JOURNAL OF PLANT NUTRITION
2018, VOL. 41, NO. 19, 2446–2469
https://doi.org/10.1080/01904167.2018.1527935

Spatial variability of selected soil properties and its impact on the grain yield of oats (*Avena sativa* L.) in small fields

Ruth-Maria Hausherr Lüder[a], Ruijun Qin[a,b], Walter Richner[a,c], Peter Stamp[a], and Christos Noulas[a,d]

[a]Department of Environmental Systems Science (D-USYS), Institute of Agricultural Sciences Swiss Federal Institute of Technology (ETH), Zürich, Switzerland; [b]Hermiston Agricultural Research & Extension Center Oregon State University, Hermiston, OR, USA; [c]Agroscope Reckenholz - Tänikon Research Station ART, Zurich, Switzerland; [d]Department of Soil Water Resources, Institute of Industrial and Forage Crops, Hellenic Agricultural Organization – "Demeter", Larissa, Greece

ABSTRACT

To investigate spatial variability in topsoil (0–20 cm) pH, available phosphorus (P), potassium (K), total nitrogen (N), and soil organic matter (SOM) of small fields (∼2 ha), and to determine the impact of soil heterogeneity on the spatial variability of crop yield two fields were cropped with spring oats and one with winter wheat under humid-temperate conditions. In the two oat fields, some of the measured soil properties (P, K) and the grain yield varied considerably, and strong spatial trends were recorded for most of the soil traits. In the third field, soil properties showed only a moderate spatial variation, and no spatial trends were found. The spatial distribution of SOM and total N in the topsoil had some influence on the spatial pattern of the oat grain yield in the field of Gränichen; however, spatial relationships between soil chemical properties and grain yield were rather weak in our study.

ARTICLE HISTORY
Received 6 March 2018
Accepted 12 April 2018

KEYWORDS
geostatistics; small fields; soil properties; spatial variability; spring oat grain yield

Introduction

There is a growing awareness of the need to manage the soil sustainably, and as a result regulatory frameworks have been developed to ensure that soil quality is maintained (e.g. European Commission 2006). Understanding spatial and temporal variability within fields is a requirement in modern agriculture because such variation is essential for site-specific crop management and the delineation of management zones (Lan et al. 2010; Basso et al. 2011; Basso et al. 2013; Bogunovic et al. 2017; Rosemary et al. 2017). In the last two decades the concept of precision farming was developed and propagated first in the USA, with farmers requiring higher returns to adopt such technologies (Schimmelpfennig and Ebel 2011; Schimmelpfennig and Ebel 2016). Precision farming is the adjustment of crop husbandry in a field in relation to measured spatial variability (Sylvester-Bradley et al. 1999; Geesing, Diacono, and Schmidhalter 2014). For the majority of crop fields, it is usual to apply agrochemicals as uniformly as possible within fields and to adjust rates from field to field. However, recently available new developments, i.e. GPS-equipped yield monitors and technological advances now allow the variable-rate application of agrochemicals within fields (Sawyer 1994; Blackmore et al. 1995; Sadler et al. 1998; Sylvester-Bradley et al. 1999; Robertson et al. 2012; Diacono, Rubino, and Montemurro 2013;

CONTACT Noulas Christos noulaschristos@gmail.com Department of Soil Water Resources, Institute of Industrial and Forage Crops, Hellenic Agricultural Organization – "Demeter", 41335, Larissa, Greece.

Basso et al. 2016). These new technologies could help to reduce the environmental impacts of intensive agriculture, while retaining, or even improving, current levels of productivity (Blackmore et al. 1995; Basso et al. 2016). The variable-rate application of fertilizer within fields has the potential to improve nutrient use efficiency and field profitability and to decrease water pollution (Sawyer 1994; Basso et al. 2013; Diacono, Rubino, and Montemurro 2013; Tagarakis and Ketterings 2018; Muschietti-Piana et al. 2018). As Bone et al (2010) observe, the assessment of soil quality is challenging, potentially costly and prone to uncertainty because of the variability of soil material. It is therefore important that sampling schemes for soil assessment are carefully designed. Wibawa et al (1993) found that variability in soil contents of nitrate, phosphorus (P) and potassium (K) occurred over short distances in cereal fields. They reported that variable-rate fertilizer application based on such variation increased yield. For P and K a finer sampling resolution than one sample per hectare is required, while for OM and clay coarser resolutions of one sample every two and three hectares, respectively, may be acceptable (Nanni et al. 2011). The high spatial variability of soil P, K, and pH justify the variable application of P and K fertilizers as well as lime as indicated by Weisz et al. (2003) and by Robertson, Lyle, and Bowden (2008). In a two-year study, yield monitor data indicated that the variable-rate treatment resulted in significantly higher grain yields than the uniform application of nitrogen (N) and P (Yang, Everitt, and Bradford 2001). However, the higher yields did not cover the additional costs of variable-rate treatment in all the fields. Studies in Europe (Van Meirvenne and Hofman 1989; Bahri and Berndtsson 1996; Dampney et al. 1997; Usowicz and Lipiec 2017) and in the USA (Mohanty and Kanwar 1994; Cahn, Hummel, and Brouer 1994; Mzuku et al. 2005) all indicated that soil N supply is spatially variable, whether measured as nitrate or indirectly through the mineralizable soil organic matter (SOM). In the UK, results of the detailed sampling of soil mineral N also indicate that soil N supply is spatially dependent (Dampney et al. 1997). Maps of soil P and K confirmed that the levels of these nutrients in the soil varied spatially within fields, and that the patterns of spatial variability for P were different than those of K (Wollenhaupt, Wolkowski, and Clayton 1994). When there is a large heterogeneity of soil pH within a field, variation in the soil pH can be mapped and used as a basis for variable-rate lime application (Sylvester-Bradley et al. 1999; Goulding 2016). Most of the above-mentioned studies considered field sizes of 16 to 80 ha. Mulla and Hammond (1988) sampled soils using a grid with intervals of 30, 61, and 122 m and concluded that the latter resolution was too coarse for soil test maps in precision farming. Franzen and Peck (1995) found 30-m grids to be the maximum spacing for the accurate application of fertilizer in precision farming. Similarly, Hergert et al (1995) concluded that grids of 61 to 91 m were the maximum for conditions in Nebraska. In Brazil, the sampling grids that are commonly adopted have dimensions ranging from 100 to 225 m or in other regions at somewhat smaller distances, from 100 to 175 m (Nanni et al. 2011). Each of these studies concluded that a finer resolution is needed to characterize spatial variation for precision farming than that the current resolution. However, there are still uncertainties with regard to the ideal size which would allow capture of the spatial variability of the chemical soil properties. The determination of such dimensions for the grids is primarily based on economic and practical reasons and sometimes neglects the geostatistical principles of spatial dependence (Webster and Oliver 2007).

A reliable field map of any soil property can be produced only when the density of sampling points is sufficient to allow interpolation between the known points using geostatistical techniques (Webster and Oliver 1992; Wollenhaupt, Wolkowski, and Reetz 1993; Heuvelink, Brus, and de Gruijter 2006; Sylvester-Bradley et al. 1999; Li et al. 2007). Deriving variograms for fewer than 50 data points is generally not recommended (Webster, Oliver, and Webster 1990; Wollenhaupt, Wolkowski, and Clayton 1994).

