-average precipitation. All these characteristics represent positive responses to weather patterns, which European clusters generally suffered from or did not respond to (*SI Appendix*, Fig. S1). This and other observed complementarities could be exploited to enhance resilience through cultivation and breeding. However, the properties of the cultivars that were adapted to different conditions, such as day length, maritime versus continental conditions, and length of the growing season, limit their utilization across Europe.

Possible Causes of Decline and Differences in Response Diversity. Repeated selection for few desirable characteristics from a continuously homogenizing and declining cultivar or genetic pool could be the reason for the observed decline in response diversity. While no genetic erosion in terms of loss of alleles was observed for wheat before the 1990s (45, 46), such a decline in alleles was found for durum after that period (47) and such a decline cannot be excluded for wheat in general. An activity called "face-lifting" of cultivars by breeders was identified as the cause of the decline in response diversity of Finnish barley in the main cultivation areas (17, 48). The homogenization of the genetic pool could be a consequence of a lack of incentives for breeders to introduce divergent material with uncertain benefits. The observed decline in response diversity coincides with an increasing dominance of crop improvement by private breeders, which accelerated in Europe around 2000. Increased competition and demand for cost efficiency increases the pressure for a shortened breeding cycle, irrespective of technology developments, and may contribute to the greater similarity among new cultivars launched in the market (48, 49). Periods of cultivar import from surrounding countries varied with a focus on local breeding in Belgium and led to a high diversity in weather responses. Conversely, a turn to mainly local cultivar selection in Denmark narrowed the response diversity and thus reduced the climate resilience of this export-oriented agricultural country.

The obvious explanation for the alarming decline and gaps in response diversity in European wheat is the absence of the explicit perspective of resilience to intensifying climatic variability and extremes in the wheat value chain. The prioritization of the yield potential of individual cultivars under current or projected average long-term climatic conditions, with a focus on harvest index and disease resistance (39), may have been influenced by early climate projections that did not consider uncertainty and variability. Since crop responses are nonlinear and exhibit thresholds in yield and quality (50) and the climatic variability is increasing (2), the benefit of response diversity will be even greater than that suggested by past yield data. An enhancement of response diversity through increased awareness of the significance of diversity in weather responses within the available set of cultivars is therefore of primary importance for wheat production and food security.

Enhancing Climate Resilience of European Wheat Through Response Diversity. There appears to be greater cultivar diversity in the trials at the European (*SI Appendix*, Fig. S1) than at the country level, but the substantial differences in conditions aggravate the direct utilization of cultivars across Europe. Funding for targeted research and an economic incentive to companies to utilize more cultivars from the European list of approved cultivars might diversify the cultivars used in national trials. Specific parts of wheat genome were also shown responsible, for example, for temperature response (51), which can be used in breeding a wheat cultivar portfolio with sufficient response diversity for Europe. Yield losses due to weather are currently not recorded in cultivar trials, which creates a tendency to not learn from the diversity of responses to weather variability. An option for immediate improvement thus is to document yield losses due to extreme weather events, and perhaps include them in a separate analysis.

The costs to breed a selection of genuinely different cultivars are likely higher than the costs to breed a homogenous selection. A broader selection also poses additional costs to traders even if indirect benefits through lower risks and reduced contract area requirements may also follow. For farmers, several cultivars do not necessarily cause additional costs but may even temporally equalize work demand. The benefits from response diversity may be greatest to the weakest actors in the wheat supply chain, such as farmers (yield stability) and disadvantaged consumers (price stability), while the public actor in charge of food security might benefit most. The development in response diversity of wheat appeared, indeed, less alarming in countries with traditions in private–public breeding partnerships such as Finland and Belgium, while in Germany, with low response diversity, private breeders have dominated for more than a century.

Farmers' demand could act as the incentive to breeders to diversify weather responses among wheat cultivars, but farmers currently focus on yield potential and quality. There is, however, no inherent trade-off between yield potential and diversity in weather responses. Yield stability is a complementary breeding goal in addition to yield potential and the average yield in the long term. While the example given here (Fig. 2) is mainly illustrative, in Finnish regions with high barley cultivar diversity where yield variations among years were low, also the average yield was greater than that in the regions with low cultivar diversities (52). Risk aversion varies among farmers, but the notable share (46%) of yield-independent subsidies in farm income in Europe (10) acts as a disincentive to innovations for yield security. For instance, the subsidies in Czechia are lower than in most European Union countries, and most of the farmland is rented, which creates a notable cost relative to the subsidies. Consequently, the demand by farmers for drought-resistant cultivars is clearly articulated in that country. Therefore, a cultivar portfolio with diversity in responses to weather could be a prerequisite for subsidies or loss compensation to farmers, and for a reduced price of an insurance.

The main challenge for enhancing the diversity in crop responses to weather events and thus the climate resilience lies in the required shift of the perspective to cover this aspect. The actors in wheat supply chains must shift the focus from individual cultivars and yield potential in good conditions to a portfolio of cultivars to include complementary responses to critical weather events. The lack of awareness and experience of the diversity approach keeps the focus on individual cultivars, which have a more limited yield stability potential than a portfolio of cultivars with diverse responses. The shift in perspectives toward resilience could be achieved through simple tools to demonstrate and communicate the diversity in cultivar responses between breeders, farmers, and traders (48), good examples rewarded by recognition (53), and "learning-by-doing" facilitated by the economic incentives or, likely most effectively, regulation. Initiating a dialogue within wheat value chains, for example by national emergency supply agencies, involving also research and policy makers, could help enhance the resilience of wheat supply chains and food systems (54). Diversity in responses provides a practical means to enhance robustness under weather variability and adapt to the uncertainty in climate change through portfolios of not only cultivars but also crops (18) and even marketing channels (17).

Conclusions

This assessment suggests that current breeding programs and cultivar selection practices do not sufficiently prepare for climatic uncertainty and variability. Human feedback to coupled social–ecological systems, such as agriculture and food systems, depends on institutional arrangements. Strong institutions can assist farmers and managers in breeding and seed trading companies to shift crop-yield-related tipping points induced by intensifying climate variability and price volatility and thus protect the stability (55) of the European wheat, as well as other staple food crops around the world.

The national action plans and the Common Agricultural Policy of the European Union are instrumental to removing the current disincentives and introducing new incentives and regulation for diversity in crop responses to climatic uncertainties. However, regulation needs to imply sufficient flexibility to allow adaptive management and continuous collective learning. The European Commission might include effective diversification through assessment and management of response diversity in its toolkit of risk management measures for the use by the member states to support viable farm income and resilience to enhance food security (56).

Research is needed to advance the understanding of the genetic basis to yield and quality response to weather (51). Furthermore, the costs of the portfolio approach and benefits to security need to be quantified for communication of the value added and targeting the economic incentives in the value chain. The institutions should primarily facilitate overcoming the perceived uncertainty in costs and benefits before sufficient experiences are gathered for the transition (57) toward resilient cultivar choices. The approach of response diversity can be applied to counteract the observed decline of the resilience in food systems (12) under social–ecological volatility and uncertainty.

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Publication III

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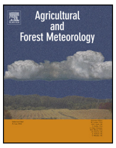

Shifts in soil–climate combination deserve attention

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ABSTRACT

In addition to causing shifts in regional climate, climate change will also affect the combination of climatic conditions and dominant soil type. This may be reflected in crop responses; however, currently, empirical knowledge in this regard is limited. We hypothesised that 1) the weather patterns most influencing forage crop yield variation vary among soil types 2) the yield responses of forage crop species and cultivars to agro-climatic variables depend on soil type, and 3) response diversity of the forage crop species and cultivars to agro-climatic factors depends on soil type. To assess these assumptions, we utilized the Finnish long-term multi-location Official Variety Trial and weather data for 1979–2012 as a case study. The yield responses of timothy (*Phleum pratense* L.), meadow fescue (*Festuca pratensis* Huds.), tall fescue (*Lolium arundinaceum* (Schreb)/*Festuca arundinacea* (Schreb)), Festulolium (*Festuca* sp. × *Lolium* sp.), red clover (*Trifolium pratense* L.), and Italian ryegrass (*Lolium multiflorum* L.) to the critical agro-climatic variables depended in most cases on whether the trials were located on clay, coarse mineral, or organic soils. The average yield response to weather was 10% in clay and organic soils and 8% in coarse mineral soils. The diversity of forage crop responses was also dependent on soil type. The demonstrated dependency of crop responses to climate change on soil type emphasizes that attention should be paid to the plausible shifts in soil–climate combinations when planning adaptation.

1. Introduction

The vulnerability of agriculture to climate variability and change is widely established in the literature (Maracchi et al., 2005; Pachauri et al., 2014). Variation in weather, particularly in temperature, precipitation, and their interaction, is responsible for a third of the variability in global yield (Ray et al., 2015). In addition to an intensification in climate variability (Christidis et al., 2014), rapid shifts in agro-ecological zones in northern Europe are also predicted, including an increase in climate suitability for warm-season crops and the northward extension of cultivation (Tuck et al., 2006; Fronzek and Carter, 2007). In this regard for instance, Audsley et al. (2006) determined Finland to be the only European country in which agriculture could respond to climate change by increasing the area for cultivation at the expense of forests. Accordingly, considerable changes in agricultural land use are likely (Olesen and Bindi, 2002; Fronzek and Carter, 2007; Peltonen-Sainio et al., 2008). Indeed, land-use change perhaps represents the main impact of climate change on soils (Rounsevell et al., 1999). Soil is an increasingly essential component in modelling climate change effects (Tuck et al., 2006; Srivastava et al., 2012; Rötter et al., 2013; Constantin et al., 2015); however, there has been limited empirical research aimed at clarifying the connection between climate, soils, and crop responses.

Numerous studies have been published regarding particular climatic drivers related to soil processes (Rounsevell et al., 1999; Smith et al., 2015), and climate change effects on soil biological, chemical, and physical health indicators were reviewed by Allen et al. (2011). Relatively short-term responses to climate change by soil organic carbon, erosion, and greenhouse gas emissions are also well represented in the literature (e.g. Rounsevell et al., 1999; Jones et al., 2009; Edenhofer et al., 2014; Frank et al., 2015). The direct influence of air temperature and precipitation on soil temperature regimes and hydrology has also been determined in the agricultural context (Gregory et al., 1997; Trnka et al., 2013). Nevertheless, even though progress has been made in understanding the impact of human activities on soil function, a comprehensive understanding of how crop–soil systems respond to climatic and land-use change is lacking (Rounsevell et al., 1999; Nikolaidis, 2011).

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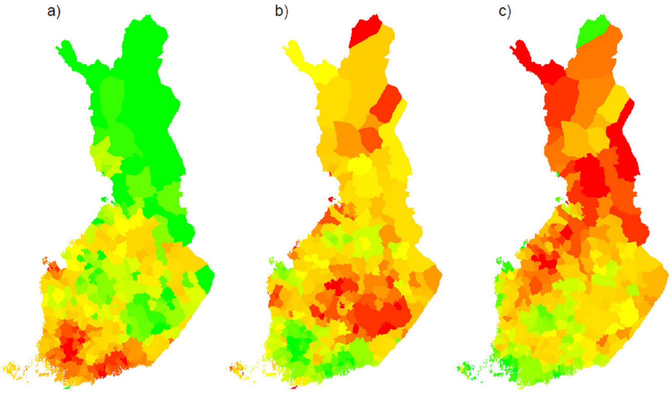

Fig. 1. The proportions of a) clay soils, b) coarse mineral soils, and c) organic soils in Finland. Red colour corresponds to high, yellow to moderate, and green to low proportions of the soil type of the cultivation area of municipalities.

Soil–climate combination plays a key role in projections of agricultural land use, driven by future expected change factors such as policy or climate (Rounsevell et al., 2003; Audsley et al., 2006). Agronomic characteristics of different soil types vary; for instance, clay soils are characterized by a high water-holding capacity, whereas coarse mineral soils have generally low water-holding capacity, and organic soils have low thermal conductivity as well as high water-holding capacity (Mukula and Rantanen, 1987). Furthermore, because soil characteristics vary geographically (for instance in Finland, see Fig. 1) and the magnitude of crop responses to climate is highly sensitive to the soil type (Rötter et al., 2013; Lisson et al., 2016), climate-induced change in land use is essential in adaptation. Although there have been a few systematic empirical studies on crop yield responses to agro-climatic variables (Hakala et al., 2012; Kahiluoto et al., 2014; Mäkinen et al., 2015, 2016), there is, to our knowledge, practically no quantitative empirical information regarding the dependence on soil type of the yield response to agro-climatic variables. For designing and assessing adaptation of cropping, for instance breeding goals and cultivation techniques, the soil–climate combination is, however, critical.

Increased volatility in the social-ecological conditions of agriculture, and particularly the increasing variability in climate and the frequency of extreme weather events (Coumou and Rahmstorf, 2012), have highlighted the need for climate resilience (Lin, 2011). Functional redundancy, more specifically response diversity, has been posited as a key determinant of resilience (Elmqvist et al., 2003). Such response diversity, a largely unexplored aspect of resilience, refers to how species, cultivars, or genotypes responsible for a similar function within a system, respond differently to change and variation. Although the contribution of response diversity to system performance has been demonstrated in plant (Walker et al., 1999) and animal (Winfree and Kremen, 2009) communities, the application of this approach to explore adaptive management in agriculture has been limited (but see Kahiluoto et al., 2014; Mäkinen et al., 2015).

In the present study, we quantified the interrelation of (1) crop yield, (2) weather variability and climate change, and (3) soil types, to unravel the importance of changes in the soil type of cultivation areas in response to climate change. Specifically, we determined the dependence of crop response diversity to agro-climatic factors in different soil types. The most important forage crops and cultivars as well as the different soil types in Finland were used as a case. Finland was selected to represent a region where rapid climate change, while leading to a shift northward in the main cultivation areas of crops, will simultaneously lead to a marked shift in the combination of the agro-climatic factors and soil types, due to the geographically divided dominance of the main soil types. Forage crops play an important role in northern and central European agriculture, being the cornerstone of livestock farming and having a high economic significance in these regions (Eurostat, 2016). In this regard, we used long-term multi-location forage crop yield trials and weather data in this study. The hypothesis tested was that the response of forage crops to climate change depends on soil type. The more specific hypotheses were as follows:

1. The weather patterns, the combination of the agro-climatic variables (agro-climatic factors), most influencing forage crop yield variation vary among soil types
2. The yield responses of forage crop species and cultivars to agro-climatic variables depend on soil type
3. Response diversity, i.e., diversity in the yield responses across the forage crop species and cultivars to agro-climatic factors, depends on soil type.

