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Improved evaluation of field experiments by accounting for inherent soil variability

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ABSTRACT

Well-controlled field experiments are used to test agronomic management practices and evaluate the performance of cultivars in highly managed plots at experimental stations, in breeding nurseries or on-farm. However, the performance of crops and therefore the interpretation of experiments is affected by the inherent soil variability. To avoid large residual errors, replicate measurements or optimized designs are usually helpful but seldom adequately consider the unknown soil variability. The use of spatial covariates, such as proximally sensed data, in the statistical modelling of the target variable may provide a better estimate of such experimental residual variations (errors). Therefore, the purpose of this study was to determine whether the apparent soil electrical conductivity, topographical parameters and location information (expressed as Gauß-Krüger coordinates) could be used for an enhanced spatial and temporal characterization of the long-term and annual wheat yields within a static, long-term nitrogen fertilizer experiment that included six different forms of nitrogen and three levels of nitrogen fertilizer. Furthermore, this investigation aimed to propose statistical strategies for analysing this background variation by testing ANOVA (Analysis of variance) and ANCOVA (Analysis of covariance). ANCOVA with soil EC_a, location information and topographic parameters as covariates improved the accuracy of the yield estimates of the multi-annual means for all treatments. Without these independent variables in ANOVA, the coefficient of determination (R^2) was smaller and the root mean square difference (RMSD) was larger than those of ANCOVA (fertilized plots ANOVA: $R^2 = 0.19$, RMSD = 3.26 dt ha^{-1}; ANCOVA: $R^2 = 0.87$, RMSD = 1.29 dt ha^{-1}). In addition to the factor level of fertilization and form of nitrogen fertilizer, EC_a was the dominant covariate for the averaged long-term and annual yields. The EC_a was measured with different sensors and configurations and represented a significant independent variable. Of the topographic relief parameters, the predictor plancurvature was the dominant independent variable. The inclusion of plot-wise, time-invariant soil and relief parameters significantly improved the discrimination of testing the treatment performance within the long-term field trial. A further application of this approach to other experimental sites and breeding nurseries would likely be highly rewarding.

1. Introduction

Field experimentation is the common practice to test hypotheses in agronomy, breeding, physiology and ecology. Within agricultural field experiments, exact comparisons of treatments are the primary objective. Nevertheless, spatial site variability among different plots can negatively affect the accuracy and efficiency of such trials. To avoid bias in estimating the influence of tested variables, replications are mandatory, and optimized designs are adopted for the interpretation of results. However, even with the best design, soil variability can only be partially accounted for, even when it is considered.

Whereas large contrasts are relatively easy to detect, many research questions concern variations that are relatively small. For example, when comparing different forms of nitrogen at given levels of nitrogen or the effects of different herbicide or pesticide applications or alternatively, relatively uniform lines or cultivars, relatively small differences can prevent distinguishing among treatments or cultivars. Ultimately, soil variability, frequently unknown, affects all experimentation to some significant degree. This soil variability is of enormous relevance; for example, different forms of mineral nitrogen may cause only slight differences in plant growth and final yield (Hu et al., 2014) or cultivars tested in registration trials may differ by only a few percentages in their yields (Erdle et al., 2013). Therefore, soil variability that is not accounted for is clearly an obstacle towards improved assessments.

Intensive measurements of soil parameters are expensive, and even

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after interpolation; marked point-wise estimation errors may remain. The spatial variability of soils and yields has largely contributed to the development of site-specific farming activities, and enormous gains in information have been obtained and powerful new tools and technologies to assess the soil and crop variability at the level of the farm field have emerged (e.g., Schmidhalter et al., 2008; Adamchuk et al., 2004; Geesing et al., 2014). However, the investigation of the site-specific variability in dedicated field trials on experimental stations or in breeding nurseries has largely stagnated, and until recently, soil variability was only accounted for by optimized field trial designs. In the literature to date, relatively few reports have used the information gained from improved detection in dedicated field trials to improve the understanding of the tested factors or variables.

For that reason, soil conductivity (EC_a), topographical parameters and coordinates are increasingly used as a proxy for soil conditions. These variables are relatively easy and inexpensive to derive and produce area-wide, high-density data sets.

Kravchenko et al. (2005) used EC_a as an additional variable to increase the accuracy of estimates of phosphorus values in fields with different levels of manure application, and standard errors for the means of P concentrations without EC_a as a covariate were larger than those with EC_a. In the plots that received no manure and had higher soil EC_a readings, the concentrations of P were significantly lower.

According to Johnson et al. (2005), EC_a classification can be used as a basis for creating block plots only when EC_a and yield are correlated. At the investigated sites, the dominant factors were salinity and clay content, and the authors described the application of EC_a as a "compelling tool in statistical design".

Lawes and Bramley (2012) explored a new and simple method in the analysis of strip experiments that combined the spatial variability of treatment response. The authors applied the spatial distribution of yield data and a moving pairwise comparison of treatments. The results indicated that the pairwise comparisons adequately identified treatment differences and their significance. This method can be readily applied and also used with EC_a values and therefore, offers an important advance to establish in on-farm experimentation.