In parts of central Europe and in Switzerland the average field size is much smaller. Hence, investigations of spatial variation in soil and crop parameters must be done on a smaller scale in these regions to account for small fields and to provide enough data points for geostatistical analysis. There is very little literature about soil and crop variation within small fields. Tsegaye and Hill (1998) examined the spatial variability of soil chemical properties, plant growth and nutrient uptake in a 0.17-ha rye field. The field was sampled along four transects at 1-m intervals. Biomass exhibited strong positional similarities with soil NO_3-N and pH. On the other hand, spatial correlations between plant tissue and soil nutrient contents were not observed (Tsegaye and Hill 1998). Chancellor and Goronca (1994) collected field data for soil moisture, N and weeds at 1-m intervals in a 1.68-ha irrigated field of winter wheat. Simulated advantages in terms of N use efficiency were obtained with spatially variable applications of N, mainly at low (0–100 kg N ha^{-1}) and intermediate (100–150 kg N ha^{-1}) rates of application (Chancellor and Goronca 1994). To study the spatial variability of soil properties and wheat yield, Bhatti et al (1999) sampled the topsoil (0–15 cm) at a regular grid spacing of 50×15 m in a 1.87-ha field. They concluded that the variation in the potential crop productivity could be used to divide the field into two different management zones. Funk and Maidl (1997) investigated the growth and N uptake of winter wheat in fractions of several arable fields (1.9–6.5 ha) in upper Bavaria. Their results suggest a classifying of the fractions into three groups of different N fertilization need. In Brazil, two fields of 1-ha each were cultivated with crop sequences which included corn, soybean, cotton, oats, black oats, wheat, rye, rice, and green manure. Soil fertility, soil physical properties and crop yield were measured in a 10-m grid. The results showed that the factors affecting the variability of crop yield varied from one crop to another. The changes in yield from one year to another suggested that the causes of variability may change with time (Vieira and Gonzalez 2003). The spatial variability patterns of wheat growth parameters and soil properties, e.g. nitrate, available phosphate, pH, and soil surface hardness, were investigated on a 0.25 ha field in Tokyo, Japan. It is concluded that modification of fertilizer application based on the trend data may improve the efficiency of fertilizer use while small scale site-specific management based on the residual data may be practically difficult (Nakamoto et al. 2002). In Ontario, in 23 fields ranging in even bigger size (from 8.5 to 30 ha) soils were sampled from the top 15 cm on a 30-m grid for soil test P, K and pH. It was concluded that a grid spacing of 30 m or less would be required to adequately assess the spatial variation of these soil properties (Lauzon et al. 2005). The average field size in central European and in developing countries (small-holder systems) is much smaller than typical field sizes in North America, Australia or Argentina. Hence, soil sampling patterns at higher spatial resolution are needed to record natural and man-made soil variability within small fields. To date only a few studies have investigated the spatial variability of soil and plant parameters within fields at small scales (<20 m). In agricultural soils studies for spatial variability have been conducted either under diverse temperate conditions in UK (Blackmore et al. 1999), Belgium (Geypens et al. 1999; Hupet and Vanclooster 2002), Denmark (Heisel, Ersbøll, and Andreasen 1999), The Netherlands (Verhagen 1997), Germany (Domsch and Wendroth 1997), Poland (Usowicz and Lipiec 2017), at Iowa, USA (Cambardella and Karlen 1999), under semiarid Mediterranean conditions (López-Granados et al. 2002; Ryan et al. 2012) or in humid subtropical climates (Vieira and Gonzalez 2003). Information for spatial variability of soil chemical properties in small fields typical in certain European regions is meager. In our study we tested the small-scale variation in soil chemical properties at three sites and in the grain yield of oats at two of these sites; the soil types and soil genesis (geology) were similar but the cropping history different at the three sites. The objectives were: (i) to examine the spatial heterogeneity of soil chemical properties and the yield of untilled oat crops in small fields typical of the Swiss midlands, (ii) to evaluate the positional dependency of soil properties and crop yield, and (iii) to investigate the potential of variable-rate applications of fertilizer and lime in small arable fields.

Materials and methods

Experimental sites

The study was conducted at three sites in the Swiss midlands: in 1995 in Zollikofen (47° 00′ N, 7° 28′ E; 555 m above sea level) and in Gränichen (47° 21′ N, 8° 06′ E; 410 m above sea level) and in 1996 in Schafisheim (47° 23′ N, 8° 09′ E; 429 m above sea level). All three sites belong to the Swiss molasse basin (Von Moos 1942). In Gränichen and in Schafisheim the soil was classified as *Orthic Luvisol* (FAO 1988) with loamy (L, 27% clay, 39% silt, 34% sand) or sandy-loam (SL, 15% clay, 35% silt, 50% sand) soil texture (Bouyoucos hydrometer method; Gee and Bauder 1986) respectively and in Zollikofen the soil type was *Gleyic Cambisol* (FAO 1988) with a loamy-silt texture (LSi, 14% clay, 51% silt, 35% sand). The soils of the three fields were sufficient or rich in organic matter content (SOM > 2.7%). According to the Swiss Meteorological Institute in Zurich average annual mean temperature and average annual precipitation for the last 20 years before the experiments were 7.8, 8.7, and 9.2 °C and 1,024, 1,075, and 1,047 mm in Gränichen, Zollikofen, and Schafisheim respectively.

Cropping practices and field history

The cropping history of the fields at the three sites was different. The field in Gränichen was under permanent grassland (intensive *Lolium perenne* L. meadow), in Zollikofen arable crops, including temporary grass-clover leys, were grown and in Schafisheim arable crops were cultivated continuously.

The fields also differed in former fertilization practices. In Gränichen mineral fertilizers were used and sewage sludge was additionally applied at regular intervals, in Zollikofen mineral fertilizers and some pig slurry were applied, and in Schafisheim a combination of mineral fertilizer and cattle slurry was applied.

In Gränichen and Zollikofen spring oats (cultivar; 'Ebene', seeding rate: 180 kg ha^{-1}) were sown in the first week of April in 1995 without prior tillage using a no-till planter with a single-disk opener (John Deere 'NT 750 A', Deere and Co., Moline IL, USA). In Schafisheim, winter wheat (cultivar: 'Arina', seeding rate: 188 kg ha^{-1}) was sown in mid-October in 1995 after chisel-plowing to a depth of 15 cm using a conventional planter with double-disk openers (Nodet Planter II, Kuhn, Montereau, France). One week before sowing spring oats in Zollikofen and Gränichen, 1,080 g a.i. ha^{-1} of glyphosate (Roundup®, Monsanto) and 10 kg ha^{-1} of ammonium sulfate were sprayed on the fields to eliminate weeds. The spring oats were not fertilized. In Schafisheim weed control was done according to local recommendations and the wheat crop received 170 kg N ha^{-1}.

Soil sampling and laboratory analyses

The fields were rectangular at all three sites: 189 × 114 m (2.1 ha) in Gränichen, 157 × 141 m (2.2 ha) in Zollikofen and 181 × 126 m (2.3 ha) in Schafisheim. The three selected fields in Gränichen, Zollikofen, and Schafisheim were sampled in regular grids of 12 × 13, 12 × 15.6, and 12 × 14 m, respectively. Within one week after harvesting the oat crops ten 20-cm deep soil cores ("Pũrckhauer" auger, diameter 5 cm; Eijkelkamp, Giesbeek, the Netherlands) were randomly collected at each sampling location within a radius of 20 cm. The soil cores were mixed thoroughly to obtain a representative soil sample for each grid point. Reference points at the field boundaries were used to establish X and Y coordinates to determine the sampling locations. In total, 140 soil samples were collected in Zollikofen and Schafisheim, and 147 in Gränichen.