2. Materials and methods

2.1. Data

2.1.1. Plant material

The effect of agro-climatic variables on the annual dry matter (DM) yield of forage crops was examined for the period 1979–2012 (Mäkinen et al., 2015). For this, we used the MTT (Agrifood Research Finland) Official Variety Trials yield data (Kangas et al., 2009). The following species and their cultivars were investigated: the perennials timothy (*Phleum pratense* L.), meadow fescue (*Festuca pratensis* Huds.), tall fescue [*Lolium arundinaceum* (Schreb)/*Festuca arundinacea* (Schreb)], Festulolium (*Festuca* sp. × *Lolium* sp.), red clover (*Trifolium pratense* L.), and Italian ryegrass (*Lolium multiflorum* L.) (annual in Finland). Cultivars in more than 20 trials (126 cultivars in total) were included (8361 yield records) from 16 different trial sites in Finland. The southernmost station is located at 60°23′N and 22°33′E, and the northernmost station at 66°36′N and 26°01′E).

The MTT Official Variety Trials were carried out using typical on-farm practices under high-latitude conditions. All experiments at all sites were arranged as randomized complete block designs or incomplete block designs. Plots were 7−10 m × 1·25 m in size, depending on location and year. The number of replicates was 3–4. Although the test set of cultivars were changed each year, long-term control cultivars were used. The plots were productive for 3–4 years. Italian ryegrass was established each year. The yield was harvested two to three times during each production year (although this was not done in the year of establishment for the perennial crops). The yield was weighed, the DM content was determined, and the annual DM yield was calculated. Harvest times within the growth period depended on the target digestibility of the DM yield. The last harvest was performed to ensure successful overwintering according to the common practice under high-latitude conditions. Thus, the harvest dates varied among years and trials according to weather conditions and trial locations (e.g. latitude and soil type). The experimental design and the management of the MTT Official Variety Trials are described in detail by Kangas et al. (2009) and Hakala et al. (2012).

2.1.2. *Weather and soil data*

The year-round weather data (1979–2012) from the Finnish Meteorological Institute weather stations closest to the MTT Official Variety Trials were utilized for assessing the yield response to weather variables (Fig. 2). We used agro-climatic variables that we had previously shown to be critical to forage yield performance in northern Europe (Table 1) using linear mixed models (Mäkinen et al., 2015). Such agro-climatic variables were preliminarily selected based on published literature (Bélanger et al., 2002; Volenec and Nelson, 2007; Thorsen and Höglind, 2010) and experimental knowledge.

The weather data was deficient in a few instances regarding harvesting and sowing dates, the latter, however, only being important in the case of Italian ryegrass. Accordingly, approximately 1% of the harvesting dates were estimated using a linear mixed model, relying on data for the harvesting dates of other cultivars at the same site and year. The trials with missing data regarding the agro-climatic variables for the growing season were not included in this study.

The soil conditions were station specific and represented typical soils in Finland (Table 2, A). The effect of soil conditions on crop responses was assessed by comparing the following soil types: clay, coarse mineral, and organic.

The analysis is described in the following sections. Firstly, we estimated the yield responses to the critical weather variables in different soil types. The model considered the effects of the site, year, species/cultivar, and soil type. Secondly, we modelled the structure of the critical weather variables based on yield responses under different soil types. Thirdly, we clustered cultivars based on principal component scores under different soil types.

3. Data analysis

3.1. *Modelling the effect of agro-climatic variables on crop yield*

Each agro-climatic variable was divided into three categories (low, neutral, and high) (Hakala et al., 2012; Mäkinen et al., 2015, 2016) (Table 1). This was done, firstly, because some weather variables were strongly correlated, leading to multicollinearity in regression analysis, and, secondly, because the assumptions of linearity were violated due to the relationships between the yield and weather variables being nonlinear in most cases. Most importantly, the random effects of year, site, and experiment were known to contain most of the total variation, and thus had to be taken into account. Accordingly, linear mixed models, which are generally best suited to test our hypothesis, were used in the data analysis (Mäkinen et al., 2015). Categories with 45% (low), 10% (neutral)

Table 1
The interaction between soil type, cultivar (G), species (S), and agro-climatic variable (E). *P* values refer to the statistical significance for 3-way-interaction between the soil type, cultivar or species, and the agro-climatic variable in yield response. *, **, and *** indicate statistical significance at the 0.05, 0.01, and 0.001 levels, respectively.

Period	Agro-climatic variable	Description	Low	High	G × E × Soil *P-value*	S × E × Soil *P-value*
Fall hardening (FH) FH was defined as starting from the latest day as the sum of daily difference between cold degree-days below 5 °C and degree-days above 5 °C was 0 from 1 Aug. and to last to the day of the first occurrence of minimum air temperatures ≤−10 °C.	FH	Length of FH, days	9–59	70–152	***	***
	FH-COLD	Accumulation of cold temperatures during FH <5 °C, degree-days	−8.2–8.8	9.7–19.8	***	***
	FH-RAIN	Mean daily rainfall during FH, mm	0.04–1.96	2.07–5.09	***	***
Winter (W) W was defined as starting from the day following the end of FH and ending on the day before GP began, which was defined as starting from the fifth day of the first five-day spell when daily mean air temperature exceeded 5 °C.	W-THAW	Mean daily accumulation of temperature >0 °C during W, degree-days	0.38–0.75	0.82–2.60	***	***
	W-STRESS	Accumulation of cold stress days with temperature <−15 °C, days	0–15	18–56	***	*
Growth period (GP) GP was defined as starting from the fifth day of the first five-day spell when daily mean air temperature exceeded 5 °C and to end on the last harvesting day.	GP-DD5	Temperature sum > 5 °C, degree-days	206–1017	1058–1500	0.165	***
	GP-TEMP	Mean daily temperature sum accumulation rate, degree-days	8.6–13.1	13.4–17.4	*	***
	GP-TEMP28	Number of days with maximum temperature of 28 °C, days	0	2–18	0.238	***
First cut	GP-TEMP25_1	Number of days with maximum temperature of 25 °C from GP start to 1 st cut, days	0–2	4–20	**	***
Second cut	GP-TEMP25_2	Number of days with maximum temperature of 25 °C from 1 st cut to 2nd cut, days	0–4	6–38	***	***
	GP-RAIN_2	Accumulation of precipitation from 1 st cut to 2nd cut, mm	0–102.8	117.5–396.4	***	***
	GP-RAIN_14	Accumulation of precipitation 2 weeks after 1 st cut, mm	0.2–26.9	33.0–161.5	***	**
	GP-TEMP_2_7	Accumulation of temperature sum 7 days after 1 st cut, degree-days	10.7–118.6	123.1–183.7	***	***

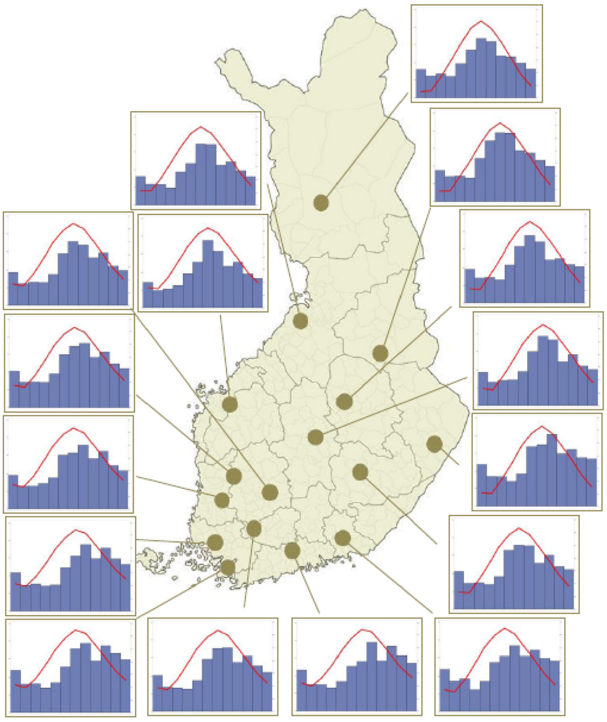

Fig. 2. The monthly averages of precipitation (mm, bars) and mean temperature (°C, line) of the 16 Finnish trial sites for forage crops over the years 1979–2012. Starting from January, Y-axis for precipitation ranges from 0 to 100 mm and for temperature −1 to +20C, respectively.

Table 2
The soil types and the number of observations of cultivars (1980–2012) included per soil. In parenthesis are the number of trials per soil type and species. The average DM yield (kg ha^{-1}) with standard deviations are also shown.

Soil type	DM Yield (kg ha^{-1})	Timothy	Meadow fescue	Tall fescue	Festu-lolium	Italian ryegrass	Red clover	All
Coarse mineral	7890 ± 2800	1755 (254)	983 (228)	211 (130)	68 (52)	376 (88)	797 (143)	4190 (895)
Clay	8440 ± 2930	1259 (189)	646 (148)	115 (90)	44 (32)	26 (9)	587 (102)	2677 (570)
Organic	7720 ± 2850	666 (92)	153 (37)	12 (12)	2 (2)	132 (26)	22 (5)	987 (174)
Total		3680	1782	338	114	534	1406	7854

and 45% (high) of the observations were used. The interaction of cultivars, soil type, and categories of agro-climatic variables, was analysed using the following mixed model:

$$y_{ijklmn} = \mu + \text{variety}_i + \text{category}_j + \text{soiltype}_k + \text{variety} \times \text{category}_{ij} + \text{variety} \times \text{soiltype}_{ik} + \text{category} \times \text{soiltype}_{jk} + \text{variety} \times \text{category} \times \text{soiltype}_{ijk} + \text{experimentalsite} \times \text{year} \times \text{trial(category)}_{lmnj} + \varepsilon_{ijklmn}$$

where y_{ijklmn} is the observed yield, μ is the intercept, variety_i is the average yield level of the ith variety, category_j is the average yield level at the jth level of categorized environment ($j = 1, 2, 3$), soil type_k is the average yield level at the kth soil type, variety × category_{ij} and variety × soil type_{ik} are the variety-by-environment interaction. The model also includes category × soil type_{jk} interaction and the three-way-interaction of variety, category, and soil type. All the above effects are fixed in the model. Experimental site × year × $\text{trial(category)}_{lmnj}$ is the random effect of the lth experimental site, the mth year, and the nth trial within the jth category, and ε_{ijklmn} is a normally distributed residual error. The same model was also used for species instead of cultivars, because we also wanted to investigate differences at the species level.

The differences of yield estimates between extreme categories (high–low) for each cultivar were calculated, i.e. medium categories (10%) were not utilized. These yield responses were used in further analyses: PCA, cluster analysis, and calculation of practical significances in yield responses to soil types. For example, the yield estimates of the agro-climatic variable W-STRESS in the high category (18–56 days) and low category (0–5 days) were 8370 DM yield kg ha^{-1} $year^{-1}$ and 8630 DM yield kg ha^{-1} $year^{-1}$, respectively, for cultivar ‘Alma’ in clay soils. Consequently, the yield response to W-STRESS for ‘Alma’ in clay soils was −260 DM yield kg ha^{-1} $year^{-1}$, indicating some yield loss due to a high number of cold stress days during the winter period. The yield loss of ‘Alma’ in coarse mineral soils was considerable at −1860 kg ha^{-1}.

3.2. Modelling the structure of the critical weather factors to different soil types

Principal component analysis (PCA) was used to identify a simplified structure that best explained the variance in the data for the yield response of the cultivars to 13 selected agro-climatic variables (Table 1). The same 13 agro-climatic variables, used for all soil types together, were used to simplify comparison of the principal component structures of each soil type. Principal components (PCs) with eigenvalues greater than one were retained (Cattell and Jaspers, 1967). The first PC always accounts for most of the variation, and the last PC accounts for the least. Therefore, only a few PCs are needed to contain most of the information. An orthogonal varimax rotation was used to achieve a more meaningful and interpretable solution.

PCA from correlation matrices with pairwise exclusion was employed for each soil type to determine the optimal models, because there were missing data for the yield response for each agro-climatic variable: 3%, 11%, and 19% of observations were lacking for coarse mineral, clay, and organic soils, respectively. Adequacy of the correlation matrices for PCA was tested using the Kaiser–Melkin–Olkin (KMO) measure, which should be greater than 0.5 (Kaiser 1970). The sampling adequacy for the correlation matrices of organic soils and clay soils was singular, whereas that for coarse mineral soils was middling, with a KMO value of 0.78.

3.3. Clustering cultivars based on principal component scores

Next, we clustered the cultivars based on the yield responses to agro-climatic variables. Clustering was based on PC scores, which were a calculated byproduct of PCA. Multiple imputations (MI) for missing data were used to obtain the PC scores. Only 3%–4% of missing data were imputed for each soil type, because cultivars having more than two missing observations of yield responses were removed. The effects of MI on the structure of PCs for each soil were studied and found to be minor. We used the SAS procedure MI, which uses the multivariate normal approach via the Markov chain Monte Carlo (MCMC) method.

The effects of imputations on the structure of PCs for each soil were studied and found to be minor. Therefore, the imputations were used in cluster analysis. The reason for using PC scores was the relatively small sample size. Formann (1984) recommends a sample size of at least 2^m, where m equals the number of clustering variables. Therefore, 4–5 factors were preferable to 13 variables for small sample sizes varying between 72 and 126. The same method was also used for all soils together. The cultivars were clustered according to Ward (1963), which is the most commonly used hierarchical clustering method. The number of clusters was selected based on the dendrogram, the pseudo t2-criterion, and the variation in r-squared values (Yeo and Truxillo, 2005).

All analyses were carried out with SAS Enterprise guide 7.1 (SAS Institute Inc., Cary, NC, USA).

4. Results

4.1. Practical significance of the effect of soil type on the diversity of forage crop species and cultivar yield responses

There was a statistically significant interaction among soil type, cultivar, and species, and agro-climatic variable in almost every case (Table 1). The absolute yield response of forage crops and their cultivars to weather was on average 10% in clay and organic soils, and 8% in coarse mineral soils.

