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Cultivating resilience by empirically revealing response diversity

Helena Kahiluoto [a,*], Janne Kaseva [b], Kaija Hakala [b], Sari J. Himanen [a], Lauri Jauhiainen [b], Reimund P. Rötter [a], Tapio Salo [b], Mirek Trnka [c,d]

[a] MTT Agrifood Research Finland, Plant Production Research, Lönnrotinkatu 5, FI-50100 Mikkeli, Finland
[b] MTT Agrifood Research Finland, Plant Production Research, FI-31600 Jokioinen, Finland
[c] Institute of Agrosystems and Bioclimatology, Mendel University in Brno, Zemedelska 1, 613 00 Brno, Czech Republic
[d] CzechGlobe – Global Change Research Centre AV CR, v.v.i., Bělidla 986/4a, 603 00 Brno, Czech Republic

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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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[*] Corresponding author. Tel.: +358 405118335; fax: +358 20772040.
E-mail addresses: helena.kahiluoto@mtt.fi (H. Kahiluoto), Janne.Kaseva@mtt.fi (J. Kaseva), Kaija.Hakala@mtt.fi (K. Hakala), Sari.Himanen@mtt.fi (S.J. Himanen), Lauri.Jauhiainen@mtt.fi (L. Jauhiainen), Reimund.Rotter@mtt.fi (R.P. Rötter), Tapio.Salo@mtt.fi (T. Salo), mirek_trnka@yahoo.com (M. Trnka).

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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 ≥25 °C one week before through two weeks after heading (d).

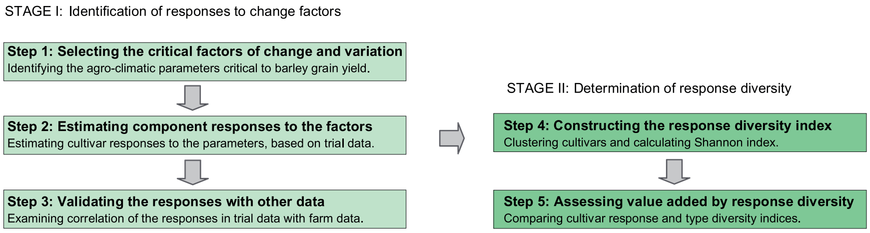

Fig. 1. The proposed approach to response diversity assessment. The steps of the generic procedure are presented in bold. The procedure that is applied to the case is specified for each step.