All the soil samples were analyzed for soil pH (H_2O), total N, SOM, plant-available P and K. Total N was determined with an auto-analyser ("LECO CHN-1000" autoanalyser, LECO Corporation, St. Joseph, MI, USA). The SOM content was determined according to Nelson and Sommers (1982). Soil pH was measured in a 1:2.5 suspension of soil and distilled water using a pH meter (Hanna HI 1295 Piccolo plus electrode, Mettler Toledo 320-S pH meter; Mettler Toledo AG, Schwerzenbach, Switzerland). P and K were extracted with CO_2-saturated water (Dirks and Scheffer 1930). From the extract available K was determined using a flame emission photometer (ELEX 6361, Eppendorf AG, Hamburg, Germany). The ammonium molybdate blue-ascorbic acid colorimetric method (Murphy and Riley 1962) was used to determine available P from the CO_2-saturated water extract. The absorbance was measured at 730 nm with a spectrophotometer (Uvikon 810; Kontron, Zurich, Switzerland).

Yield measurement

The spring oat crop was hand-harvested on 4th of August in 1995 in Gränichen and on 16th of August in 1995 in Zollikofen. The oat plants were cut at ground level on 1 m^2 surrounding the sampling locations, using the same grid spacing as for the soil samples. Oat samples were weighed and threshed immediately after harvest at the field border with a small experimental thresher. Grains and an aliquot of straw were dried for at least 72 h at 65° C to determine dry weight.

Statistical procedures

Statistical analysis of the data was performed in four steps: (i) frequency distributions were examined and normality tests were conducted using the procedure of Shapiro-Wilk (Royston 1992). Non-normal data were log-transformed to stabilize the variance, and the normality tests were recalculated using the transformed data; (ii) descriptive statistics were computed to obtain the mean, standard deviation (SD), coefficient of variation (CV) and ranges (=differences between maximum and minimum values) for the selected soil chemical and crop properties; (iii) the theory of regionalized variables was used to investigate spatial variability of selected soil and plant properties (Matheron 1971); (iv) simple and multiple linear regression analyses were used to investigate the relationships between soil chemical properties and oat grain yield (SYSTAT for Windows (version 10) 2000).

The SYSTAT for Windows (version 10) software was used for the calculation of frequency distributions, normality tests, descriptive statistics, and regression analyses. Geostatistical and surface mapping software (Surfer for Windows, Version 7; Golden Software Colorado, USA, Inc., 1999) was used to analyze the spatial structure of the data, to define the semivariograms, to estimate values of points on grid spacing by point kriging and to create contour maps of the kriged estimates. The techniques for kriging and creating variograms are described by Isaaks and Srivastava (1989), Webster, Oliver, and Webster (1990), Webster and Oliver (1992), and Cressie (1991).

If semivariogram and polynomial trend surface analysis revealed a trend in the data, then the data was detrended and the semivariogram was computed for the resulting residuals (Kitanidis 1997). If the stationarity assumption was now satisfied, we performed kriging on the detrended data (Goovaerts 1997; Wu et al. 2002). Semivariance was calculated for non transformed data to make the semivariogram parameters comparable among the three fields. Anisotropic behavior was exhibited by some of the variables, for which anisotropic semivariograms were computed. Anisotropy means that semi-variograms have different ranges of influence or sill parameters in different directions (Cressie 1993; Wang et al. 2002). The range of influence (m) for anisotropic models is given in y (across the rows) and in x direction (along the rows, i.e. in the management direction). There was no anisotropy evident in the directional

Table 1. Summarized descriptive statistics of selected soil properties in the topsoil (0–20 cm) and oat grain yield (grid sampling; n = 140).

		Variables					
Statistic	Site	SOM[a] (%)	Total N (%)	pH (H_2O)	Soil P[b]	Soil K[b]	Grain yield (g m^{-2})
Mean	Gränichen	5.4	0.50	7.4	0.66	0.6	450
	Zollikofen	2.7	0.27	6.1	0.98	3.4	412
	Schafisheim	3.3	0.22	6.2	2.98	9.9	–
Median	Gränichen	5.5	0.48	7.4	0.55	0.5	466
	Zollikofen	2.6	0.28	6.0	0.92	3.2	405
	Schafisheim	3.3	0.22	6.3	2.98	9.5	–
Range	Gränichen	2.4–7.6	0.30–0.69	6.1–7.9	0.16–2.14	0.4–1.4	57–710
	Zollikofen	2.2–4.3	0.17–0.41	5.4–7.3	0.39–2.17	1.7–7.1	108–702
	Schafisheim	2.4–4.3	0.12–0.30	5.5–6.8	1.38–4.89	4.9–16.2	–
SD[c]	Gränichen	1.3	0.10	0.2	0.4	0.2	112
	Zollikofen	0.4	0.04	0.4	0.4	1.0	128
	Schafisheim	0.4	0.03	0.3	0.6	2.2	–
CV[d] (%)	Gränichen	24	19	3	54	28	25
	Zollikofen	14	16	7	37	30	31
	Schafisheim	12	13	4	22	22	–
Skewness	Gränichen	−0.3	0.1	−2.3	1.0	2.6	−0.5
	Zollikofen	1.9	−0.4	1.0	0.7	1.1	0.1
	Schafisheim	0.3	−0.5	−0.8	0.2	0.6	–
Kurtosis	Gränichen	−0.9	−1.0	11.3	1.1	8.9	0.4
	Zollikofen	4.4	0.2	0.2	0.0	1.5	−0.7
	Schafisheim	−0.2	1.2	−0.1	0.2	0.3	–
S-W[e]	Gränichen	0.96***	0.97**	0.82***	0.90***	0.76***	0.98*
	Schafisheim	0.99 ns	0.98*	0.91***	0.99 ns	0.97**	–

[a]SOM = Soil organic matter (%).
[b]Soil-test P, and soil-test K expressed as P_2O_5 and K_2O respectively (mg 100 g^{-1} soil).
[c]SD = Standard deviation.
[d]CV = Coefficient of variation (%).
[e]S-W statistic = Shapiro-Wilk statistic. Significance indicates that the null hypothesis of a normal distribution is rejected.
*,**,***Significant at the 0.05, 0.01 and 0.001 probability levels respectively, ns = not significant.

semivariograms for some of the soil properties. In these cases, isotropic models for the semivariograms were fitted using nonlinear least-squares regression analysis. The semivariance at a lag distance $h = 0$ is called the nugget variance (C_0) (Webster 1985). It represents field and experimental variability or random variability that is not detectable on the scale of sampling. The C_0 expressed as a percentage of the total semivariance (sill variance, $C_0 + C$) was used to define distinct classes of spatial dependence for the soil and plant variables. If the ratio was less than or equal to 25%, then the variable was considered to be strongly spatially dependent (S), if the ratio was between 25 and 75%, the variable was considered to be moderately spatially dependent (M) and if the ratio was greater than 75%, the variable was considered to be weakly spatially dependent (W) (Cambardella et al. 1994).

Results

Descriptive statistics of selected soil properties and oat grain yield

The distribution of the majority of soil parameters, measured in the three fields, was highly skewed or kurtotic and thus, non-normally distributed (Table 1). Only in Schafisheim were SOM and soil-test P normally distributed; the distribution of total N was close to normal. The distribution of grain yield in Zollikofen was normal and in Gränichen almost normal. The underlying reasons for the normal and non-normal distribution of some of these variables at different sites are unknown. Log transformations normalized some of the parameters and generally reduced skewness, but the Shapiro-Wilk test indicated that many variables were still non-normal, even after log transformation (data not shown).

The mean and median were used as primary estimations of the central tendency, and SD, CV and ranges were used to estimate variability (Table 1). Despite the skewed distributions, the mean and median values of most parameters were similar, with the medians being usually smaller than the means. This indicates that the measures of the main tendency were not dominated by the outliers in the distributions.