The practical significance of soil type to the yield response of species and cultivars to the agro-climatic variables was considerable. Responses were highly variable among species and cultivars in most cases; for example, to high precipitation during the regrowth stage (Fig. 3) or high temperatures during the regrowth stage (Fig. 4), as well as for the high precipitation during fall hardening (Fig. 5) and the high mean daily accumulation of temperature >0 °C during the winter period (Fig. 6).

4.2. Critical weather patterns

In our previous study, we identified four critical agro-climatic factors (PCs) for the forage yield performance in Finland, which was taken to represent North Europe (Mäkinen et al., 2015). The PC structure across soil types is compared for the first PC of each soil type in Table 3. The agro-climatic variable that explained most of the variation depended on the soil type (Table 3). In clay and organic soils, the following growth period temperature-related agro-climatic variables explained most of the variation: a high number of days with a maximum temperature of 25 °C at the regrowth stage and high temperature accumulation rate. Regarding coarse mineral soils, precipitation during fall hardening and the length of fall hardening, the high number of days with maximum temperature of 25 °C at the primary growth, and winter-related agro-climatic variables explained the most of the variation (Table 3).

4.3. Dependency of the response diversity of species and cultivars on soil type

The species and cultivars formed different clusters depending on soil type, according to the yield responses to the agro-climatic variables. Four cultivar clusters were formed in coarse mineral soils, nine cultivar clusters in clay soils, and eight cultivar clusters in organic soils (Fig. 7). With the exception of a few cultivars, most of the timothy cultivars were grouped in the same cluster in coarse mineral soil, whereas in the clay soils, cultivars were grouped in two clusters, and in organic soils in four clusters. A similar pattern was observed for red clover, with most of the cultivars being grouped in the same cluster in coarse mineral soils, but grouped into two clusters in the clay soils.

5. Discussion

Our findings supported the hypothesis that the weather patterns most influencing forage crop yield variation vary among soil types, as well as the hypothesis that yield responses of forage crop species and cultivars to agro-climatic variables depend on soil type and response diversity of the forage crop species and cultivars to agro-climatic factors depends on soil type.

5.1. Projected climate change in the Finnish case

In Finland, climate change may increase the mean temperature of January in north-eastern by 8–9 °C and in the south-west by 6 °C according to A2 scenario for 2070–2099. Regarding July, the temperature increase can be around 3–4 °C throughout Finland (Ruosteenoja et al., 2011). A marked prolongation (in lands 40–50 days from 1971 to 2000 to 2070–2099 by A2 scenario (Ruosteenoja et al., 2011) and intensification of the growing season and warmer winter conditions are projected (Ruosteenoja et al., 2016). This will likely have favourable impacts on crop production (Peltonen-Sainio et al., 2009; Rötter et al., 2013). According to the

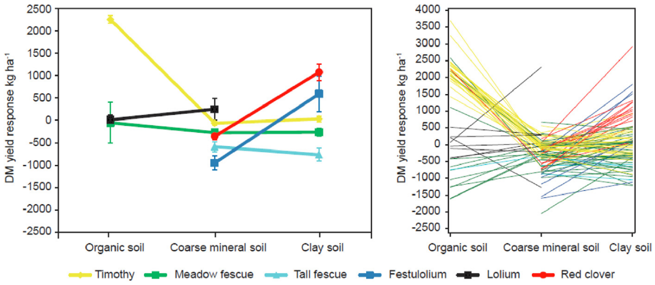

Fig. 3. The yield responses of forage crop species and cultivars separately to accumulation of precipitation from 1st cut to 2nd cut (mm) (calculated as response to high precipitation >118 mm – low precipitation <103 mm) in different soil types.

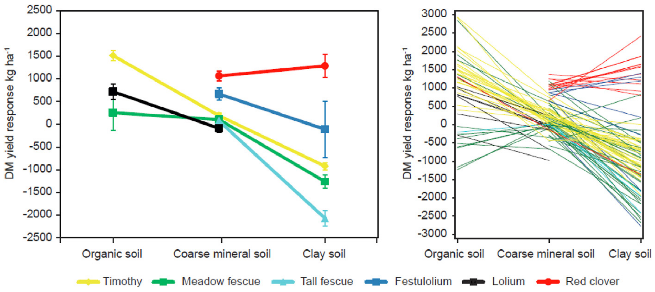

Fig. 4. The yield responses of forage crop species and cultivars separately to maximum temperature of 25 °C from 1st cut to 2nd cut (days) (calculated as response to high number of days >6 – low number of days <4) in different soil types.

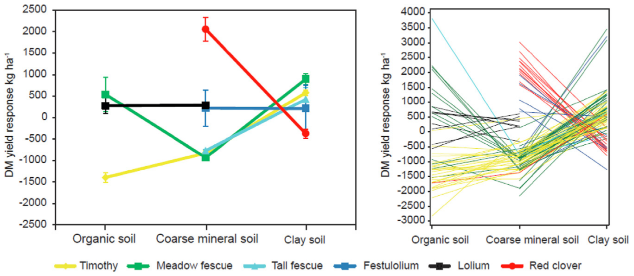

Fig. 5. The yield responses of forage crop species and cultivars separately to mean daily rainfall during fall hardening (mm) (calculated as response to high rainfall >2.1 mm – low rainfall <1.96 mm) in different soil types.

projections, precipitation is likely to gradually increase by the end of the century in Finland; especially winters are likely to get wetter. While 5- 9 mm increase in precipitation in June could increase the per hectare grain yields by 15–20% (Peltonen-Sainio et al., 2009), precipitation for summer is likely to be less than for winter, spring or autumn (Ylhäisi et al., 2010). Particularly the projected increase in precipitation during the autumn can result in harmful effects on yields (Ylhäisi et al., 2010). Even in the scenario of a 5 °C global climate change, the agricultural potential of the northern boreal conditions is likely to remain comparatively low (Trnka et al., 2011).

5.2. *Weather critical for yield performance depends on soil type*

Regarding clay soils, the agro-climatic factor explaining the most variability was related to the warm growth period. Clay soils are generally considered drought-prone, but our results did not reflect this, perhaps because of the relatively well-developed root systems of forage crops together with the high water-retention capacity of clay soils. The high precipitation during fall hardening or during the regrowth stage is generally detrimental to forage crops in clay soils, which might be explained by the heavy compacting nature of clay soils (Mukula and Rantanen, 1987).

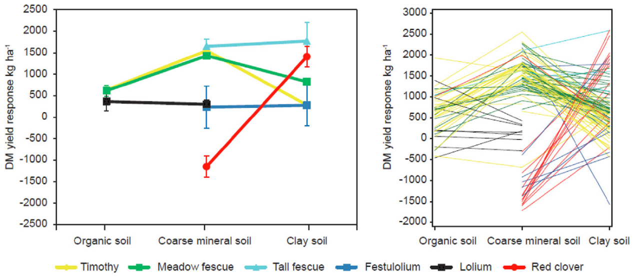

Fig. 6. The yield responses of forage crop species and cultivars separately to mean daily accumulation of temperature > 0 °C during winter (degree-days) (calculated as response to high accumulation >2.60°-days – low accumulation <0.75° -days) in different soil types.

Regarding coarse mineral soils, which are common not only in Central and Eastern Finland but also in Northern Middle Europe, the agro-climatic factor that explained most of the yield variation included high precipitation during fall hardening and high temperatures before first harvest and low accumulation of thaw days during winter together with high accumulation of cold stress days with temperature <−15 °C during winter. Although milder winter temperatures increased yields in clay and organic soils, for coarse mineral soils, the frequent occurrence of thaw days during winter appeared to be harmful, indicating the potentially detrimental effects of projected warmer winter conditions in the future (Jylhä et al., 2008), and this should be considered in breeding and agronomic management. However, the expected increase in autumn precipitation and a shorter hardening period (Ruosteenoja et al., 2011) could be beneficial for forage crop yield performance in coarse mineral soil. The tolerance to high temperature stress (maximum temperatures of 28 °C or higher) should be taken into consideration in breeding, particularly with regard to cultivation in coarse mineral soils.

Similar to clay soils, a warm growing season was the most important agro-climatic factor in organic soils. These soils are called “cold soils” and they have generally low thermal conductivity, particularly when drying (Mukula and Rantanen, 1987). A very high temperature and low precipitation during the regrowth period was noticed to be particularly beneficial for forage crops in organic soils, which can be explained by the high water-holding capacity and perhaps the high ground water table of organic soils.

5.3. Response diversity is dependent on soil

The diversity of the responses of species and cultivars was shown to be lower in coarse mineral soils than in clay or organic soils. This indicates the relatively narrower capacity of the examined set of species and cultivars in coarse mineral soils to successfully cope with uncertain change in climate than in clay or organic soils, where the diversity among species and cultivars may compensate for limitations in adaptive capacity. For instance, a high diversity in responses was shown among timothy in organic soils. The observed diversity in responses within species and cultivar pools under different soil types is crucial for the adaptation and resilience of agriculture to moderate or extreme variation in climate, coinciding a long-standing hypothesis of ecology; diversity contributes the resilience of ecosystem (Bai et al., 2004; Polley et al., 2013; Isbell et al., 2015). Diversity in responses to critical change has the potential to increase the safe space for adaptive actions. These actions can be implemented by farmers in practice, to enhance resilience of production by selecting cultivars from different clusters within each soil type, for instance, through selecting timothy cultivars from different clusters in organic soils. In breeding, it is essential to ensure response diversity in cultivar pools, by taking into account the role of combination with various soil types, to enable such selections by farmers.

5.4. Adaptation to shifts in climate-soil combinations

Under the shifts and northward extension of agricultural zones driven by climate change (Carter and Saarikko, 1996; Audsley et al., 2006; Peltonen-Sainio et al., 2008), the spatial heterogeneity of soil types may lead to marked shifts in the combinations of agro-climatic factors and soil types. For instance, clay soils are mostly located in Southern and Southwestern Finland, whereas the proportion of coarse mineral soils is highest in Central and Eastern Finland, and that of organic soils in northernmost Finland (Fig. 1). Although the main forage production areas currently occur on coarse mineral soils, if production shifts northwards, organic soils may increase in importance. Our findings revealed that the responses of forage species and cultivar yield to the agro-climatic factors critical to yield are notably dependent on soil type, as hypothesised. We note that the future land use scenarios are variable and uncertain, and thus which crops will actually shift is highly uncertain (cf. scenarios differences Nabuurs et al., 2000; Rounsevell et al., 2003; Audsley et al., 2006; Elsgaard et al., 2012). However, northward extension can happen rapidly; for example, in Finland, a 1 °C warming in mean temperature could shift the region suitable for wheat cultivation northwards by 110 km (in eastern Finland) to 290 km (in western Finland) (Carter and Saarikko, 1996). Quite similar shifts in USA maize production have been anticipated (Newman, 1980), and in Canada, marked shifts in many crops are likely (Mills, 1994, Brklacich et al., 1998). Consequently, our findings highlight the importance of climate–soil connection (and the underlying processes) for, among other reasons, planning successful adaptation of agriculture, such as the introduction of new species or the expansion of current species into new territories. However, climatic or pedochemical suitability alone does not guarantee effective adaptation of crops to new geographical distributions of agricultural land use.

5.5. Generality and reliability of the study

Our study provides insight into the criticality of climate–soil–crop combinations for adaptation, using historical data for Finland as an example. The data thus reflect a situation where only climate changes, while management practices and breeding remain unchanged. Further studies integrating the influence of increasing atmospheric CO_2 as well as the responses of climate–soil–crop systems to changes in nutrient and carbon

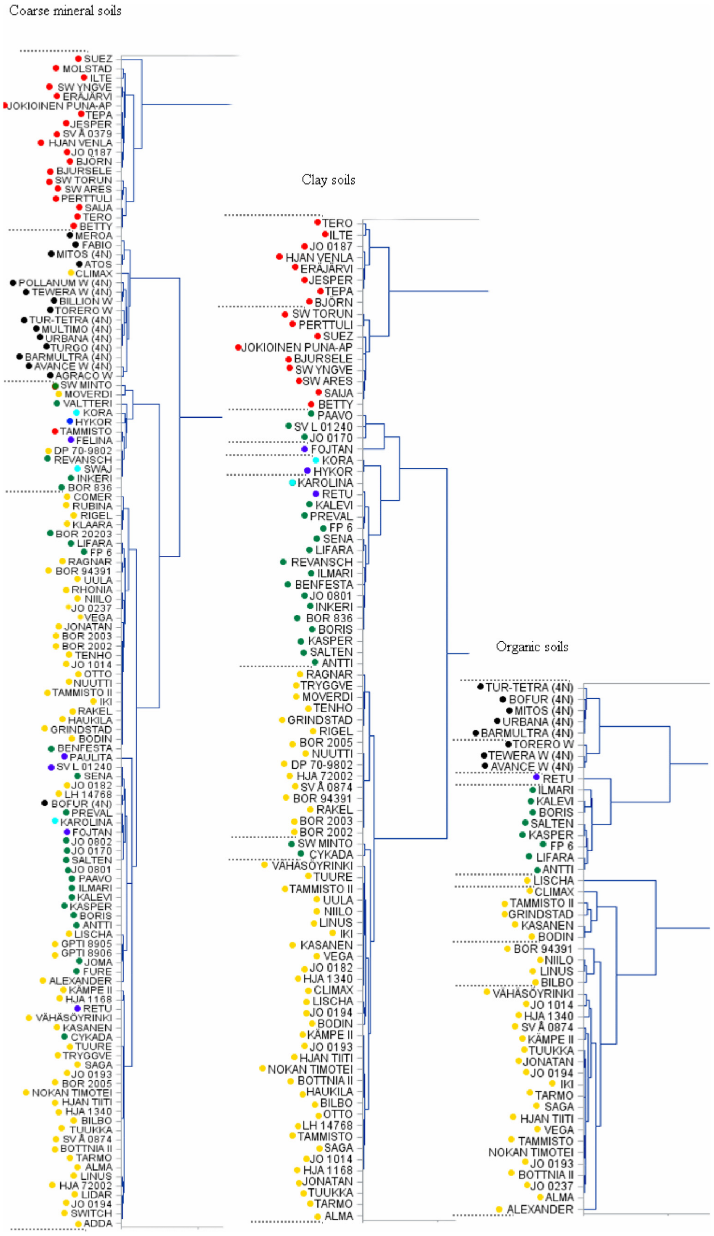

Fig. 7. Dendrograms showing the weather response clusters of different forage cultivars depending on soil type. Clusters are separated with grey lines showing four cultivar clusters in coarse mineral soils, nine in clay soils, and eight in organic soil. Different colours indicate the different species as follows: Timothy● Meadow fescue● Tall fescue● Festulolium● Italian ryegrass ● Red clover● .

