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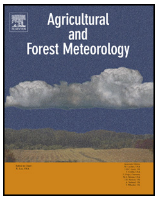

Shifts in soil–climate combination deserve attention

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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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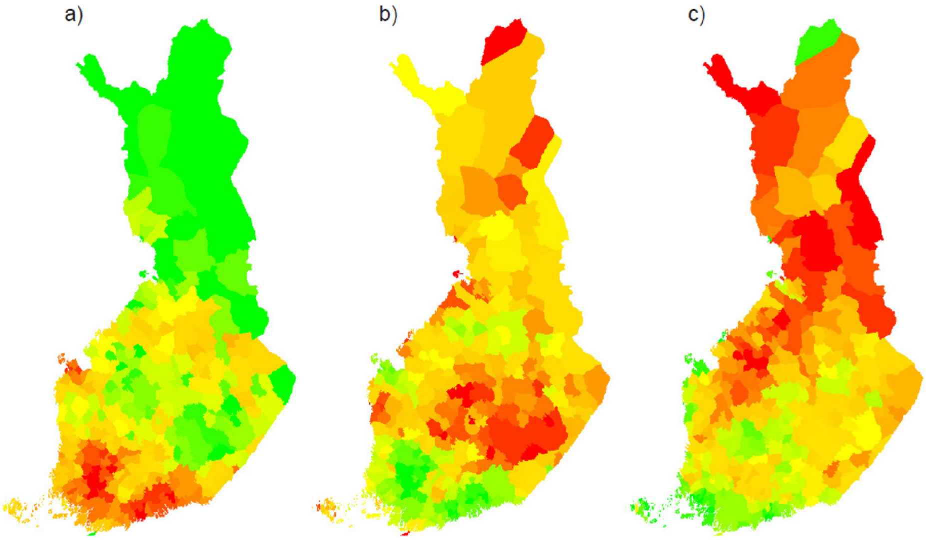

Fig. 1. The proportions of a) clay soils, b) coarse mineral soils, and c) organic soils in Finland. Red colour corresponds to high, yellow to moderate, and green to low proportions of the soil type of the cultivation area of municipalities.