The soil properties were variable to different extents. Soil-test P and K had the highest CV and pH (H_2O) the smallest CV in all three sites (Table 1). The CVs of SOM and total N were quite high in Gränichen but lower in Zollikofen and in Schafisheim. The CV of most soil properties was highest in Gränichen. Oat grain yield, recorded only at two sites, varied considerably within fields.

Soil pH (H_2O) was slightly acidic to slightly alkaline in Gränichen and acidic to neutral in Zollikofen and Schafisheim. All three fields varied between sufficient and increased level of SOM. Soil-test P fluctuated from moderate to reserve levels in Gränichen and from sufficient to reserve levels in Zollikofen. The entire field in Schafisheim exhibited a reserve of soil-test P. Soil-test K was poor to moderate in Gränichen and from moderate to reserve levels in Zollikofen. The field in Schafisheim had soil-test K values equivalent to reserve levels (Table 1).

Geostatistical analysis of soil properties and oat grain yield

Figures 1–3 show the omnidirectional semivariograms as points and the fitted models as solid lines for all the selected variables. Table 2 presents the semivariogram model parameters: model type, C_0, sill variance ($C_0 + C$), nugget ratio (%), range of influence (a) (m) and spatial class of dependency. Spherical and linear models were fitted for most of the variables measured at all three sites. The spatial dependency of the remainder of the soil variables were defined by exponential, quadratic or Gaussian semivariogram models (Table 2).

The variograms of most of the selected variables of the fields in Zollikofen and Schafisheim reached an upper bound, i.e. a sill. Such variograms suggest that variation of the properties is patchy, resulting in areas with low values and others with higher values. The average extent of these areas is given by the range of spatial correlation (a) of the variogram: from 35 m for the isotropic model of total N in Zollikofen to 120 m for the y direction of an anisotropic model of SOM and total N in Schafisheim. In contrast to the traits in Schafisheim and most of the variables in Zollikofen, the variograms of the soil-test P and pH (H_2O) in Zollikofen and of all the traits in Gränichen, with the exception of soil pH, did not reach a sill. Hence, no ranges of spatial dependence (a) are indicated for these variables. However, these variables expressed significant ($p < .001$) and more or less strong spatial trends as detected by a surface analysis of the polynomial trend. For total N, SOM and grain yield in Gränichen the variation was unbounded and anisotropic (Table 2). These three traits showed a strong linear trend in the y direction (Figures 1 and 4). The trends explained 55% of the spatial variation in total N, 52% of the variation in SOM, and 36% of the variation in grain yield (Table 2). The residuals of these parameters are spatially correlated and show an anisotropic variation with a moderate spatial dependency (data not shown). Soil-test P in Gränichen and soil-test P and pH in Zollikofen displayed strong quadratic trends (Table 2 and Figures 4 and 5), and their residuals also showed a moderate spatial dependency (data not shown). The residuals of pH and soil-test P in Zollikofen revealed an isotropic variation with short ranges (a) of 40 m and 35 m, respectively (data not shown). A cubic trend explained 70% of the variation in soil-test K within the field in Gränichen (Table 2 and Figure 4). The residuals of soil-test K reached a sill at 100 m and were moderately spatially dependent (Nugget ratio: 53%) (data not shown).

The nugget ratios revealed that all the measured parameters in Gränichen were strongly spatially dependent, while pH and grain yield were moderately dependent (Table 2). In Schafisheim and Zollikofen, all the selected variables exhibited moderate spatial dependency, except for soil

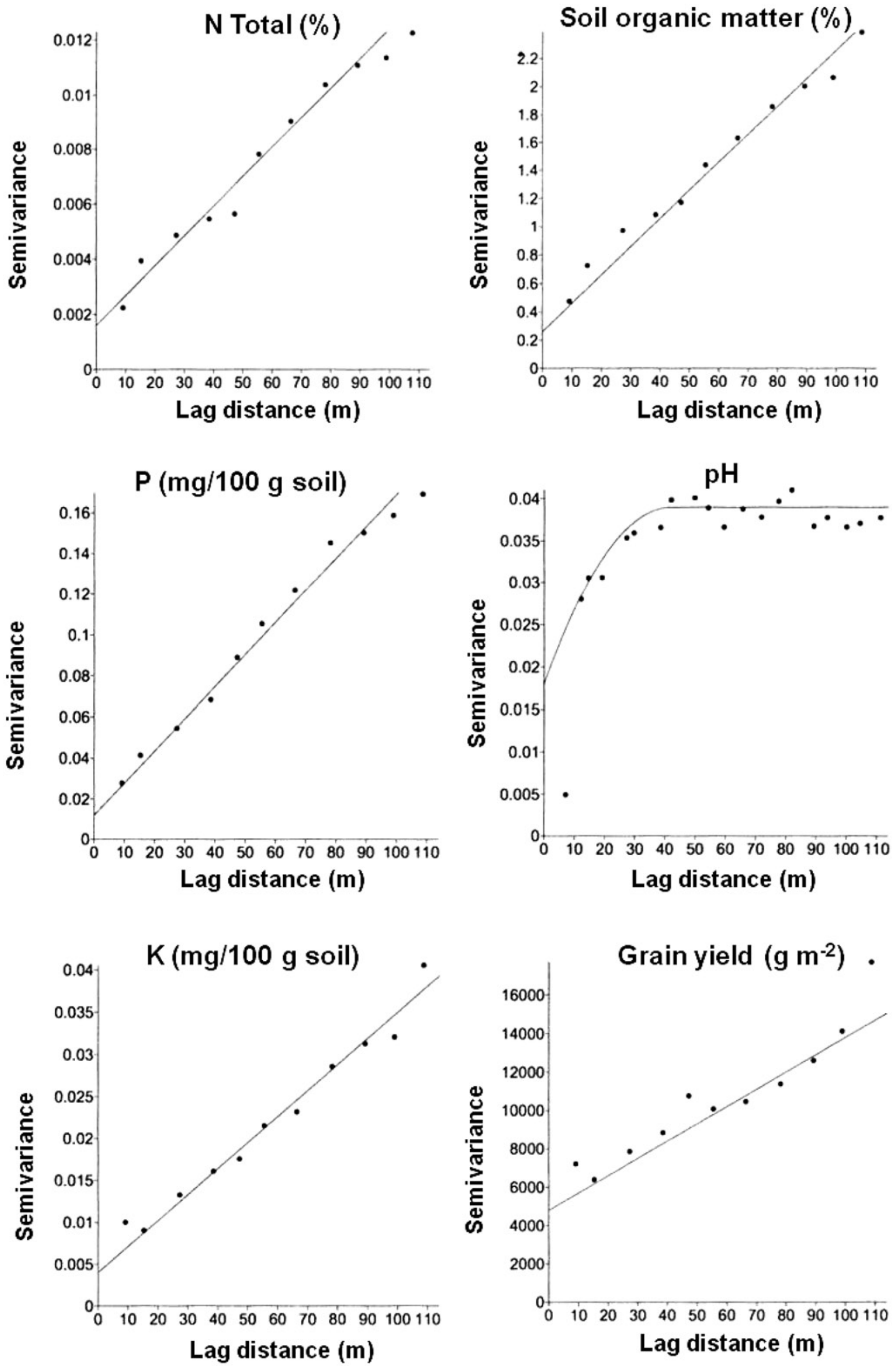

Figure 1. Omnidirectional semivariograms of selected soil properties and oat grain yield (g m^{-2}) in Gränichen. P = Soil-test P, expressed as P_2O_5, K = Soil-test K, expressed as K_2O.