Table 3
The PC structure across soil types compared for the most important PC of each soil type separately. The third column illustrates the highest component loadings of PCs for soils together, which were interpreted as follows: PC1 – Warm growth period, PC2 – High precipitation during fall hardening and high temperatures before first harvest, PC3 – Warm winter, and PC4 – High precipitation after the first harvest and a high number of hardening-supportive cold degree-days (Mäkinen et al., 2015). The following columns show PC loadings of the most important PC separately for clays, coarse mineral soils, and organic soils. The relationship between PC structure across soil types and the most important PC of each soil type is indicated by the colours grey, yellow, and green. For instance, the similarity between PC1 across soil types and the most important PC of clay soil is obvious. (For interpretation of the references to colour in this table legend, the reader is referred to the web version of this article).

	Weather variable*	Component loadings for PCs across soil types	Loadings of the first PC of soils		
			Clay	Coarse mineral soils	Organic
PC1 Warm growth period	GP-TEMP25_2[1]	0.88	0.88		0.85
	GP-TEMP[2]	0.88	0.90		0.89
	GP-DD5[3]	0.68	0.72		
	GP-TEMP_2_7[4]	0.57	0.86		
	GP-RAIN_14[5]	-0.52	-0.81		-0.95
PC2 High precipitation during fall hardening and high temperatures before first harvest	FH-RAIN[6]	0.86	-0.78	0.88	
	GP-TEMP25_1[7]	0.80		0.72	
	FH[8]	0.61		-0.82	
	GP-TEMP28[9]	-0.71		-0.65	0.91
PC3 Warm winter	W-THAW[10]	0.88		-0.87	
	W-STRESS[11]	-0.84		0.78	
PC 4 High precipitation after the first harvest and a high number of hardening-supportive cold degree-days	GP-RAIN_2[12]	0.90			
	FH-COLD[13]	0.70			
	Total variance explained by the first PC in different soil types		37%	32%	41%

FH = Fall hardening period, GP = growth period, W = Winter.
[1] Number of days with maximum temperature of 25 °C from 1st cut to 2nd cut.
[2] Mean daily temperature sum accumulation rate.
[3] Temperature sum >5 °C.
[4] Accumulation of temperature sum 7 days after 1st cut.
[5] Accumulation of precipitation 2 weeks after 1st cut.
[6] Mean daily rainfall during FH.
[7] Number of days with maximum temperature of 25 °C from GP start to 1st cut.
[8] Length of FH.
[9] Number of days with maximum temperature of 28 °C.
[10] Mean daily accumulation of temperature >0 °C during W.
[11] Accumulation of cold stress days with temperature <-15 °C.
[12] Accumulation of precipitation from 1st cut to 2nd cut.
[13] Accumulation of cold temperatures during FH <5 °C.

cycles would be highly valuable. Finland represents the northernmost agricultural country with a long day, intensive growing seasons, and a high proportion of organic soils. Therefore, although the specific agricultural adaptation implications presented here are applicable mainly to high-latitude conditions, the approach adopted in this study can be applied to agricultural adaptation in general, irrespective of the geographical location.

The characterization of weather categories in the present study was based on the real-world occurrence of each weather variable. Given the existing uncertainty of climate models (Rötter et al., 2011; Baker et al., 2016), this is a useful approach for planning adaptation and building resilience regarding the uncertainty of climate-induced changes. The probabilities of future scenarios are not of central interest in this approach. Similar approaches can be applied to other systems to ensure robust solutions.

The trial data (MTT Official Cultivar Trials by Kangas et al., 2009) include a relatively high number of species and cultivars from different locations and soil types, and this ensured that different soil type × species/cultivar combinations from different locations are represented. Thus, the reliability of estimates is relatively well ensured, despite the spatial heterogeneity of soil types and the fact that not every cultivar is grown every year at each test site. Nevertheless, there were fewer cultivars for organic soils than for the other soil types, mainly all the species do not perform well in organic soils. The used mixed models do not require the data in the equilibrium; however, to avoid asymmetry, at least 20 observations were used as criteria for cultivar selection for the study.

6. Conclusion

The results of this study show that the agro-climatic factors critical to forage crop yield performance depend on soil type, and highlight the significance of soil type to the diversity of forage crop yield responses. Climate–soil connection should be considered in planning and implementing adaptation in agriculture, particularly by plant breeders. Our study reveals the importance of addressing the shifts in climate–soil–crop combinations rather than in climate alone.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agrformet.2016.12.017.

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Managing diversity for food system resilience

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CHAPTER ONE

Managing diversity for food system resilience

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Contents

1. Introduction

Food systems face more and more fluctuation. Intensified volatility in climate and markets, and increasing complexity due to globalization of food value chains, has made resilience to a multitude of changes and variabilities an important complement to the efficient use of resources in building

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sustainability (Korhonen and Seager, 2008). In addition to trying to project future conditions, it is important to prepare for different kinds of changes and the intensifying extremes in weather conditions. While sustainability can be seen as an overall goal, and also has implications for food security for future generations, resilience is a means to achieve sustainability during change and disturbances as well (Tendall et al., 2015). Climate resilience specifically buffers against climate-related uncertainty and variability (Carpenter et al., 2001) and is currently a central part of food system resilience management. As complex social-ecological systems, food systems are indeed undergoing constant change: actor adaptations to long-term trends and sudden events modify food system dynamics including value chains and governing policies. Resilience framework acknowledged by several scientific disciplines can help in understanding and building food security.

Resilience management encompasses developing food systems and value chains comprising food production, distribution, processing, marketing, retail, consumption and waste management, and the ability to function under disturbance. The most important function of food systems and value chains is food security, or in other words, "for all people at all times to have access to sufficient, safe, nutritious food to maintain a healthy and active life" (FAO, 1996). Despite appeals to manage resilience, conceptual developments have not yet yielded a breakthrough in empirical applications. Diversification of system functions can reduce the sensitivity to disturbance and foster the capacity to adapt and transform (Gaitán-Gremaschi et al., 2019) toward various future scenarios. Most importantly, contrary to many other building blocks of resilience and adaptive capacity, diversification strategies to buffer against major crises can be tailored by food value chain actors themselves in their operational environment.

A diversity of responses to disturbance is considered a key determinant of resilience (Folke et al., 2004). Response diversity implies diversity within a function in response to change or variability critical to the function (Elmqvist et al., 2003). One example is diversity within wheat yield supply in response to climatic events that are critical to the yield. Response diversity within a functional group ensures that at least some members of the group maintain their functioning when facing disturbance and change. Consequently, not any kind of diversity within the function, e.g., in terms of genotypic diversity, is effective in this sense, but the diversity of the genotype pool in its responses to critical weather events can effectively enhance climate resilience (Kahiluoto et al., 2014). Response diversity approaches could thus provide the actors of food value chains a practical tool to assess and enhance resilience and contribute to developing food security.

In this chapter, we present various cases to illustrate how a perspective of resilience can provide new viewpoints and practical means to aid food systems and their actors from field to farm, and supply chains, in preparing for critical variations and changes that are difficult to predict. We first introduce a case of food system resilience and its determinants, including the role of diversity, based on perceptions of food chain actors. We then demonstrate an empirical approach for directly revealing response diversity as a means to manage resilience, applying this approach to key food system functions to enhance food security during times of change and variation. As examples we use climate-resilience of barley and forage crops and their cultivars in Finland, and wheat cultivars in nine European countries. We also describe response diversity as a means by which retailers can secure food sales and consumers can access food when faced with market disruptions such as strikes and global market price volatility. Furthermore, we test the assumed knowledge regarding the trade-off of (land-use) diversity as a proxy to (farm) resilience and economic efficiency, as such an assumed trade-off counteracts diversification as a means to resilience. Finally, we introduce a case of retooling efforts as a necessary condition for the wider use of the resilience perspective, and a practical method to assess response diversity.

2. Determining and enhancing resilience of food systems

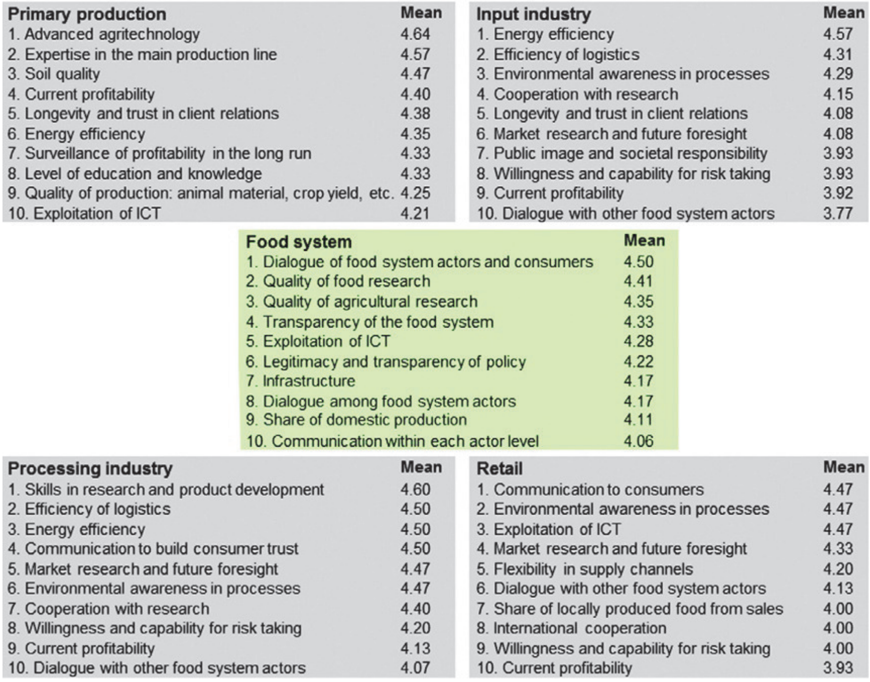
The operationalization of resilience is considered to be challenging, while the theoretical value of the concept, introduced by Holling (1973) in ecological terms, is widely acknowledged. Resilience has been, however, used as a framework to assess system stability, adaptability and recovery in various fields, including agroecosystems (Cabell and Oelofse, 2012; Peterson et al., 2018), farms (Darnhofer, 2014; Kahiluoto and Kaseva, 2016) and food systems (Himanen et al., 2016; Kahiluoto et al., 2014; Tendall et al., 2015; Worstell and Green, 2017).

Describing, determining and enhancing food system resilience requires a systems perspective, and understanding of complex interconnections and a plethora of actor perspectives and relations (Tendall et al., 2015). Due to the complexity of food systems, proxies and indicators typically need to be used to describe and assess how particular functions, actors and their linkages contribute to system resilience. Still, it is a great challenge to recognize key capacities of each actor, food system functions and their linkages that may eventually prove essential for positive adaptation and innovation, and yield local, national and regional food system stability and resilience under dynamic changes, simultaneously influenced by internal developments and external drivers. Universal indicators and resilience assessment tools useful across various scales (Douxchamps et al., 2017; Worstell and Green, 2017) may pave the way to developing resilience management in practice. However, resilience assessment and management, particularly in quantitative terms, is highly context-, scale- and time-specific. Resilience management uses determination and enhancement of resilience as a means, rather than an endpoint for development (Douxchamps et al., 2017).

Adaptive capacity, i.e., adaptability, management capacity, and coping ability, has been used as one such proxy to describe resilience-enhancing features. The concept links resilience to the vulnerability assessment methodology (Smit and Wandel, 2006). Vulnerability is defined as the product of exposure × sensitivity × adaptive capacity. Adaptive capacity represents concrete actor capabilities and assets (biophysical, social, economic) that help reduce risk resulting from exposure, and sensitivity to harmful, i.e., resilience-threatening, events or developments. Thus, good adaptive capacity, is believed to partly buffer actors or processes against abrupt changes and consequently enhance system resilience. It links resourcefulness to adaptation and innovation, which contributes to resilience (Darnhofer et al., 2010a,b). It is strongly context- and time-dependent but provides a practical aspect to resilience assessments.

According to Smit and Wandel (2006), adaptive capacity manifests as adaptation actions. Using adaptive capacity as a proxy, a stakeholder process to assess and enhance resilience of food system processes in Finland, was initiated (Himanen et al., 2016). Determinants of adaptive capacity were sought for main actor levels of the food system (primary production, input and processing industries, retail) through a future-oriented iterative Delphi process. The aim of the work was to identify key adaptive capacities that are central to enhancing resilience for both individual food system main actors and the national food production and distribution system as a whole. Furthermore, the role of diversity for the adaptive capacity of food systems was discussed. Input for the process was based on earlier studies on the role of diversity for resilience of farming (Darnhofer et al., 2010b; Lin, 2011), food systems (Hodbod and Eakin, 2015), adaptive networks in social-ecological systems (Norberg et al., 2008) and general resilience (Carpenter et al., 2012).