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	***	***

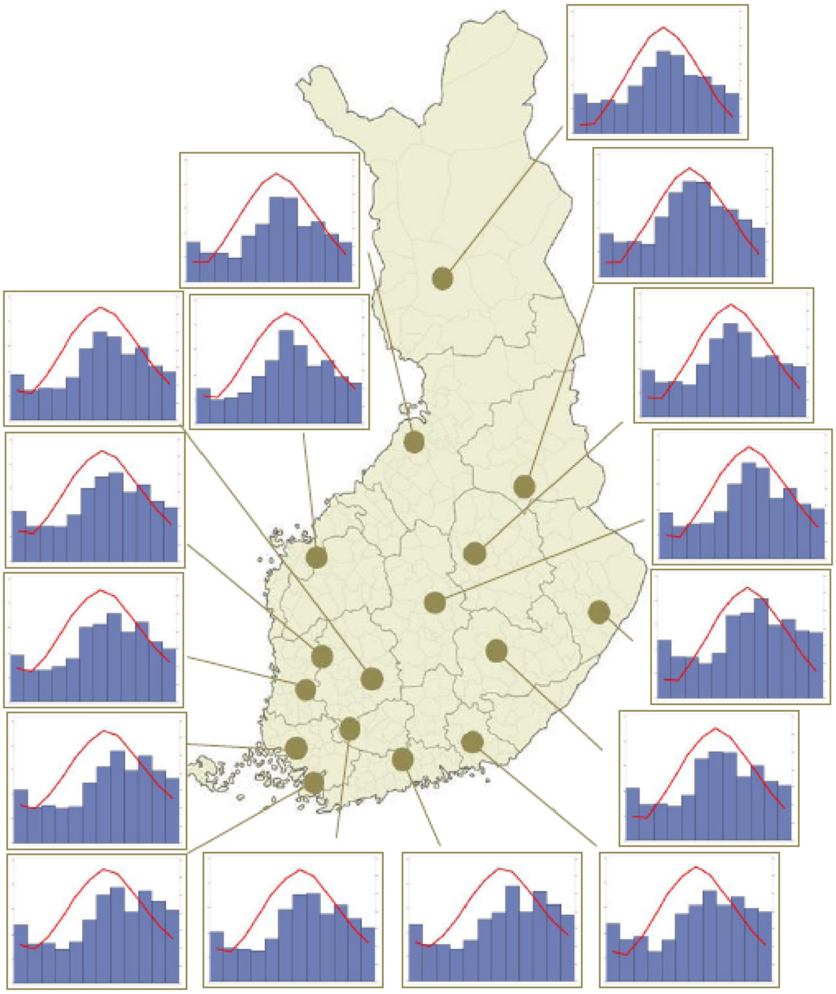

Fig. 2. The monthly averages of precipitation (mm, bars) and mean temperature (°C, line) of the 16 Finnish trial sites for forage crops over the years 1979–2012. Starting from January, Y-axis for precipitation ranges from 0 to 100 mm and for temperature −1 to +20C, respectively.

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:

$$y_{\mathrm{ijklmn}} = \mu + \mathrm{variety}_{\mathrm{i}} + \mathrm{category}_{\mathrm{j}} + \mathrm{soiltype}_{\mathrm{k}} + \mathrm{variety} \times \mathrm{category}_{\mathrm{ij}} + \mathrm{variety} \times \mathrm{soiltype}_{\mathrm{ik}} + \mathrm{category} \times \mathrm{soiltype}_{\mathrm{jk}} + \mathrm{variety} \times \mathrm{category} \times \mathrm{soiltype}_{\mathrm{ijk}} + \mathrm{experimentalsite} \times \mathrm{year} \times \mathrm{trial(category)}_{\mathrm{lmnj}} + \varepsilon_{\mathrm{ijklmn}}$$

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$_{\mathrm{ij}}$ and variety × soil type$_{\mathrm{ik}}$ are the variety-by-environment interaction. The model also includes category × soil type$_{\mathrm{jk}}$ interaction and the three-way-interaction of variety, category, and soil type. All the above effects are fixed in the model. Experimental site × year × 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

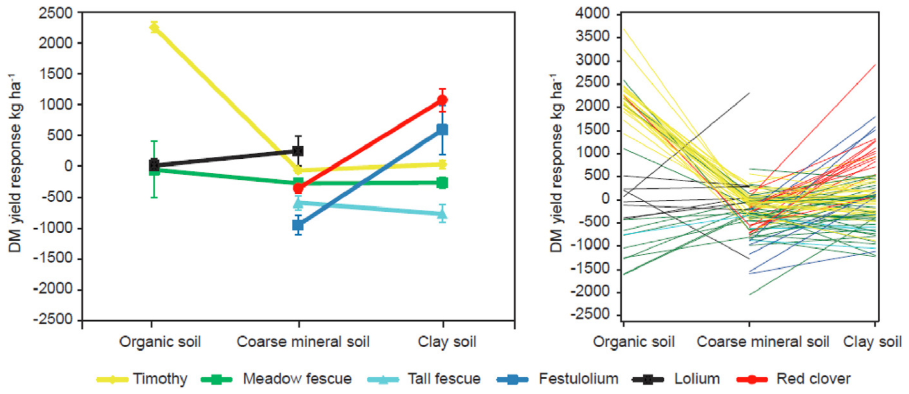

Fig. 3. The yield responses of forage crop species and cultivars separately to accumulation of precipitation from 1st cut to 2nd cut (mm) (calculated as response to high precipitation >118 mm – low precipitation <103 mm) in different soil types.