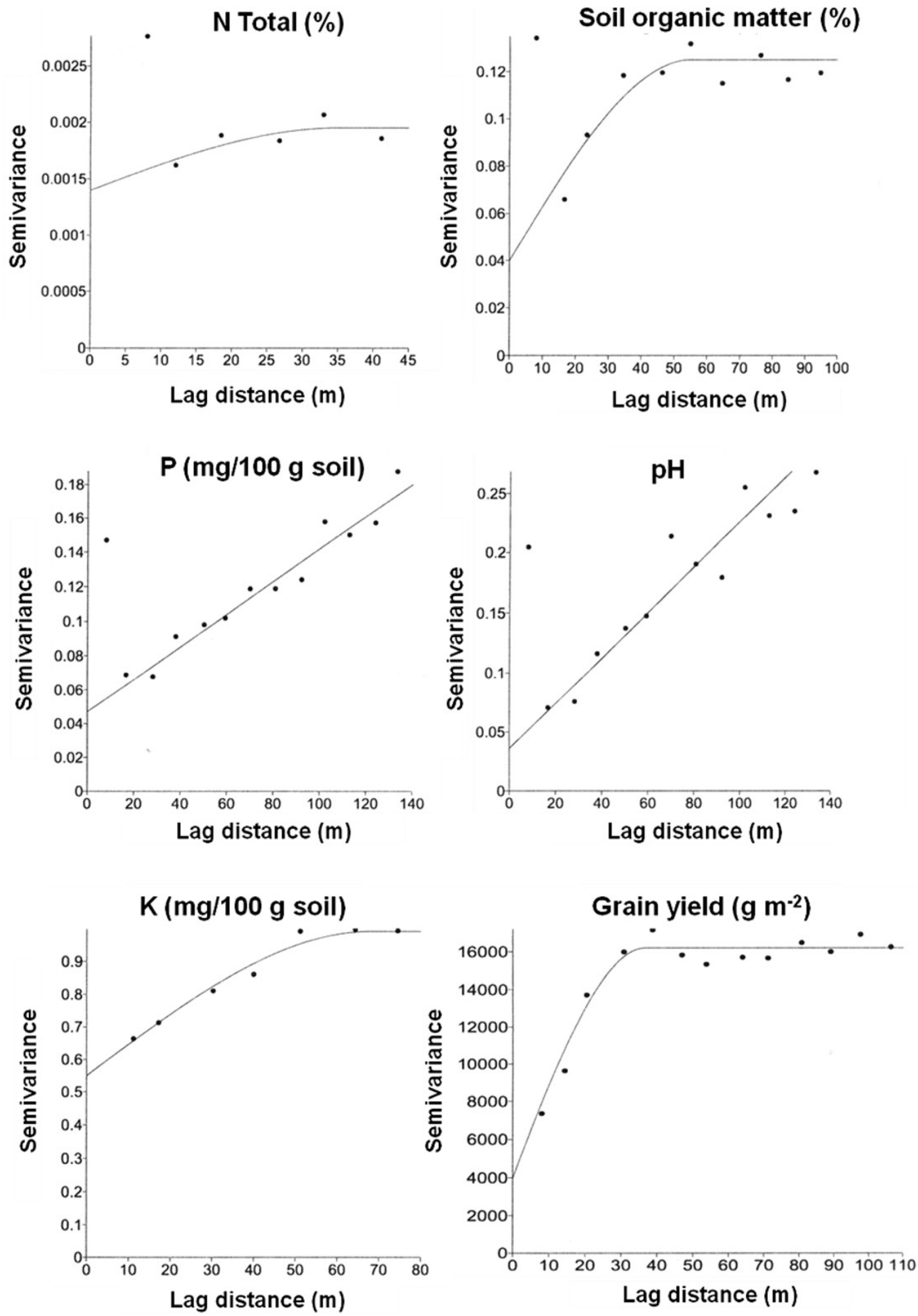

Figure 2. Omnidirectional semivariograms of selected soil properties and oat grain yield (g m^{-2}) in Zollikofen. P = Soil-test P, expressed as P_2O_5, K = Soil-test K, expressed as K_2O.

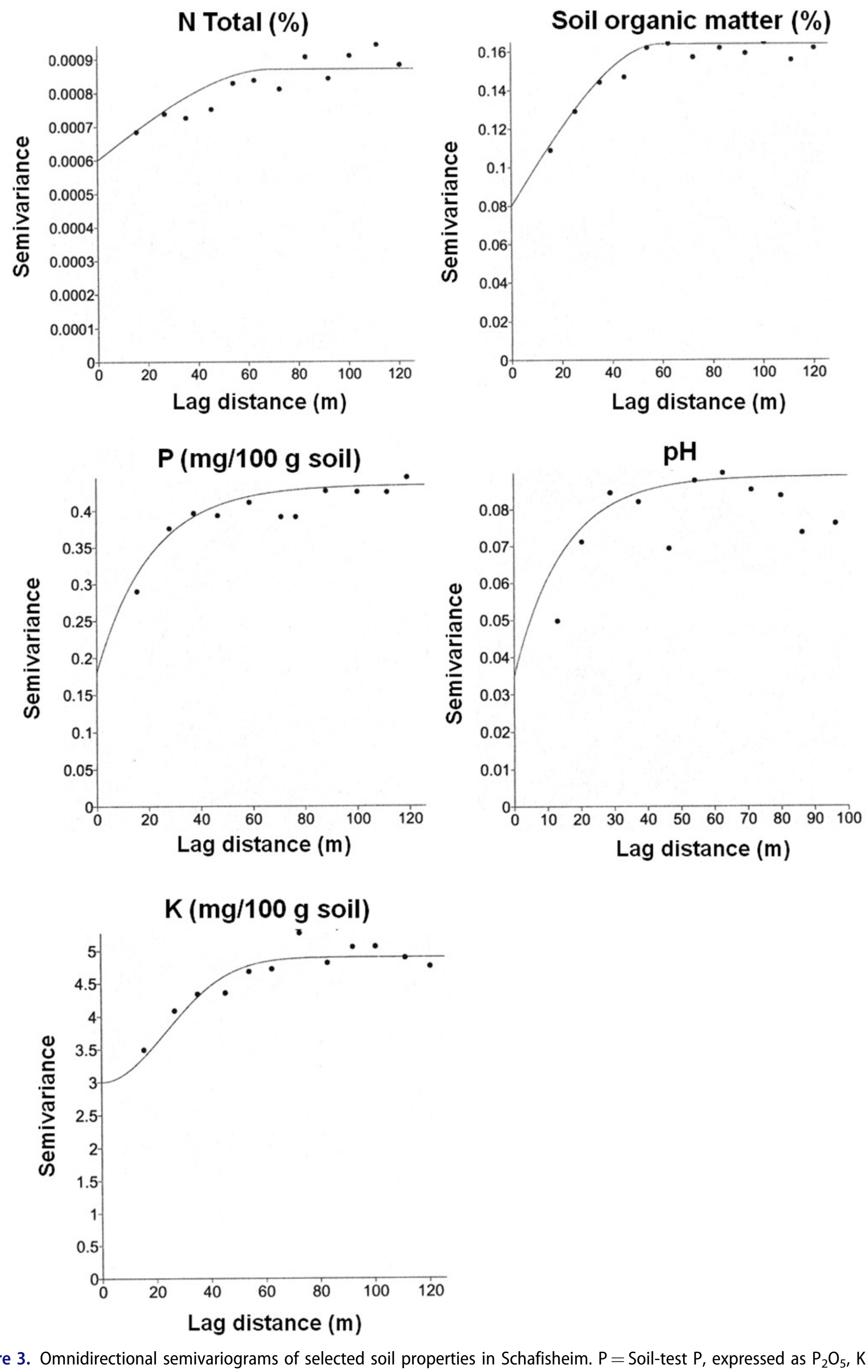

Figure 3. Omnidirectional semivariograms of selected soil properties in Schafisheim. P = Soil-test P, expressed as P_2O_5, K = Soil-test K, expressed as K_2O.