Based on the identified and ranked determinants of adaptive capacity, selected key actors' possibilities to adapt, self-regulate and innovate in face of change, as well as the overall perception on key factors for enhancing food system resilience as a whole were described (Fig. 1). However, the ranking of



Primary production	Mean
1. Advanced agritechnology	4.64
2. Expertise in the main production line	4.57
3. Soil quality	4.47
4. Current profitability	4.40
5. Longevity and trust in client relations	4.38
6. Energy efficiency	4.35
7. Surveillance of profitability in the long run	4.33
8. Level of education and knowledge	4.33
9. Quality of production: animal material, crop yield, etc.	4.25
10. Exploitation of ICT	4.21

Input industry	Mean
1. Energy efficiency	4.57
2. Efficiency of logistics	4.31
3. Environmental awareness in processes	4.29
4. Cooperation with research	4.15
5. Longevity and trust in client relations	4.08
6. Market research and future foresight	4.08
7. Public image and societal responsibility	3.93
8. Willingness and capability for risk taking	3.93
9. Current profitability	3.92
10. Dialogue with other food system actors	3.77

Food system	Mean
1. Dialogue of food system actors and consumers	4.50
2. Quality of food research	4.41
3. Quality of agricultural research	4.35
4. Transparency of the food system	4.33
5. Exploitation of ICT	4.28
6. Legitimacy and transparency of policy	4.22
7. Infrastructure	4.17
8. Dialogue among food system actors	4.17
9. Share of domestic production	4.11
10. Communication within each actor level	4.06

Processing industry	Mean
1. Skills in research and product development	4.60
2. Efficiency of logistics	4.50
3. Energy efficiency	4.50
4. Communication to build consumer trust	4.50
5. Market research and future foresight	4.47
6. Environmental awareness in processes	4.47
7. Cooperation with research	4.40
8. Willingness and capability for risk taking	4.20
9. Current profitability	4.13
10. Dialogue with other food system actors	4.07

Retail	Mean
1. Communication to consumers	4.47
2. Environmental awareness in processes	4.47
3. Exploitation of ICT	4.47
4. Market research and future foresight	4.33
5. Flexibility in supply channels	4.20
6. Dialogue with other food system actors	4.13
7. Share of locally produced food from sales	4.00
8. International cooperation	4.00
9. Willingness and capability for risk taking	4.00
10. Current profitability	3.93

Fig. 1 Determinants of adaptive capacity ranked as most significant for primary production (farm), the input industry, the food-processing industry, the retail, and the whole food system, according to the Delphi panel. A list of potential determinants to rank for significance was presented to the panel based on the brainstorming conversations. The scale was from 1 (no significance) to 5 (very high significance). ICT refers to information and communication technology n = 11–18 (Himanen et al., 2016).

the determinants was mostly useful for the purpose of the study process and not as a quantitative comparison. The determinants thus identified jointly, rather than individually, mirrored the recognized adaptive capacity building factors.

The Delphi process also included identification of food system characteristics that indicate preparation to an uncertain future more generally (Himanen et al., 2016). As such were mentioned diversity and flexibility; equality and open discussion; preparedness and agility; consumer acknowledgement; sustainability, and nutrient and energy sovereignty; locally based actions; skills and continuous learning; and profitability. A further round of iteration raised three themes most important to develop in an effort to increase the resilience of the food system: (1) energy and nutrient sovereignty via the use of domestic, renewable energy sources, such as biogas, the recycling of nutrients, and energy efficiency; (2) transparency, dialogue, and equity in the food chain; and (3) innovativeness and learning, utilizing technology, developing expertise, and research-based know-how.

Among the food system stakeholders (Himanen et al., 2016), diversification was found positive in terms of the safeguarding and flexibility of food system operations: it may secure the system against many types of risks and ensure agility in reactions for varying needs and opportunities. However, according to the respondents, diversification should not be perceived as an overwhelmingly positive characteristic. For example, efficiency was considered to override diversity in certain operations such as optimization of transportation logistics. The usefulness of diversity in agroecosystem functions, agricultural commodity selection and supplier contacts by retail were mostly agreed upon, whereas the benefit of diversification for the processing industry, in terms of suppliers of raw materials or individual farms pursuing multiple activities generated skepticism. Stakeholders believed there was an important difference in possibilities of diversification between production lines: with regard to building resilience, it is easier to diversify crop production actions than to manage farms with capital- and work-intensive animal production. Furthermore, diversification should not undermine the importance of coordination: diverse food systems may be even more dependent than less diverse systems concerning the effective planning of operations. Stakeholders lay emphasis on the importance of adding modularity to the food system, i.e., having multiple and different-sized actors interacting, to build food system-wide resilience.

The Finnish case study by Himanen et al. (2016) exemplifies the need to include both an understanding of each key actor's role and adaptation capabilities and their comparative role for system function in resilience management. Such insights might help unravel the key vulnerabilities of the system, and the reasons behind and potential solutions to building system resilience. Stakeholders mentioned that at the regional level, possibilities and advantages from diversification in resilience management could be valuable and potentially easier to achieve than at individual farms. However, resilience management across scales is not an easy task: to support resilience, all actors should be able to equally find their adaptation space in the system and acknowledge that both internal and external change constantly shapes food system dynamics. As food systems are constantly adapting and dynamic, any analysis we make of them is only as good as the current understanding of the system as a whole, and of actors' roles.

Multi-actor perspectives, motivations, incentives and barriers to action also need to be understood when visioning future development of food systems, either positive desired development or negative, non-resilient development pathways. The desire to maintain resilience is an ongoing adaptation and learning process and linked strongly to economic, governmental and structural developments in the food system operating environment. This emphasizes that both policy-makers and actors should have strong situational awareness and ability for constant learning. When aiming to design interventions or measures enabling actors themselves to influence system resilience, multiple stakeholder involvement and co-designing processes may turn critical. The downside is that due to the large number of actors involved in food systems, these may often yield qualitative outcomes and reflect the current situation quite strongly.

On the other hand, empirical tools and modeling approaches can describe the past and potential future development pathways, strengths of internal and external drivers and the likelihoods of system shocks, as well as help identify key components in need of proactive adaptation. Such tools can provide the quantitative data needed for the operationalization of supporting actions such as novel governmental regulations. Modeling can be highly useful in describing the sensitivity of particular food system key functions such as crop production (Hakala et al., 2012; Kahiluoto et al., 2014).

3. Resilience management through diversity

Resilience management encompasses efforts to ensure essential system function during adverse events and disturbances. Resilience encompasses such components as robustness, redundancy, flexibility and adaptability (Tendall et al., 2015). Redundancy means that some elements can substitute each other during a disturbance, so it is important to identify which actions most require redundancy and how it can be delivered in practice. Adding redundancy through diversification has been raised as one potential buffer to securing key operations of the food system (e.g., Lin, 2011; Peterson et al., 2018) such as farm operations (Darnhofer, 2014; Darnhofer et al., 2010a,b) and food chain functions (Babu and Blom, 2014; Benton et al., 2012).

Land-use changes and reduced functional biodiversity have been linked to some of the major challenges we face today such as losses of soil carbon and fertility, chemicalization, global biodiversity crisis and progressive climate change (e.g., Newbold et al., 2015). Strategies to transform current input-intensive, monoculture-dominated cropping systems into temporally, spatially and functionally diversified agroecosystems that foster and utilize natural self-regulation and buffering for enhanced sustainability and resilience is an active area of research (Altieri et al., 2015; Bommarco et al., 2013). In this sense, diversification seems to have great potential to build climate-resilience and self-sovereignty for nutrients and energy (Isbell et al., 2017).

Primary production, i.e., food and feed production by farmers, is undoubtedly a key function of food system resilience. While the overall food supply per capita and the number of crop commodities contributing to national food supply have increased over the last 50 years, at the same time the national food supplies worldwide have become more homogenized in composition (Khoury et al., 2014). An increase in the share of globally important cereal and oil crops, plus a decline of other cereal, oil, and starchy root species has taken place. Homogenization might increase the vulnerability of global food supply to shocks such as adverse weather changes. The climate resilience of national, regional and global staple crops, including barley, wheat, and forage crops thus plays a major role in global food security (Kahiluoto et al., 2014, 2019).

The climate resilience (Carpenter et al., 2001) of crops has become critical to stabilizing food supply (Rötter et al., 2013) and avoiding price spikes (Hajkowicz et al., 2012). According to Food and Agriculture Organization (FAO, 2018), globally the number of extreme climate-related disasters, caused by droughts, extreme heat episodes, floods and storms, has doubled since the early 1990s, with an average of 213 of these events occurring each year from 1990 to 2016. The capacity of a single crop genotype to maintain a good yield performance under climatic variability and extremes is limited, and therefore, it will be extremely important to have a selection of crops and cultivars with diverse responses to critical weather conditions to ensure local, regional, and ultimately global, yield. According to United Nations (UN, 2019), since the 1900s circa 75% of crop diversity has been lost from farmers' fields globally. The sustainable development goal for zero hunger emphasizes that better use of agricultural biodiversity should result in more nutritious diets, enhanced livelihood for farming communities and higher resilience of farming systems.

In the long term, the sustainable provision of ecosystem services needs to be adjusted with productivity goals. Crop diversification via crop and cultivar mixtures, crop rotations, and landscape biodiversity enhancements are all means to create synergistically higher agricultural productivity and yield security (Isbell et al., 2017). "Win–win" solutions that support resilience of both farming and agricultural productivity are needed. For example, diversification of regional cultivar use, when potentiated by a sufficiently diverse available cultivar pool, has been shown to positively impact yielding (Himanen et al., 2013). An average annual yield increase of 415–1338 kg/ha was shown per one unit increase in the Shannon diversity index for feed barley cultivar use in Finnish regions. The relation was found every year but was strongest during the rainy growing seasons. The study comprised

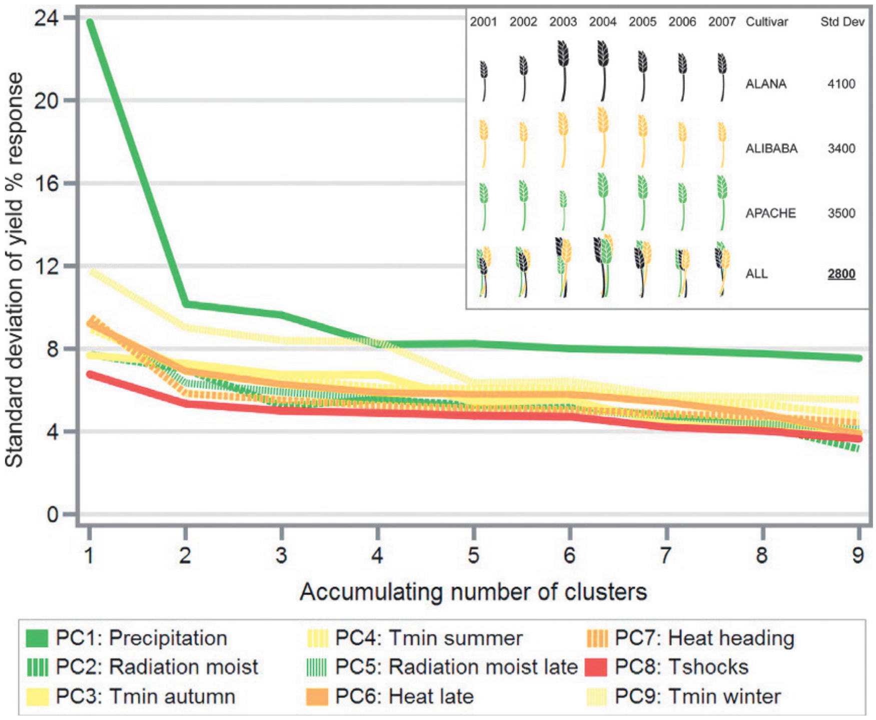


Fig. 2 Increase in the climate resilience of European wheat with increasing response diversity. The main figure shows the decrease in the variation in the percentage yield response to the weather patterns (agroclimatic PCs) critical to yield due to the increase in the number of weather response clusters considered. All of the cultivar yield data were utilized (n = 100,985). The box shows how combining cultivars from different clusters increases the yield stability under weather variability. The three exemplary cultivars (dark, yellow and green heads) represent clusters 1, 3 and 5, respectively, from Caslav, Czechia and were selected based on the largest number of observations and similar average yields (n = 78). If the cultivation area was evenly divided among the three cultivars from 2001 to 2007 in comparison with the cultivation of only the cultivar with the highest total yield (Apache), a 2% loss in total yield appeared, but the SD among the years declined by 16–32%. The relative size of the heads refers to the relative annual yields of the three cultivars (Kahiluoto et al., 2019).

4500–5000 farms annually during the time period 1998–2009 (see also Section 4, Fig. 2). The diversity benefit was more clearly evident in barley with the highest cultivar diversity relative to other crops, whereas the effect was rather the contrary (two seasons) regarding spring rapeseed with the smallest and genetically most narrow cultivar pool with good yield potential. Such diversification might also have other benefits, still to be unraveled, for resilience management. Tools are needed to identify what kind of diversification strategies work best, to address different challenges that our food systems face. Such information could be highly valuable in reversing the risks associated with the homogenization of food system functions and their components.

4. From diversity to response diversity

To recognize resilience, we should move beyond species, cultivar and genetic diversity. Diversity per se, i.e., *type diversity* (Page, 2010), does not enhance resilience, whereas diversity in responses to critical variability and change, i.e., *response diversity*, can maintain the system function in change and turbulence (Elmqvist et al., 2003; Nyström, 2006). Consequently, if the key components and levels of diversity that fosters resilience is identified, more resilience can be achieved with targeted, more effective diversification actions for system functioning, which may even mean less diversity.

In an agri-food system, the response traits of fodder and food supply may be different for shifts in, for example, climate and pests, local strikes, or global demand and price, even at the cultivar level. Furthermore, cropping and farming systems or food value chains again require specific kinds of response diversities. Therefore, response diversity must be determined directly (Aubin et al., 2009) for each given question and case (Petchey and Gaston, 2006). Multivariate statistical methods, such as clustering and ordination methods that are often applied to assess genetic or species diversity (Laliberte et al., 2010; Mohammadi and Prasanna, 2003; Petchey and Gaston, 2006), can provide methodological solutions to empirically quantify response diversity.

Cultivars vary in response to weather variables (e.g., Hakala et al., 2012). For example, some cultivars are susceptible to drought, whereas others do not tolerate flooding or heat stress. Based on this, it can be hypothesized that an assessment of response diversity would yield a different estimate of regional cultivar diversity than obtained from mere type diversity (discrete cultivars used individually). Then the approach based on response diversity would allow a more valid assessment of diversity in terms of the response to climate variability and change. In the case of added value by response diversity, this approach could provide a generic procedure as a practical tool to manage resilience.

4.1 Response diversity is not equal to cultivar or genetic diversity

As an obvious example, the occurrence of diversity in responses to weather variability within a functional group or species, such as European wheat that supplies bread and pasta, can ensure a reasonable yield level regardless of weather conditions and provides information for cultivar selection under changing climate (Chapin et al., 1997). To exemplify the difference between type diversity and response diversity, we have shown with forage crops that genetic diversity is not directly related to response diversity in Mäkinen et al. (2015). Genetic closeness does not fully explain responses to critical weather conditions; most of the forage crop species were distributed among several clusters and most of the clusters contained several species (Mäkinen et al., 2015).