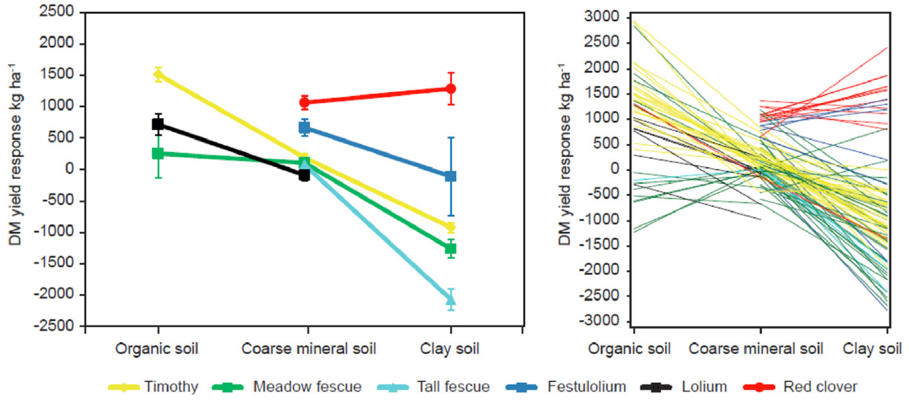

Fig. 4. The yield responses of forage crop species and cultivars separately to maximum temperature of 25 °C from 1st cut to 2nd cut (days) (calculated as response to high number of days >6 – low number of days <4) in different soil types.

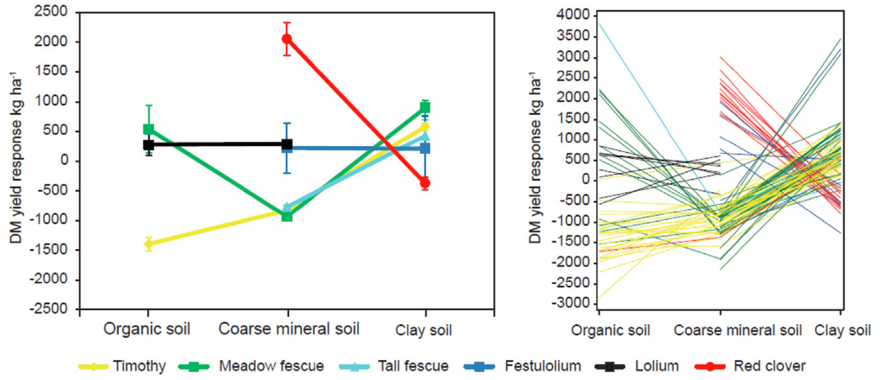

Fig. 5. The yield responses of forage crop species and cultivars separately to mean daily rainfall during fall hardening (mm) (calculated as response to high rainfall >2.1 mm – low rainfall <1.96 mm) in different soil types.

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).

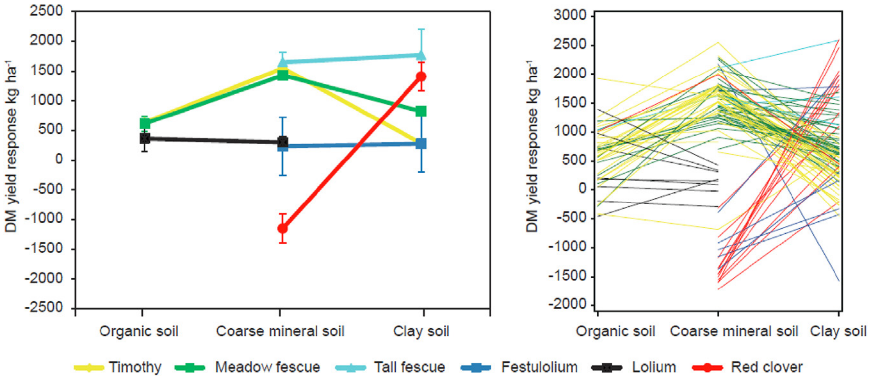

Fig. 6. The yield responses of forage crop species and cultivars separately to mean daily accumulation of temperature > 0 °C during winter (degree-days) (calculated as response to high accumulation >2.60°-days – low accumulation <0.75° -days) in different soil types.