Brevik, (2012) investigated the use of EC_a readings in fields with more homogeneous soil properties and selected a field of lacustrine-derived soils with only weak spatial variability in soil properties. Although the highly uniform EC_a readings did not differentiate among soil map units, the EC_a results confirmed the uniform status of the soils in the field, thereby meeting a critical criterion for precision agriculture applications.

Tarr et al. (2003, 2005) used stratification of EC_a and terrain attributes to derive a heterogeneous pasture in relatively homogeneous sampling zones with fuzzy k-means clustering. The five zones identified had significant differences in the target variables (i.e., P, K, pH, organic matter and soil moisture).

Topography is closely related to soil development and soil types and therefore, is related to the distribution of yield. However, the precision and direction (Kravchenko et al., 2003) of this relationship differ strictly with the soil types and their positions on the landscape. On a site in Andalucía, southern Spain (Lozano-García et al., 2016), the organic carbon content was higher in the north-position than that in the other topographic aspects. The topography (primarily elevation, slope, and aspect) plays a significant role in affecting temperature and moisture regimes (Bale et al., 1998; Griffiths et al., 2009), and the differences in microclimate affect the distribution of plant communities and soil processes (Lenka et al., 2013; Bochet, 2015). Therefore, topographic aspects should be included in models (Meier and Leuschner, 2010; Ping et al., 2015; Scowcroft et al., 2008) and in estimations at local and regional scales.

The objective of this research was a comprehensive analysis of a long-term fertilizer experiment with treatments that included six different forms of N-fertilizer applied at three levels of nitrogen fertilization, which included control plots. The principal goal of this paper was to delineate yields of wheat as influenced by the nominal factors of fertilization level and fertilizer form and in a second step, by the additional metric parameters of EC_a, topographic variables and coordinates. Statistical analyses were conducted with ANOVA and ANCOVA to predict annual and multi-annual means of yields. In this paper, the evaluation of this 36-year, continuous N-fertilizer experiment is presented.

2. Materials and methods

2.1. General description, soil, and physiography of the Dürnast long-term study area

The study area is approximately 0.31 ha and is located in Freising, 30 km north of Munich, Germany (4477221.13 E, 5362908.78 N), in a hilly, Tertiary landscape. The study is a part of the long-term experiment of the Chair of Plant Nutrition from the Technical University of Munich. The average annual temperature is approximately 7.8 °C, and the average annual precipitation is 800 mm.

Tertiary sediments with secondary deposits of Pleistocene loess were the predominant soil material. The composition of the area is a consequence of Pleistocene loess deposition and subsequent erosion in the periglacial time period and Holocene erosion and deposition. According to the German Soil Survey (Bodenkundliche Kartieranleitung, 2005), fine-silty Dystric Eutrochrept and fine-loamy Typic Udifluvent are the dominant soil types.

The primary characteristics of the relief and soil parameters are listed in Table 1. The area has a slight slope in the south direction with a silt content of approximately 60%. The trend was for clay, C and N to increase from the south to the north-west of the area. The relatively high content of C and N in soil layers deeper than 25 cm is evidence of the erosive processes that formed this area.

2.2. Experimental design

The basic features (i.e., fertilizer amount and form, crop rotation, and plot size) of the N fertilizer experiment are listed in Table 2. In Table 3, the years of cultivation with wheat, the cultivars, the amount of fertilizer applied and the number of replications are presented. In Figs. 1 and 2, the layout of the experimental field is presented.

Of note, CAN (Calcium ammonium nitrate) was tested twice, and the control plots that did not receive N-fertilizer were located within the rows with low and high fertilization. In both cases, the result for each single plot was used as an independent value in the calculations.

Furthermore after 2006, the experiment was reduced to four replications, identified as a–d.

Table 1
Site description of the long-term nitrogen fertilization experiment in Dürnast.

Site description				
Elevation [m]		470 (469–472)		
Slope [rad]		0.05 (0.05–0.09)		
Aspect [rad]		2.64 (1.97–3.46)		
		0–25 cm	25–50 cm	50–75 cm
Soil texture [kg kg^{-1}]	Clay	20.8 (15.7–27.3)	23.3 (15.2–34.9)	26.2 (13.6–34.8)
	Silt	61.5 (54.4–67.5)	61.7 (35.7–72.9)	60.7 (32.8–76.8)
	Sand	16.6 (11.9–21.3)	14.4 (8.5–40.5)	12.4 (5.3–46.8)
	Skeleton	1.2 (0–3.0)	0.6 (0–7.0)	0.4 (0–3.0)
pH		6.44 (5.94–6.84)	6.36 (5.96–7.12)	6.31 (5.98–7.18)
C-content [%]		1.18 (0.94–1.38)	0.56 (0.35–1.14)	0.4 (0.22–1.11)
N-content [%]		0.1 (0.08–0.12)	0.06 (0.03–0.12)	0.04 (0.02–0.12)