4.2 Response diversity enhances yield resilience

The potential yield stability under environmental variation should be higher if a group of cultivars with different responses to the varied environments is cultivated rather than a single genotype. Selecting cultivars based on empirical data of responses to weather events that are critical to yield, response diversity has the potential to secure yields and financial returns to farmers through reducing yield variation. The box in Fig. 2 demonstrates this relevance of response diversity to yield variation and average yield over 7 years from one site in Czechia. When applying the approach, farmers could choose from a group of cultivars that have both significant response diversity and high yield potential. The steps of the analysis are more closely described in Section 6.

In European wheat case (Kahiluoto et al. 2019), we found a low diversity of weather response clusters, i.e., a response diversity *desert*, in trials of Czechia (Fig. 3). The highest diversity of weather response clusters, i.e., a response diversity *hotspot*, was found in Slovakia. The development towards the same dominant weather response clusters among northern and central, and among southern European countries was alarming. Respectively, the diversity of yield responses to weather patterns critical to yield was declining also in farmers' fields in most European countries. While Europe produces one-fifth of world's wheat (FAOSTAT, 2017), the lack of diversification exposes yield to greater fluctuations, which increases the risk of impaired food security. Wheat is usually cultivated either for bread or for pasta flour, and the cultivars are distinct in each case, whereas for feed mainly wheat not meeting the quality requirements for those purposes is used. Especially the durum wheat cultivars for pasta appear to lack response diversity; nearly all of the European durum cultivars responded to weather events the same way.

In Finnish barley case (Kahiluoto et al., 2014), we found the structure of 12 weather response clusters of cultivars most suitable. Based on this, type

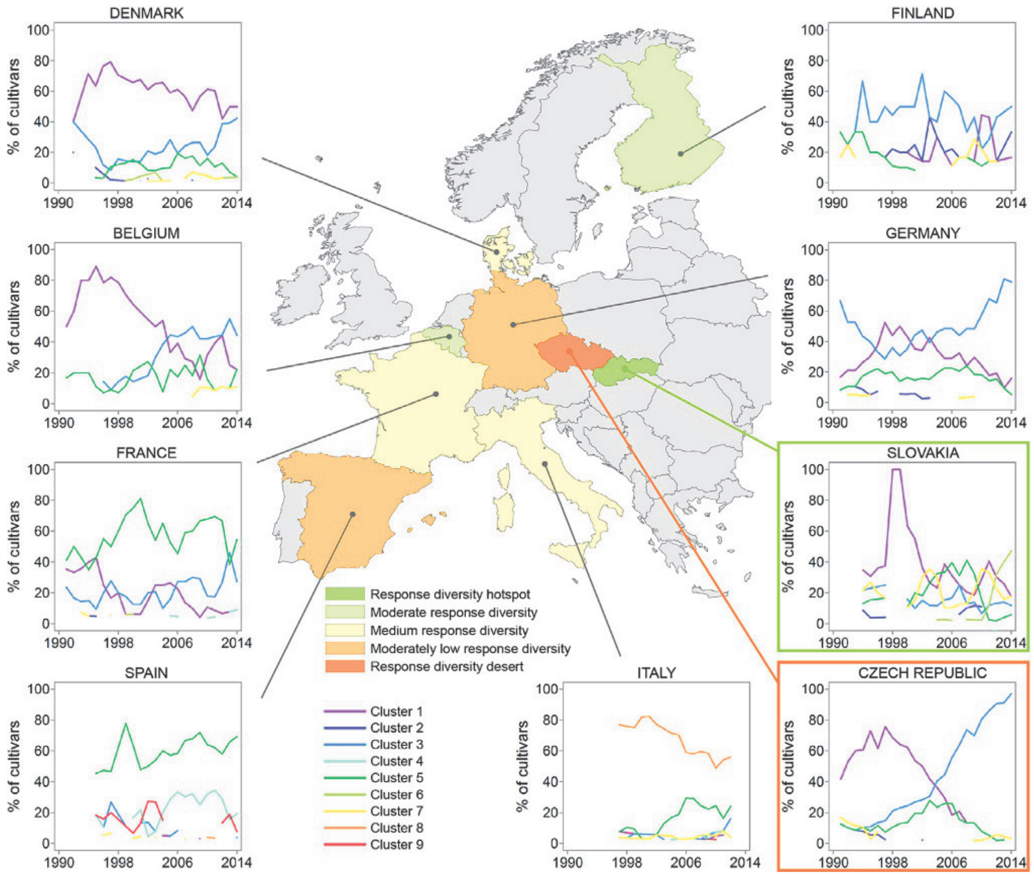


Fig. 3 Climate resilience hotspots and deserts of European wheat. The country charts show the percentages of cultivars in each weather response cluster with different responses to weather patterns (agroclimatic PCs) critical to yield in cultivar trials. The colored (green to orange) areas on the map illustrate the response diversity classes based on the proportion of the dominant cluster (>90% to <50%), the number of other simultaneously important clusters (0–4), and the trends. All of the cultivar yield data were utilized (n = 100,985) (Kahiluoto et al., 2019).

and response diversity indices were calculated, and the slopes were statistically compared to 16 regions (Fig. 4). As expected, type diversities were much higher, because Shannon index depends on sample size. In the southern regions, both the indices increased evenly in value from 1998 to 2009. However, the discrepancy between the two indices in the central and northern regions tended to increase slightly at the start of the 2000s and again in the middle of the decade. Especially in the central and northern regions, the response diversity index decreased, although the cultivar type diversity index increased. The same kind of effect was later found in European wheat.

The decrease in the equitability of barley cultivar response diversity in Central and Northern Finland coincided with the increase in the cultivation area of a single response cluster, the grain yield of which is reduced by drought and which benefits from a relatively early sowing. This cluster (Cluster 3) replaced cultivars from another, previously equally extensively cultivated response cluster (Cluster 1) (Fig. 5), which showed minor response to the weather variables but only had a moderate yield level.

Regarding response diversity in the field, for example forage crop species and cultivars varied significantly in their yield response to four critical agro-climatic factors in Finland (Mäkinen et al., 2015). The most critical agro-climatic factors were responsible for almost half of forage yield variation. Temperature accumulation, high temperatures during the growing season and high precipitation during the fall hardening period were the most influential factors. The magnitude of variation in dry matter yield among the cultivars caused by agro-climatic factors ranged from 12% to 17% of the mean yield and can be considered significant, even at the farm level. There appeared, however, no single species, which would have performed well under all the critical agro-climatic factors.

4.3 Crop diversity in response to weather may depend on soil types

Cultivar or crop mixtures are common in forage cultivation. Sometimes, such mixtures are also used with cereals to enhance yielding or resistance to pathogen and insect pests (Borg et al., 2018; Reiss and Drinkwater, 2018). Such mixtures have not been experimented specifically for their response diversity and deserve further study. Crop or cultivar mixtures designed based on response diversity and ecological compatibility have the potential to compensate for possible challenges in growth responses and resulting yield losses during the growing season. When applying response diversity to resilience management of crops, it is important to note

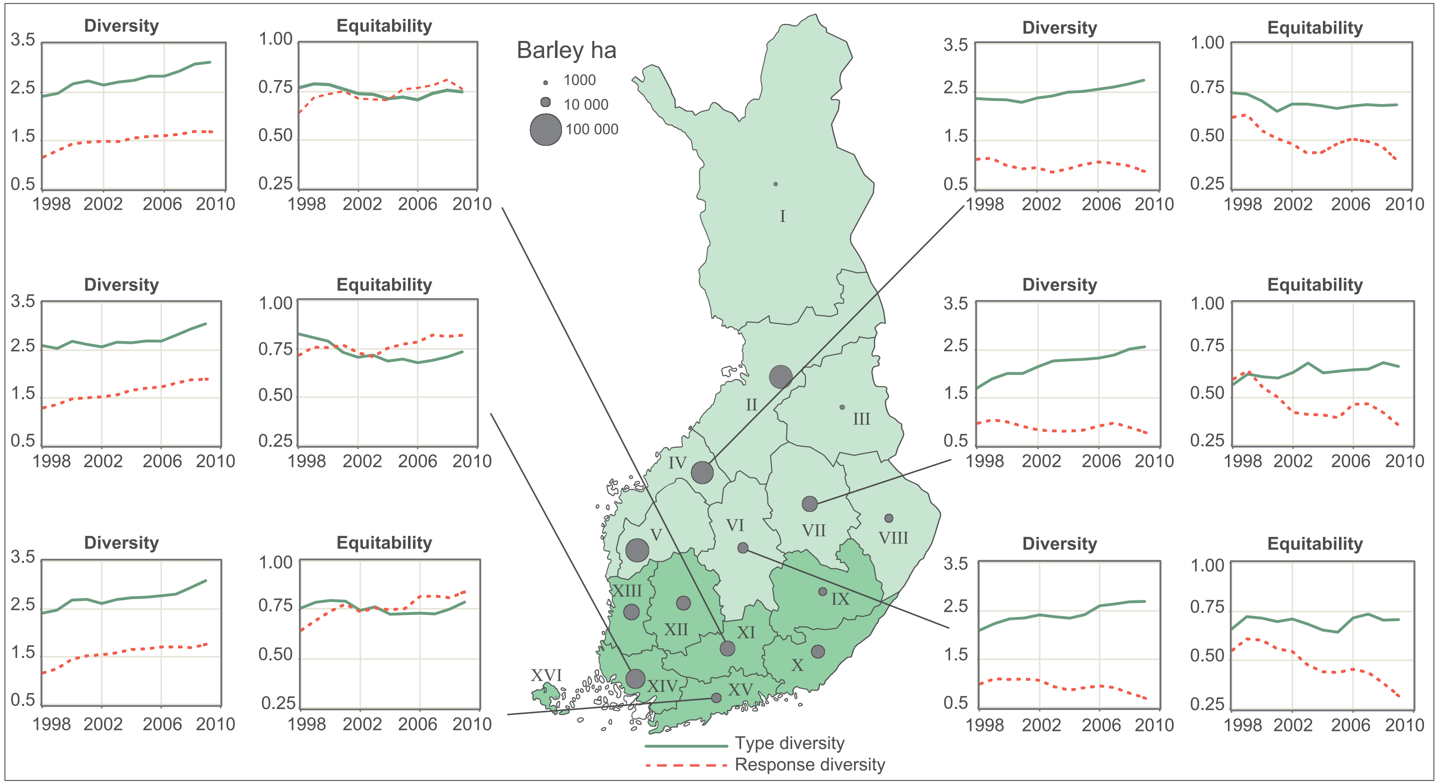


Fig. 4 Disparity between the Shannon indices and the equitabilities for the barley cultivar type diversity (continuous line) and response diversity (dashed line). Equitability represents the evenness component of the diversity indices which also include the component of richness. Equitability was calculated by dividing each value of the Shannon diversity index by the theoretical maximum for that value. The development in the regions with the smallest and greatest disparity between the indices since 2005 is shown. Dark green indicates the regions for which the disparity values were in the lower half of all regional values (the charts to the left). The size of the circles illustrates the barley cultivation area in 2005–2009. The Roman numerals refer to the regions (Kahiluoto et al., 2014).

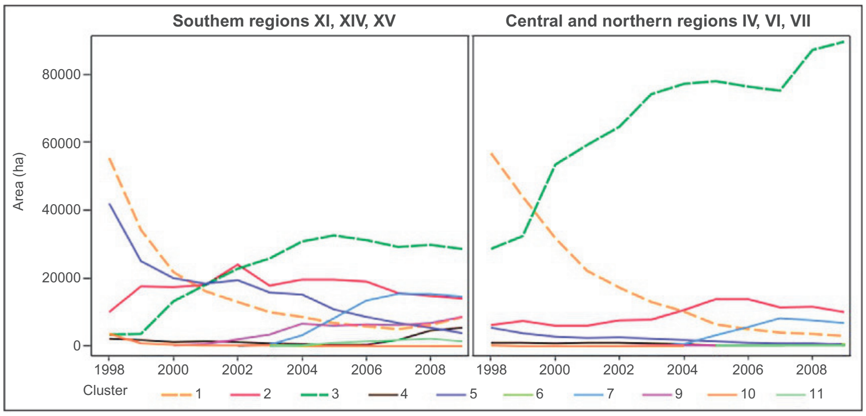


Fig. 5 Development of the cultivation area of the barley cultivar response clusters (1998–2009) in the Southern regions (left) and in the Central and Northern regions (right) of Finland. Cluster 3 represents cultivars, the grain yield of which is clearly reduced by drought and benefits from relatively early sowing. Cluster 1 represents cultivars with a stable but only moderate yield (Kahiluoto et al., 2014).

that soil type also affects the responses of crops and cultivars to specific weather events (Figs. 6 and 7) (Mäkinen et al., 2017). At the farm scale, for example, land use diversity (Kahiluoto and Kaseva, 2016) or diversity of income sources may play a role in stabilizing farmers' inter-annual income variations.

4.4 Managing supply chain resilience through response diversity

The approach of response diversity assessments is useful not only regarding agriculture, but to any part of the food system. Supply chain disruptions have become increasingly critical, having severe effects on firms (Hendricks and Singhal, 2005; Kim et al., 2015). In particular, food supply chains suffer from the increase in weather extremes (Ray et al., 2015) and the linkages among food, (bio) energy and financial markets aggravate the volatility (Tadesse et al., 2016). Supplying food is the core function of food supply chains and supplying stability during disruptions and volatility as well as adaptability (Stone and Rahimifard, 2018), are of primary importance for supply chain actors and societies (Galtier, 2013; Stone and Rahimifard, 2018).