Table 2. Semivariogram parameters of soil properties and oat grain yield for non-detrended data sets (grid sampling; n = 140). The range of influence (m) for anisotropic models is given in y (across the rows) and in x direction (along the rows, i.e. in the management direction).

Parameter	Site	Variables SOM[a] (%)	Total N (%)	pH (H_2O)	Soil P[b]	Soil K[b]	Grain yield (g m^{-2})
Surface trend[c]	Gränichen	linear ($R^2 = 0.52$)	linear ($R^2 = 0.55$)	no	quadratic ($R^2 = 0.60$)	cubic ($R^2 = 0.70$)	linear ($R^2 = 0.36$)
	Zollikofen	no	no	quadratic ($R^2 = 0.68$)	quadratic ($R^2 = 0.41$)	no	no
	Schafisheim	no	no	no	no	no	–
Model (without detrending)	Gränichen	linear, anisotropic	linear, anisotropic	quadratic, isotropic	linear, isotropic	linear, isotropic	linear, anisotropic
	Zollikofen	spherical, isotropic	spherical, isotropic	linear, isotropic	linear, isotropic	spherical, isotropic	spherical, anisotropic
	Schafisheim	spherical, anisotropic	spherical, anisotropic	exponential, isotropic	exponential, isotropic	Guassian, isotropic	–
		SOM[a] (%)	Total N (%)	pH (H_2O)	Soil P[b]	Soil K[b]	Grain yield (g m^{-2})
Nugget variance (C_0)	Gränichen	0.26	0.0016	0.018	0.012	0.004	4,800
	Zollikofen	0.04	0.0014	0.036	0.047	0.550	4,000
	Schafisheim	0.08	0.0006	0.035	0.180	3.0	–
Sill variance ($C_0 + C$)	Gränichen	>2.2	>0.012	0.039	>0.16	>0.03	>16,000
	Zollikofen	0.125	0.00195	>0.25	>0.18	0.99	16,200
	Schafisheim	0.164	0.00087	0.089	0.435	4.9	–
Nugget[d] (%)	Gränichen	<12	<13	46	<8	<13	<30
	Zollikofen	32	72	<14	<26	56	25
	Schafisheim	49	69	39	41	61	–
Range of influence (a) (m)	Gränichen	>114y, 57x	>114y, 38x	42	>114	>114	>114y, 57x
	Zollikofen	55	35	40	35	68	110x, 36y
	Schafisheim	60x, 120y	60x, 120y	60	63	100	–
Spatial class[e]	Gränichen	S	S	M	S	S	M
	Zollikofen	M	close to W	S	close to S	M	close to S
	Schafisheim	M	close to W	M	M	M	–

[a]SOM = Soil organic matter (%).
[b]Soil-test P, and soil-test K expressed as P_2O_5 and K_2O respectively (mg 100 g^{-1} soil).
[c]All surface trends were significant at 0.001 probability level.
[d]Nugget ratio (%) = (nugget variance/sill variance) × 100.
[e]Spatial class (Cambardella et al.1994): S = strong spatial dependency (% Nugget <25); M = moderate spatial dependency (% Nugget between 25 and 75); W = weak spatial dependency (% Nugget >75).

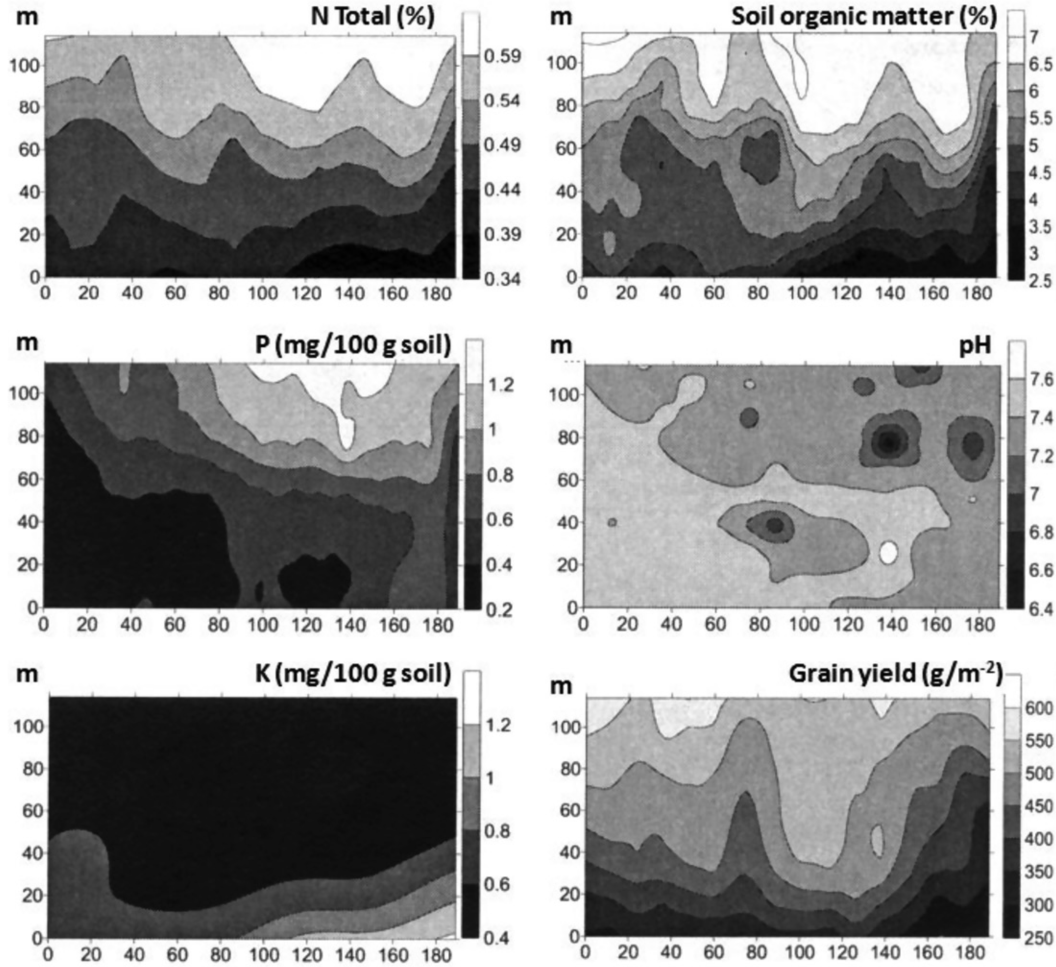

Figure 4. Spatial patterns of kriged estimates of selected soil parameters and oat grain yield in yield (g m^{-2}) in Gränichen. In x and y direction distance is in meters (m). P = Soil-test P, expressed as P_2O_5, K = Soil-test K, expressed as K_2O.

pH in Zollikofen, which was strongly spatially dependent. The kriged estimates of all the variables were contoured so that the patterns of variation could be compared visually (Figures 4–6).

Relationship among soil properties and between soil properties and oat grain yield

To allow for a quantitative evaluation of these relationships, the adjusted squared multiple coefficients of determination (R^2) of a simple linear regression analysis were computed.

In Zollikofen the pattern of variation in soil-test P was weakly correlated with that of grain yield ($R^2 = 0.13$) (Table 3). The spatial variation in soil-test K in Gränichen showed a weak inverse relationship with grain yield ($R^2 = 0.17$) (Table 3 and Figure 4). The patterns of variation in SOM and in total N in Gränichen were similar to grain yield variability and were weakly and positively correlated with it ($R^2 = 0.24$ and 0.21, respectively) (Table 3 and Figure 4). The pattern of variation in SOM showed a relatively good match with that of total N in all sites (Figures 4–6 and Table 3), but the relationship was close only in Gränichen ($R^2 = 0.74$).