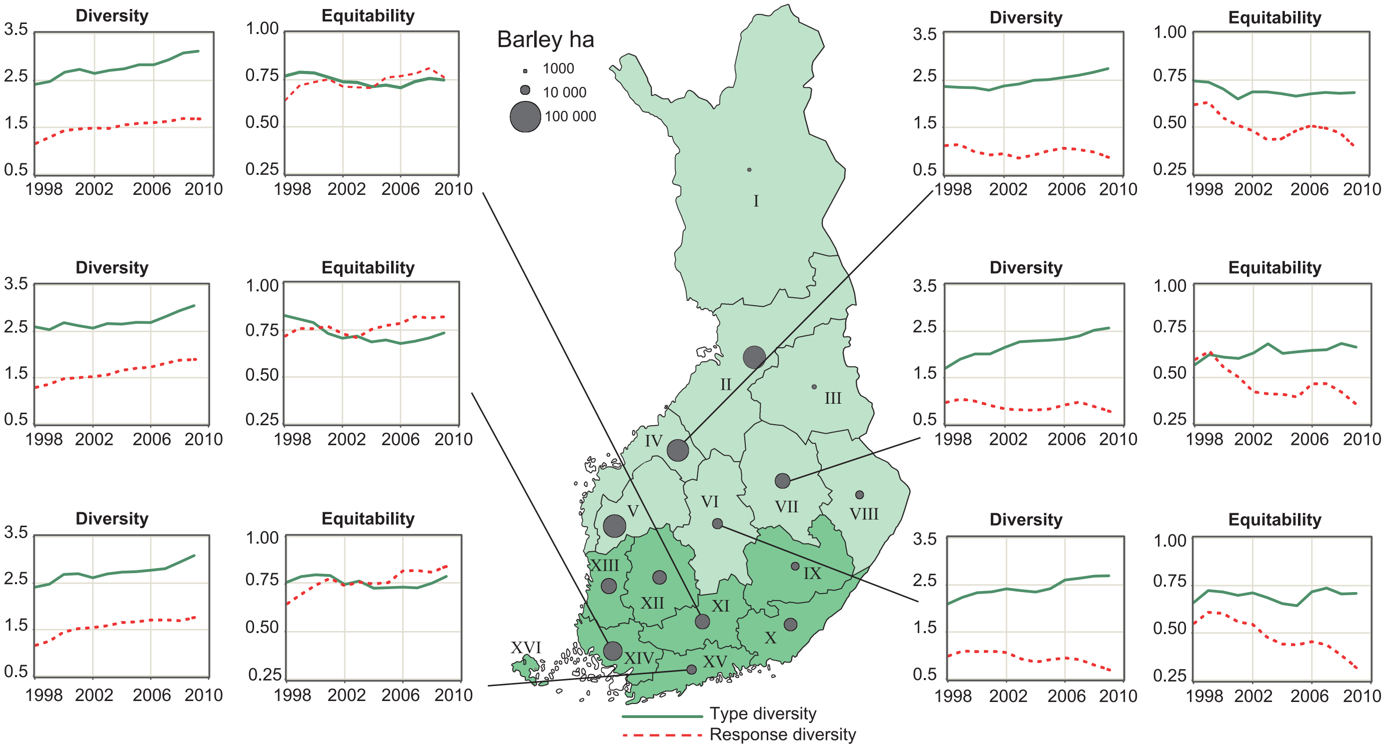

Fig. 2. Disparity between the Shannon indices and the equitabilities for the barley cultivar type diversity (continuous line) and response diversity (dashed line). Equitability represents the evenness component of the diversity indices which also include the component of richness. Equitability was calculated 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 $\geq$28 °C one week before through two weeks after heading (d).

(6) Temperature sum ($T_{\text{sum}} > 5$ °C) accumulation from 14 d before heading until heading (°C) ($T_{\text{sum}} > 5$ °C is the sum of degrees above 5 °C for all days, for which $T_{\text{mean}} > 5$ °C).

(7) $T_{\text{sum}} > 5$ °C accumulation rate from heading until yellow ripeness (°C).

(8) $T_{\text{sum}} > 5$ °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 $T_{\text{mean}} > 5$ °C).

(10) Sum of effective growing days from sowing until yellow ripeness (d) (number of days with $T_{\text{mean}} > 5$ °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 $\geq$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 $\geq$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:

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

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 $\text{cultivar} \times \text{category}_{ij}$ is the cultivar-by-environment interaction. All the above effects are fixed in the model. Experimental $\text{site} \times \text{year} \times \text{trial}(\text{category})_{klmj}$ 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 *i*th index, region_j is the average level at the *j*th level of index ($i = 1, 2$) and $\text{index} \times \text{region}_{ij}$ is the interaction of the *i*th index within the *j*th region. The index refers to both H and E_H. All the above effects are fixed in the model. $\text{Year} \times \text{region}_{kj}$ is the random effect of the *k*th year within the *j*th 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, $\alpha = 0.05$, $n = 24$.

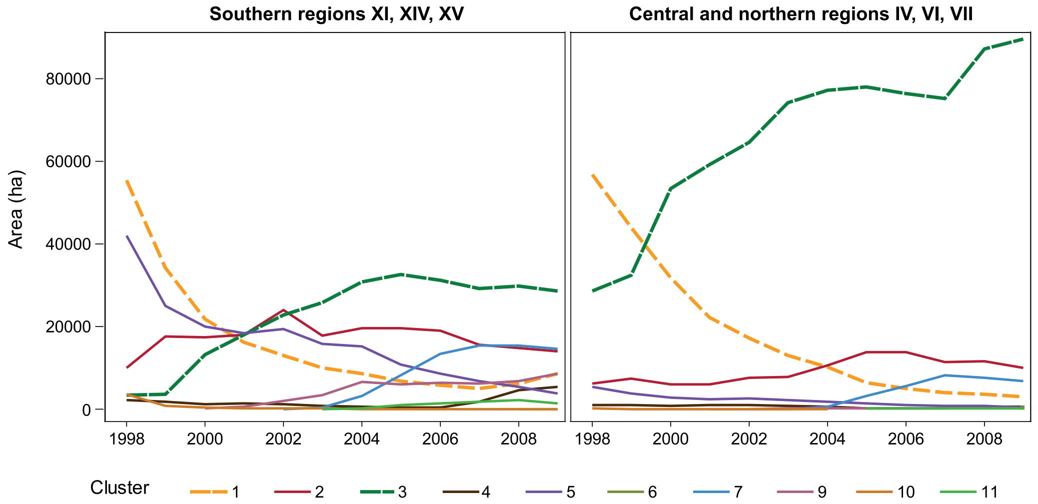

Fig. 3. Development of the cultivation area of the barley cultivar response clusters (1998–2009) in the Southern regions (left) and in the Central and Northern regions (right) of Finland. Cluster 3 represents cultivars, the grain yield of which is clearly reduced by drought and benefits from relatively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