Supply chain disruptions may originate within the supply chain or be external, and they can be domestic or global. One example of domestic disruptions are strikes, and global disruptions can be represented by a price anomaly, epidemics spreading through slaughterhouses, or demographic changes such as abrupt immigration affecting food demand. The effective

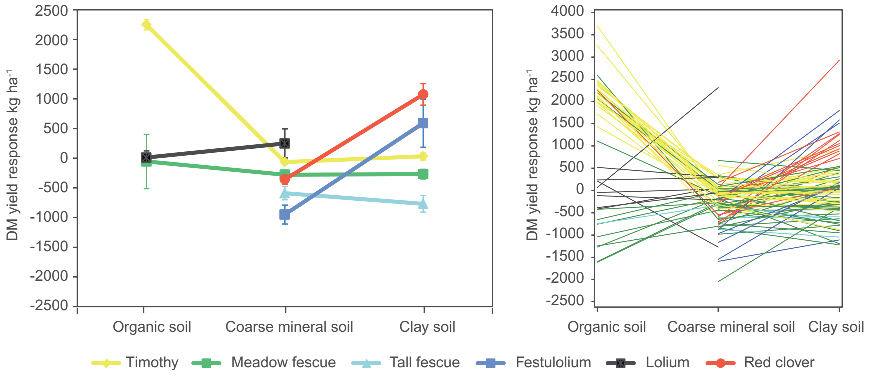


Fig. 6 Theyield responses of forage crop species (left) and cultivars (right) separately to accumulation of precipitation from 1st cut to 2nd cut (mm) (calculated as response to high precipitation >118 mm—low precipitation <103 mm) in different soil types (Mäkinen et al., 2017).

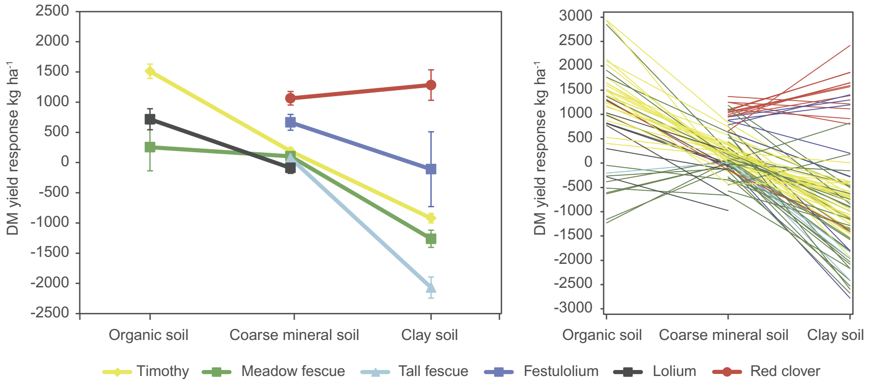


Fig. 7 The yield responses of forage crop species (left) and cultivars (right) separately to maximum temperature of 25 °C from first cut to second cut (days) (calculated as response to high number of days >6—low number of days <4) in different soil types (Mäkinen et al., 2017).

diversity in responses to such changes can be empirically assessed using big data or be hypothetically set and tested. For example, an on-going Finnish case study examines the maintenance of sales of retail stores depending on their supplier diversity when facing a strike in food industry or price anomaly on the global food market. The aim is to analyze, whether response diversity of suppliers can maintain the sales under supply disruptions. The response groups of suppliers are in that case based on previous literature and experiential knowledge rather than empirical data on past events, due to data limitations.

Weather variability and extremes will very likely continue to intensify in the near future, and uncertainty will remain high, despite efforts to better predict developments and provide early warnings to enable proper preparation. The increasing length and complexity of supply chains and intensified turbulence in terms of market volatility and political instability appears to increase rather than decline. Fortunately, the increasing access to big data will facilitate the use of the approach tremendously and enable its application to new fields. The inherent deficit of the approach is, however, that if the future evolves very differently relative to the past, and the degree of variations and extremes vastly exceed those ever experienced, the past data will not necessarily predict the critical change factors well. However, hypothetical determinants of response diversity, based on theory or practical experience, can also be used and tested in case of lack of empirical data.

5. What about the trade-off between resilience and efficiency?

Efficiency is a key economic concept, and on a simplistic level it means maximum or optimal output with minimum effort or waste. The idea of more from less, eco-efficiency, has long been associated with sustainability. Increasing resource-use efficiency is believed to promote economic performance, food security and environmental protection (Lankoski and Ollikainen, 2011; Tilman et al., 2001). However, the complementarity of the two perspectives, efficiency and resilience, in sustainable development, has been increasingly argued (Goerner et al., 2009; Korhonen and Seager, 2008; Ulanowicz et al., 2009).

In recent decades, systems efficiency has been streamlined for expected conditions, which has led to less diverse systems in many cases. Since diversity is known to increase the stability of production in agricultural environments (Tilman et al., 2006), and land-use diversity appears to increase farm resilience (Lin, 2011) also in terms of economic returns (Abson et al., 2013; Schippers et al., 2014), there is much potential for growth in this sector. Lack of resilience may also affect efficiency negatively, and response diversity offers a tool to tackle this. Empirical evidence for the dependence between resource-use (or economic) efficiency and diversity of production is scarce or non-existent. The current understanding of a trade-off relation between economic efficiency and diversity in farming informs agricultural policies, and thus more research on this topic is needed.

In Kahiluoto and Kaseva (2016), we tested with empirical data from Finnish farms, whether there was trade-off between diversity and efficiency of resource-use on farms. The size and specialization of Finnish farms increased rapidly during the last decades, attempting to achieve greater resource-use efficiency through economies of scale (Lehtonen and Pyykkönen, 2005). Due to its northern location, and therefore rapid climate change, resilience is an essential issue on farms. In the study, we hypothesized that land-use diversity was negatively related to farm efficiency, when economical inputs were taken into account. Resource-use efficiency was measured as a relation between the use of the major farm resources land (ha), labor (h), capital (€) and land-use diversity index and farm revenue (€) using Cobb-Douglas regression model. In addition, technical efficiency was measured with stochastic frontier models as the ratio between the total revenue to the maximum output under the assumption of fixed inputs. Use of farm capital was calculated as the sum of the average of the working capital of livestock, permanent crops, land improvements, buildings, machinery and equipment, and circulating capital. Total revenue was calculated as output from crops and crop products, livestock and livestock products and other output. The Shannon-Weaver index was used to illustrate farm land-use diversity, describing the number and proportional area distribution (richness and evenness) of eight land-use types on farms. A Shannon index equal to zero indicated that the farm had only one land-use type, and the index increased as the number of different land-use types and/or their evenness increased. The Shannon index was preferred over other indices, because it gives an equal weight to each observation and is comparable among cases with different compositions (Jost, 2007). The Shannon index is expressed in logarithmic scale and was converted to a linear scale to describe the true diversity of land-use.

The elasticities, in Fig. 8, illustrate the dependence of resource-use efficiency on land-use diversity and inputs. The small negative elasticities of land-use diversity in 2004 and 2006 indicate that a 10% increase in land-use diversity results in about half a percent decrease in total revenue. The positive elasticities indicate that increasing inputs would increase total revenue. The confidence intervals indicate that total revenues could at maximum increase (2001) or decrease (2004) by almost 3% due to 10% increase in land-use diversity. The lack of statistical significance (CLs includes zero) in the dependence of resource-use efficiency on land-use diversity, together with low percentage of land-use diversity, indicated that there was either no dependence of resource-use efficiency on land-use diversity, or the dependence was low.

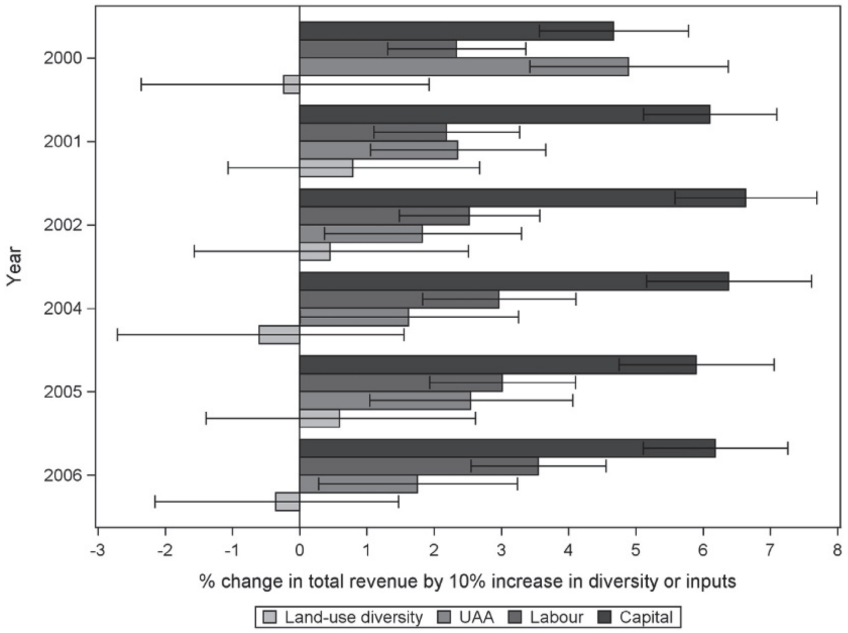


Fig. 8 Dependence of resource-use efficiency on land-use diversity. Estimated elasticities of land-use diversity and inputs in years 2000–2002 and 2004–2006 summarized based on the results of the adequate model for each year. The elasticities illustrate the dependence of resource-use efficiency on land-use diversity and inputs. The small negative elasticities of in 2004 and 2006 indicate that a 10% increase in land-use diversity, with an average input use, would result in approximately half a percentage decrease in total revenue. The positive elasticities indicate increase in total revenue by increasing inputs. UAA = utilized agricultural area (Kahiluoto and Kaseva, 2016).

According to our analysis, the revenue per unit of land, labor and capital, had no relation or only a negligible relation with land-use diversity. Consequently, the results did not support our hypothesis of an inverse dependence between farm resource-use efficiency and diversity. The slight relations observed were inconsequent and weak enough to suggest a low economic significance for the relation in practice. Contrary to the assumption of an unavoidable trade-off between efficiency and diversity, we concluded that diversification hardly constrains resource-use efficiency. Furthermore, seeking better resilience is not necessarily opposed to even short-term economic efficiency.

6. How to measure response diversity

In our analysis of response diversity, we have used some widely known statistical methods such as linear mixed models, principal component analysis (PCA) and cluster analysis. All indices and weather variables were calculated

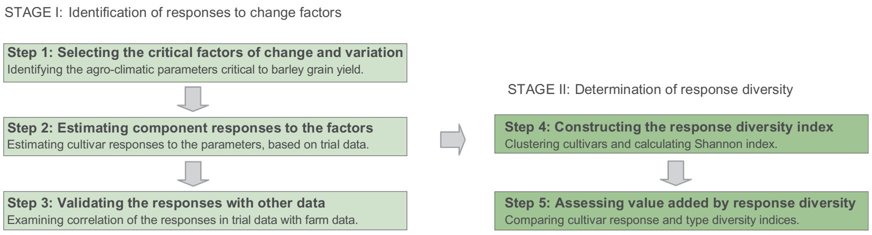


Fig. 9 The proposed approach to response diversity assessment. The steps of the generic procedure are presented in bold font. The procedure that is applied to the case is specified for each step (Kahiluoto et al., 2014).

without any specialties. All analyses are repeatable according to the steps in Fig. 9. Our approach consists of two stages and five steps. Not all steps are always necessary and can be omitted depending on data and research questions. In particular, the third step may be unnecessary or impossible to implement in many cases. The fifth step may be difficult to implement in the absence of suitable data.

In stage I, we determined the factors of change that are critical to system performance, and the component responses to variations in these factors. In our study examples, we considered the agro-climatic variables most critical to barley, wheat and forage crop yields, and the yield response of cultivars to variations in these variables in multi-location trials. Validating the critical change factors and responses using other data can test the generality of the results. In our first study (Kahiluoto et al., 2014), we determined the correlation in cultivar responses between the trial data and data from farms, to test whether the cultivars respond similarly to the agro-climatic variables under farm conditions as in the trials. We wanted to confirm that the response diversity model created using the trial data was valid in practical farming conditions, and thus applicable to guide the adaptive management of farmers and decision-making in, for example, breeding or agricultural policy. In stage II we used multivariate methods to analyze the structure of the yield responses. The Shannon diversity index was used to calculate the response diversity based on this structure. Statistics on the national cultivation areas for cultivars in Finland, Denmark, Belgium, France, Germany, Czechia, and Spain were utilized in this stage.

6.1 Step 1: Selecting the critical factors of change and variation

In the studies described this meant that we identified the agro-climatic variables critical to yield. All studies used data of the official variety trials. In Finland, we had sites from 14 locations, but in the European stage we had data from over 600 sites in nine countries. Relatively large and representative data is a prerequisite for performing the analyses.

The agro-climatic variables that were potentially critical to yield were selected based on responses reported in the literature. Data on these agro-climatic variables during crop phenological stages were obtained from the stations closest to the cultivar trial sites. In some cases, grid-based data were used. Missing data on sowing, heading, or maturity dates were mainly estimated based on the corresponding dates for all of the cultivars from the same site and year. Usually, when a sowing date was missing it was assumed that the sowing dates of all cultivars did not differ. Non-available sowing dates for a given site and year led to removal of data from further analysis. If the heading and maturity dates were missing, then the missing values were estimated using correlation analysis with overlapping data for the cultivars from the same site across the other seasons. In the absence of available overlapping data or limited data pairs, the heading and/or maturity dates were estimated using the thermal time above 5 °C obtained for the given cultivar from nearby sites and preceding and/or subsequent seasons.

The trials were of a randomized complete block design or an incomplete block design, and the number of replicates varied from three to four. Standard reference cultivars were used across the trials, while other cultivars in the experiments differed in the long term. The use of fertilizers depended on the cropping history, soil type and soil fertility, and was consistent with the farmers' practices. Cultivars with at least 20 observations were included in the analysis, with the expectation that they contained sufficient information about the cultivar's climate variability.