The map of SOM in Gränichen indicated a similar pattern in variation to that of soil-test P and an inverse relation with soil-test K (Figure 4). Soil pH was correlated with soil-test P in all

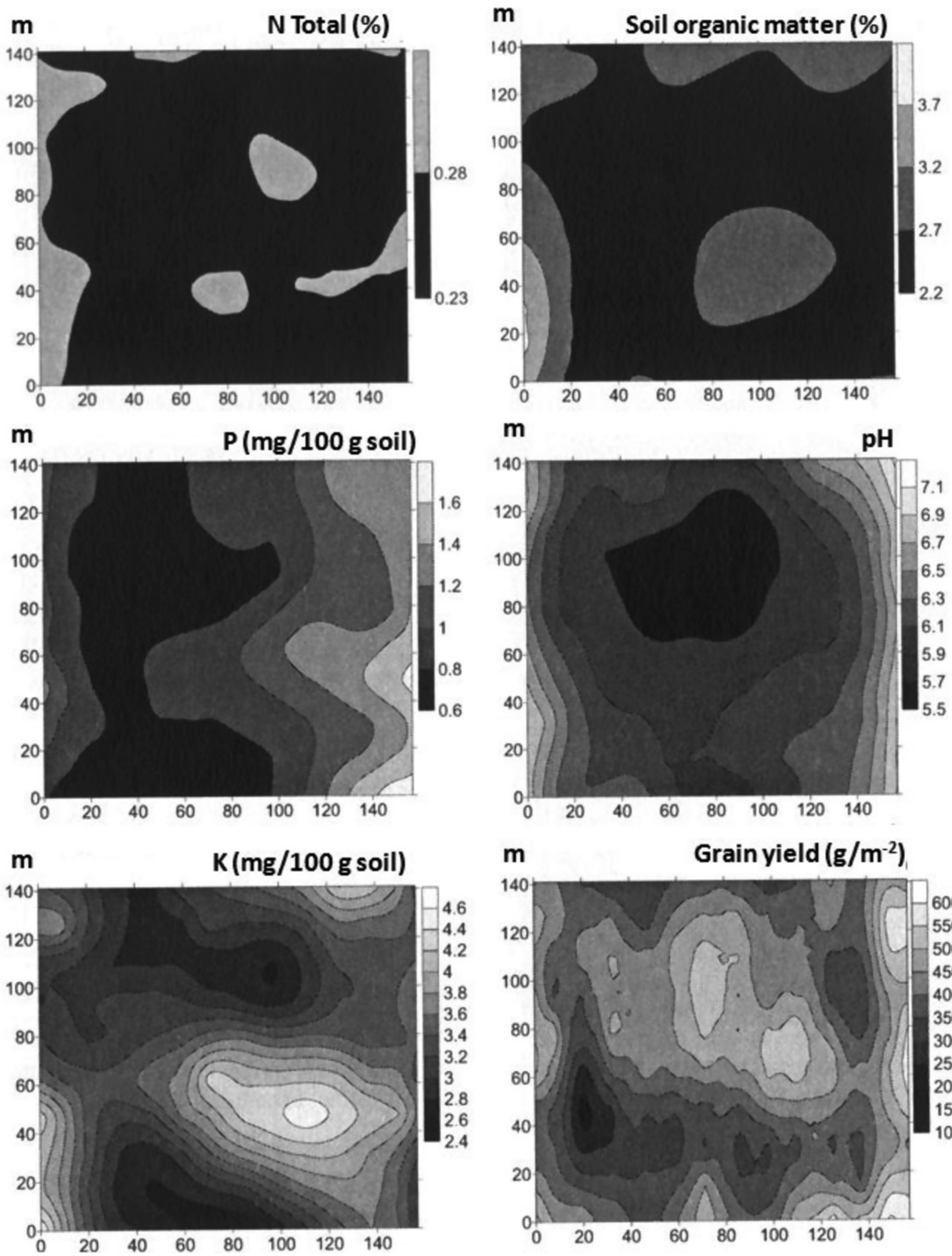

Figure 5. Spatial patterns of kriged estimates of selected soil parameters and oat grain yield in yield (g m^{-2}) in Zollikofen. In x and y direction distance is in meters (m). P = Soil-test P, expressed as P_2O_5, K = Soil-test K, expressed as K_2O.

three sites but to a different extent (Table 3). Soil pH revealed a negative spatial relationship to soil-test P in Gränichen ($R^2 = 0.48$) (Figure 4). In Zollikofen and Schafisheim soil pH was positively but weakly correlated with soil-test P ($R^2 = 0.23$ and $R^2 = 0.12$, respectively) (Table 3 and Figures 5 and 6). A stepwise multiple linear regression analysis indicated that the impact of the measured soil properties on grain yield was small. In Gränichen and in Zollikofen, the