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

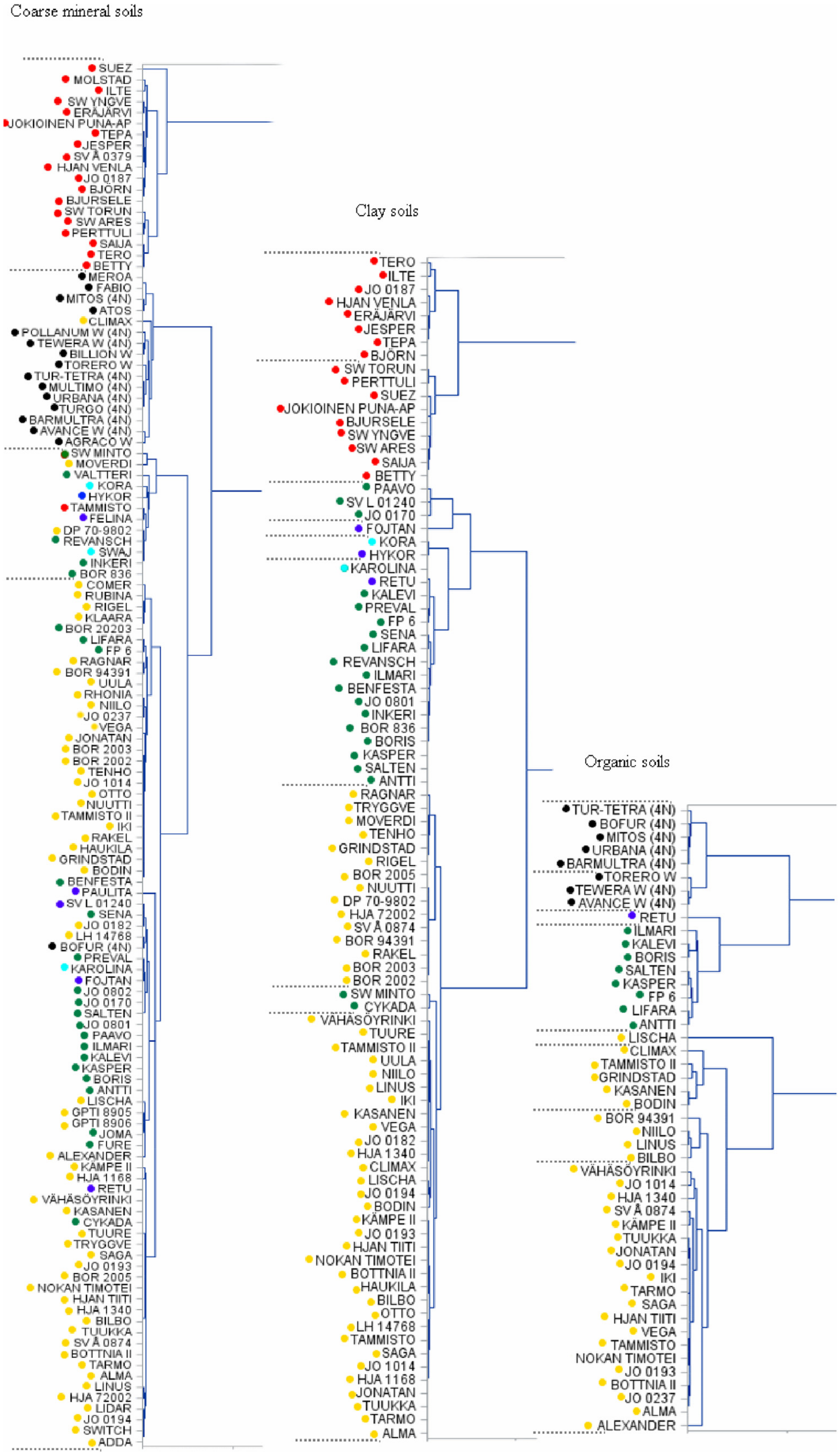

Fig. 7. Dendrograms showing the weather response clusters of different forage cultivars depending on soil type. Clusters are separated with grey lines showing four cultivar clusters in coarse mineral soils, nine in clay soils, and eight in organic soil. Different colours indicate the different species 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.

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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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