6.2 Step 2: Estimating component responses to the factors

In the studies described this meant that we estimated cultivar yield responses to the chosen agro-climatic variables. The observations for each agro-climatic variable were classified into three categories, because the relationship between yield and agro-climatic variables were nonlinear in most cases. Usually these types of variables can also be strongly correlated, leading to multicollinearity in the regression analysis. The random environmental effects (country, site and year) are also known to contain most of the variations, and thus have to be taken into account. The limits of categories can be modified depending on type of data or the amount of observations, but we used limits of 33rd and 66th or 40th and 60th percentiles of the distributions of the agro-climatic variables to form categories of low, moderate and high values for each variable. For example, the yield observations were divided into groups based on the number of rainy days experienced from sowing to maturity: fewer than *x*, between *x* and *y* and above *y*. The interaction of these categories with the yield of each cultivar was analyzed using the following mixed model:

$$\begin{aligned} y_{ijklmn} = \mu &+ \text{cultivar}_i + \text{category}_j + \text{cultivar} \\ &\times \text{category}_{ij} + \text{treated}_k + \text{country}_l + \text{site}_m + \text{year}_n + \text{treated} \\ &\times \text{country} \times \text{site} \times \text{year}(\text{category})_{jklmn} + \varepsilon_{ijklmn} \end{aligned}$$

where y_{ijklmn} is the observed (annual) yield, μ is the intercept, cultivar_i is the average yield level of the *i*th cultivar, category_j is the average yield level at the *j*th level of the categorized environment, $\text{cultivar} \times \text{category}_{ij}$ is the cultivar-by-environment interaction and treated_k refers to the use of pesticides. All of the above effects are fixed in the model. Country_l, site_m, year_n and the interaction of treated × country × site × year $(\text{category})_{jklmn}$ are the random effects of the *l*th country, *m*th experimental site and *n*th year within the *j*th category. The effects of country and treated were excluded from the equation when those were missing data (for barley and forage crops).

For each cultivar and agro-climatic variable, the difference in yield between the extreme categories (high-low) was calculated. Consequently, a positive yield response implied a positive effect of numerous rainy days. Instead of yield difference, it is possible to use the relative difference, which might be better when yield level of cultivars differ notably, as well. However, it is important to realize that relative difference depends on which one is used as denominator. Data used in the second stage consisted of the yield responses of all cultivars (rows) to all agro-climatic variables (columns).

6.3 Step 3: Validating the responses with other data

The validity of the estimated barley yield responses in the trials was tested under the conditions occurring on farms, to ensure the validity of the conclusions for practical agriculture. Due to the potentially high variation in farm conditions (cultivation practices changes more on farms), which may affect yield responses to the agro-climatic variables, only the cultivars for which there were >100 observations from farms (15 cultivars) were selected for validation. The interaction of the yield of each cultivar and each agro-climatic variable was tested in the farm data in a similar manner to that for the trial data. Pearson's correlation coefficient was calculated to compare the trial and farm data for the yield responses to the agro-climatic variables.

Additionally, a PCA (principle component analysis) was performed for both the trial and the farm data, to compare the trial and farm results for validation. However, these results were only tentative due to the relatively low number of analyzed units relative to the requirements of a robust PCA; only 40 cultivars in the farm data were suitable for use.

6.4 Step 4: Constructing the response diversity index

A cluster analysis using Ward's method (Ward, 1963) was employed for the data created in Step 2, to cluster the cultivars according to yield responses to the agro-climatic variables. The cluster number was selected based on the dendrogram, the pseudo T2-criterion and the variation in r-square values (Yeo and Truxillo, 2005). There are several ways to carry out cluster analysis. In our first article the clustering was based on a Mahalanobis distance matrix, which uses the full multivariate information of the yield responses (McLachlan, 1999). The Mahalanobis distance gives less weight to variables with a high variance and to highly correlated variables, such that all the characteristics are treated as being equally important (Mimmack et al., 2001). In our other articles clustering was based on the principal component (PC) scores, calculated as a byproduct of PCA. In these cases, Mahalanobis distances were also examined but were found less interpretative. We recommend carrying out PCA in every case, because it provides important information about the structure behind agro-climatic variables. Statistically speaking, it identifies a simplified structure that best explains the variance on the yield responses of the cultivars to agro-climatic variables. It also offers the possibility to establish the agro-climatic variables that behave in similar ways. The first PC, i.e., agro-climatic factor, always accounts for most of the variability, and the last PC accounts for the least variability; therefore, only a few PCs are needed to gather most of the information, leaving out the noise. In principle, PCs with eigenvalues above one were retained, and usually explained 70–80% of the total variation. An orthogonal varimax rotation was used to achieve a more meaningful and interpretable solution. An oblique promax rotation was also tested, but was found unnecessary based on relatively low correlations between PCs.

Cluster analysis is not suitable for scarce data, which makes it important to manage missing data. Firstly, we excluded cultivars that were missing more than one-third of the yield responses to the agro-climatic variables in order to reduce the number of imputations, and thus improve reliability. In addition, a small number of cultivars were excluded as outliers because their score for one of the significant PCs was more than six standard deviations beyond the sample mean. Secondly, multiple imputations (MI) with 100 replicates for missing data were used to obtain the PC scores, which were further used to analyze each cultivar. A multivariate normal approach via the Markov chain Monte Carlo (MCMC) method was used for the MI. The effects of the imputations on the PCA structure were compared to PCA based on a correlation matrix without imputations and were found to be negligible. PC scores were left unstandardized to give less weight to a possible noise element and decrease the sensitivity of the clustering results to the number of PCs retained. Shannon indices were previously calculated in this step, but in our latest article about wheat, it was moved to the fifth step.

6.5 Step 5: Assessing response diversity

The annual Shannon diversity index (H), which reflects the richness and evenness of the distribution, was calculated for the cultivated area of cultivars (type diversity) and for the clusters (response diversity) in every area (country or province). In the former case, the index was calculated using each individual cultivar as a diversity unit and in latter case, each cluster was a diversity unit. The statistics on the national cultivation areas for cultivars in Finland, Denmark, Belgium, France, Germany, Czechia, and Spain, apart from Andalusia, during the period from 1991 to 2014 were utilized. In addition, the country-wise annual response diversity indices were calculated based on the relative number of cultivars in each cluster in the trials.

A Shannon index equal to zero indicates that only one cultivar or cluster was cultivated in the country in that year; the Shannon index increases as the number of cultivars or clusters and/or the evenness of the distribution of cultivated hectares increases. The Shannon index, which gives an equal weight to each observation and is comparable among cases with different compositions, was calculated according to the following equation:

$$H_i = -\sum\nolimits_{k=1}^{K} \frac{w_{ik}}{W_i} ln \frac{w_{ik}}{W_i}, i = 1, \ldots, n$$

where n refers to the number of countries, k = 1,…, K refers to the number of clusters; $\mathrm{w_{ik}}$ is the area cultivated by cluster k in country *i*; $\mathrm{W_i}$ represents the total area cultivated in country *i*; and $\mathrm{w_{ik}/w_i}$ is the proportion of area cultivated by cluster *k*. Indices were interpreted through true diversity (i.e., the effective number of cultivars or response clusters), which is the exponent of Shannon index. On this scale, a community with a true diversity three times larger than that of another community is three times as diverse as the other community (Jost, 2007).

In the barley study, we also compared the differences between the slopes, which illustrated the development of the diversity indices for response and type diversity over time. The slopes for the indices were calculated for each region using a linear regression model. The equality of the slopes within each region was tested for the indices using Student's two-tailed *t*-test. The difference of the annual means of the two indices was also tested by linear mixed model (Kahiluoto et al., 2014).

7. Retooling to enable resilience management

Resilience management has been difficult to operationalize in concrete measures, and one potential approach is characterizing means to enhance resilience in smaller, more manageable social-ecological systems (Folke et al., 2010). After publication in 2014, the case concerning the diversity of responses of barley cultivars in Finland towards varying weather factors and weather conditions, was further discussed with a group of plant breeders on the basis of the research results by Kahiluoto et al. (2014). On the basis of the dialogue with such key actors that determine the future available cultivar pool, we hoped to improve the conceptualization of our method and learn whether it could be usable in practice to enhance response diversity in barley cultivation. For resilience management in this case, we found the idea of retooling especially important, the idea that changes in practices requires the development of novel kinds of tools and artifacts, which are used as practical means of activity (Miettinen and Virkkunen, 2005).

The two main research questions of concern during the meetings with breeders were to explore possible uses and the reservations about response diversity approach, and how it could be introduced in actual processing (Paavola et al., 2015). It was hypothesized that response diversity can provide a better means of enhancing resilience than traditional scenario-based approaches or provide added value. Predicting weather conditions in the future is difficult, but it seems likely that extreme weather conditions will be more frequent, and overall variability will increase. Local changes and variations will be even more difficult to predict, and thus it will be important to prepare for a multitude of potential scenarios rather than the most likely scenario.

We have stated that diversification is one key factor in enhancing resilience, and that response diversity can bring a new perspective to the dimensions of diversity. The key idea is that a larger amount of diversity in a particular function or system itself is not necessarily a guarantee of the desired, resilience-enhancing diversity. For example, a wider pool of cultivars in use does not mean that the diversity in their responses to specific weather conditions would be secured. The cultivar pool has expanded partly because breeders are continuously forced to introduce new cultivars to the market. Those cultivars that can offer the greatest yield potential under the prevailing conditions are easily marketable to farmers, which may narrow the response diversity to weather with the cultivar pool. From breeders' point of view, resilience to weather conditions is just one desired feature of a cultivar pool, and not necessarily the main one.

The three phases determined were to define the product, key actors and data gathering process. The product in our studies was a Finnish barley cultivar, key actors were agri-food researchers and breeders, and data gathering consisted of three meetings among social scientists, researchers and breeders. In these meetings, the results of the research on the response diversity were presented to the breeders, and participants discussed whether it could be used or developed as a practical tool to enhance resilience in plant breeding, or more generally with other stakeholders in the food production chain. The results of cluster analysis, weather clusters, were found to have potential decision-making tool capabilities for the different actors involved in crop production and agri-food supply. The end-users of a tool could be, for example, a plant breeder who reflects on whether cultivars for different conditions are, or should be made, available, or a farmer who tries to optimize the selection of cultivars in use for enhanced yield security.

From the researchers' point of view, it was interesting to discuss whether practitioners found this kind of approach promising and developable further for practical use. The analyses behind the clustering were somewhat complex, making it fruitful to discuss the interpretations with the breeders, because they looked at these connections of cultivars from a totally different perspective. The interpretations were found a bit problematic, especially in certain weather factors. The results were found enlightening, and in some cases even surprising. Overall, the breeders were interested in the method, though they were hesitant about its practical usability in the current breeding process. The amount of cultivars needed for clustering was problematic to breeders, which makes the method more interesting to use, in a sense backward-looking. It seemed to provide a complementary perspective to some of their own analyses. They pointed out that they had already, at least to some extent, taken these kinds of issues into account. The long-term perspective was found to be the strongest dimension of response diversity. Even though breeders found response diversity an important goal, they have to meet the short-term cultivar requirements of their customers. This made it hard for them to be responsible for a long-term perspective. It was also agreed that ensuring response diversity is an economic issue that requires wider community support and more cooperation between different actors. Other actors also need to get involved in markets that control and restrict farmers' possibility to choose cultivars.

The case presented how plant breeders, a key food and feed system actor, determine the availability of genetic material that then determines resilience of field cropping, understood and valued the response diversity approach. Although perceived as highly interesting from the point of view of general crop resilience and in national terms, it had limited potential to empower the breeders to act proactively for resilience. This mirrors well the situation often faced by individual actors of the food system: their opportunities to act are focused primarily on their own concrete development goals, while the overall food system resilience is considered important as well. Consequently, proactive actions for resilience management may be easiest for actors when they perceive it as being tightly linked to the setting of strategic development goals. Perspectives that are too abstract or retrospective may not induce the desired action in time.

It was even clearer than expected that the interests of various stakeholders should be taken into account. The interests of commercial companies seem to differ from the long-term perspective analyzed by the response diversity. Breeders felt that public actors should take more responsibility for ensuring resilience in the long-term, although they are the ones doing the pre-breeding, and thus determining the future availability of the cultivars. Thus, this tool could be useful especially for them. The meeting between the researchers and breeders also helped to clarify the development of the tool for response diversity, and potential partners for future collaborations. In order to serve current needs and to make it usable in practical decision-making, the data has to consist of currently available cultivars, and the cultivar groups need to be identified more explicitly. The tool development process to enhance resilience and adapt farming to face climate changes requires persistence, collaboration and initiatives from all the actors involved. The next step could be an extension of this discussion with other relevant partners, like industry, seed retailers and national emergency supply agencies.

The development of response diversity of wheat appeared less alarming in countries with traditions of private–public breeding partnerships (Belgium and Finland), while in Germany, with low response diversity, private breeders have dominated for more than a century (Kahiluoto et al., 2019). The benefits from response diversity may be greatest to the weakest actors in the wheat supply chain; farmers could improve their annual yield stability, consumers will benefit from increased price stability and the public actor in charge of food security will benefit from increased knowledge. Also, policy-makers and authorities, like the European Commission, could include effective diversification through assessment and management of response diversity in its toolkit of risk management measures for use by the member states to support viable farm income and resilience to enhance food security (EC, 2018).

Food security under climate change depends on the yield performance of staple food crops.

Alarming declines and gaps in response diversity in European wheat implied the absence of the explicit perspective of resilience to intensifying climatic variability in the wheat value chain. The prioritization of the yield potential of individual cultivars under predicted average long-term climatic conditions, with a focus on harvest index and disease resistance (Lin and Huybers, 2012), may have been influenced by early climate projections that did not consider uncertainty and variability. The benefit of response diversity will most likely be even greater in the future while the climatic variability is increasing. An enhancement of response diversity through increased awareness of the significance of diversity in weather responses within the available set of potential cultivars, is therefore of primary importance for wheat production and food security.

8. Conclusions

We conclude that resilience perspective brings value-added to food chain actors by way of helping them to prepare for variations and changes that are difficult to predict. Current strategies in food value chains or breeding programs do not sufficiently prepare for the increasing uncertainty and variability. Diversification can be a useful strategy for practical management of resilience in various parts of food systems.

Empirical assessments of diversity in responses to critical changes and variations appeared to be an effective tool for actors to identify and manage the types of diversity that most enhance the resilience of their actions. Response diversity appeared to be more effective than mere diversification, i.e., crop management based on responses was more effective than genetic diversity.

When the key diversity that fosters resilience is identified, greater resilience can be achieved with less diversity. An increase in the efficiency of diversification helps to successfully combine the complementary dimensions of sustainability, i.e., resilience and efficiency.

The dependence between resource-use efficiency, or productivity, on the other hand, and production diversity on the other, appeared to be scarce or non-existent and avoidable through system management, even if the assumed trade-off relation has informed agricultural policies for decades. The operationalization of the response diversity approach and its usability in resilience management, however, requires retooling in collaborative processes among relevant private, public and civil society actors.

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