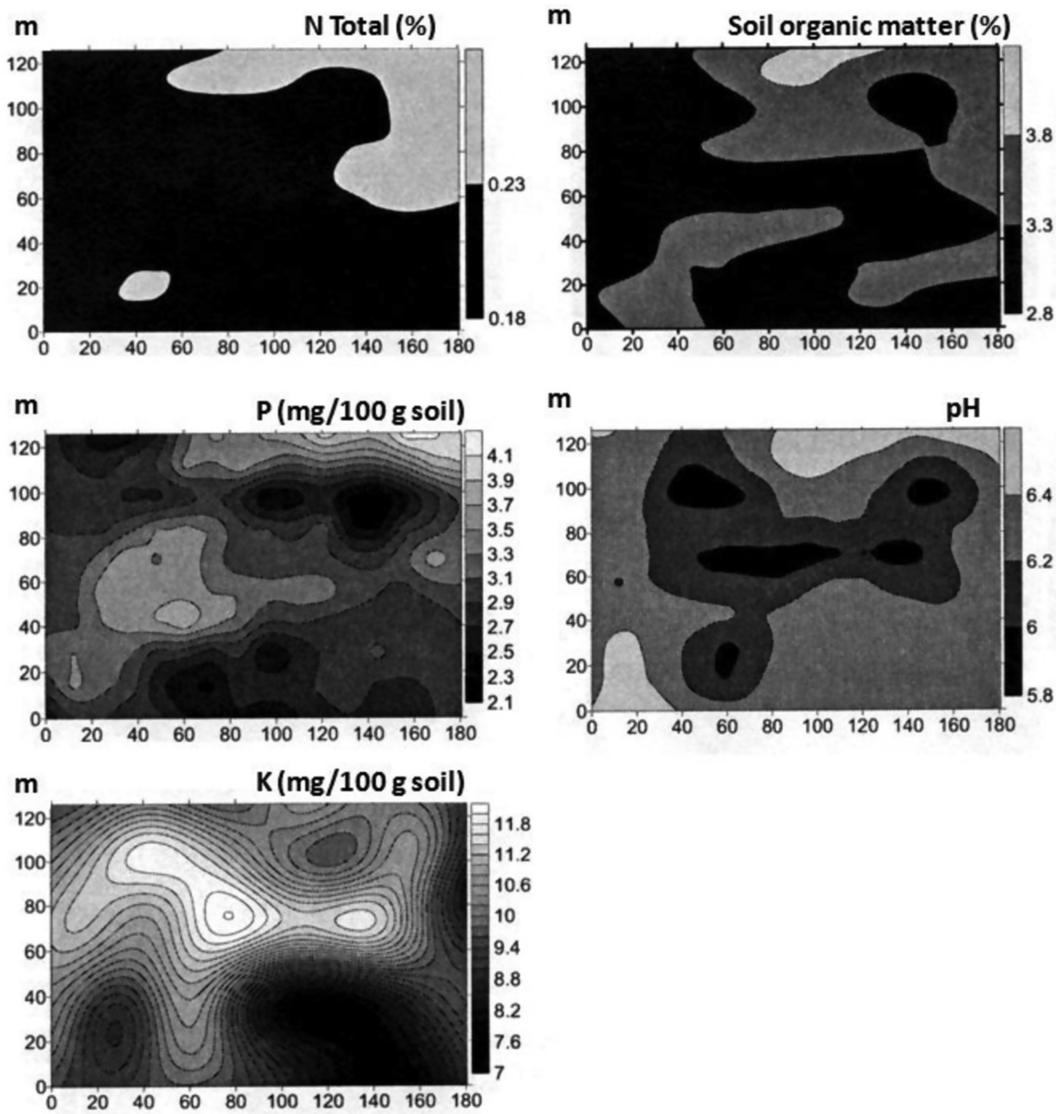

Figure 6. Spatial patterns of kriged estimates of selected soil parameters in Schafisheim. In x and y direction distance is in meters (m). P = Soil-test P, expressed as P_2O_5, K = Soil-test K, expressed as K_2O.

variation in soil chemical properties explained only 28 and 11% of the variability in grain yield, respectively.

Discussion

Descriptive statistics of soil properties

In our study most of the measured soil properties were not normally distributed (Table 1). Even after a natural log transformation, the distribution of most of the analyzed soil traits exhibited a significant departure from a normal distribution; however, the transformation did reduce the skewness of the original distributions considerably. This was to be expected as the distributions of many soil parameters, including nitrate-N, are usually not normally distributed but are log-normally distributed (Reuss, Soltanpour, and Ludwick 1977; Parkin and Robinson 1992; Starr,

Table 3. Adjusted coefficients of determination (R^2) of the linear relationships between soil properties and soil organic matter (SOM), pH (H_2O) and oat grain yield in the experimental sites (grid sampling; n = 140).

	Sites		
Soil properties	Gränichen	Zollikofen	Schafisheim
		SOM	
Total N (%)	0.74***	0.20***	0.33***
Soil P (P_2O_5)	0.43***	0.07**	0.29***
Soil K (K_2O)	0.38***	0.23***	0.00 ns
pH (H_2O)	0.18***	0.24***	0.27***
		pH (H_2O)	
Soil P (P_2O_5)	0.48***	0.23***	0.12***
		Grain yield	
Total N (%)	0.21***	0.01 ns	
Soil P (P_2O_5)	0.07**	0.13***	
Soil K (K_2O)	0.17***	0.00 ns	
pH (H_2O)	0.01 ns	0.02 ns	
SOM	0.24***	0.00 ns	

,*Significant at the 0.01 and 0.001 probability levels, respectively, ns = not significant.

Meisinger, and Parkin 1992; Sharmasarkar et al. 1999; Limpert and Stahel 2011). For example, Hergert et al (1995) tested soil nitrate values of 61 sites for normality; at 17 sites the distribution was neither normal nor log-normal. Plant available P, plant available K, soil pH and SOM content did not follow normal distribution in the study by Bogunovic et al (2014) on a sandy loam soil in central Croatia. The variation and non-normal distribution of the soil properties may also be due to adoption of different soil and crop management practices (Srinivasarao et al. 2014; Behera et al. 2016).

The magnitude and extent of spatial variability of soil properties within our tested fields in a single season was, in some cases, comparatively high (Tables 1 and 2 and Figures 4–6)but was generally lower than that found by other researchers. Most researchers found the highest coefficients of variation (CV) for soil P, soil K and soil nitrate-N (between 20 and 84%), moderate CVs for SOM and total N (between 12 and 46.5%) and lower CVs for soil pH (between 3 and 14.7%) (Cahn, Hummel, and Brouer 1994; Cambardella et al. 1994; Wollenhaupt, Wolkowski, and Clayton 1994; Pierce, Wamcke, and Everett 1995; Timlin et al. 1998; Cambardella and Karlen 1999; Nordmeyer and Dunker 1999; Frogbrook et al. 2002; Shukla et al. 2016; Bogunovic et al. 2017; Gozdowski et al. 2017; Usowicz and Lipiec 2017).

The range of pH among the three sites was probably strongly influenced by the fertilization history. The field in Gränichen, which had been fertilized with sewage sludge, exhibited the highest mean soil pH and SOM (Table 1 and Figure 4). The long-term application of sewage sludge increases soil pH and SOM (Gisi et al. 1990; Cambardella and Karlen 1999; García-Gil et al. 2004). Application of sewage sludge has effect on different soil properties in a direction that is consistent with improving soil fertility including, increase in organic carbon, N, P, and other plant nutrients (Mondal et al. 2015; Herzel et al. 2016; Rigby et al. 2016). However, other researches indicated that sludge addition has also produced undesirable changes, such as decreases in pH, increases in salinity and heavy metal contents (Navas, Bermúdez, and Machín 1998; Veeresh et al. 2003; Singh and Agrawal 2008). Fertilizers containing urea or NH_4 cause a decrease in pH (Gisi et al. 1990); at Zollikofen and Schafisheim some of the areas with a low pH were probably due to the heterogeneous distribution of liquid manure from pigs and cattle, respectively (Figures 5 and 6) as was similarly reported in other studies (Uprety et al. 2009; Vašák et al. 2015).

Geostatistical analysis

The fields at Gränichen and Zollikofen, and to a lesser extent at Schafisheim, showed a large spatial variation in soil-test P and soil-test K (Table 1). Large spatial variations in soil P

(CV = 94.3%), and K (CV =50.6%) were also found by Reza et al (2017) in 85 alluvial soil samples representative of the plow layer (0–25 cm depth). In two long-term experiments in Germany variations of soil test P occurred at both sites, a finding which could not be explained by P budgets and might be reasoned with vertical P transport (Zicker et al. 2018). They concluded that different responses of crops to P supply and the temporal variations in soil test P should be considered more in P fertilizer recommendations. A large spatial variability in soil P and K was found too in three farm fields in glacial soils of Michigan; however, recommendations for P and K fertilizer per ha did not differ for uniform management versus site-specific management, but the distribution of fertilizers within the field varied considerably (Pierce, Wamcke, and Everett 1995). Momtaz et al. (2017) found also high available P variability and suggested that in order to reduce environmental risks, the method of applying P fertilizer needs to be mainly based on created P sorption index distribution map. To develop an improved management strategy for variable-rate applications of P fertilizer, the spatial variation in P-fixation capacity should also be taken into account (Juang, Liou, and Lee 2002). In their study, Juang, Liou, and Lee (2002) found that the index of the availability of P fertilizer in the soil (Sharpley et al. 1984; Jones, Sharpley, and Williams 1984) is closely related to the oxalate-extractable Fe and Al in soils (Juang, Liou, and Lee 2002). The deviation of a uniform P application, based on the mean P value, from the ideal P application was used to determine the potential of a site-specific application of P (Schmidt, Taylor, and Milliken 2002). This approach will help to avoid the expense of high-density soil sampling.

The apparent trend in the map of P in Zollikofen was probably the result of the heterogeneous distribution of pig slurry in the past (Figure 5). Effects of the application technique of fertilizers on the spatial variation in soil nutrient contents are described in literature. Fu, Tunney, and Zhang (2010) found high soil P concentrations at the areas surrounding the main grassland farm and close to the traffic route, due to high applications of cattle and pig slurry and therefore, no more P fertilizer or slurry was needed in order to avoid economic loss and environmental pollution. According to Mallarino (1996) small-scale cyclic patterns of soil P and soil K over a distance of about one meter, as occurs in some fields, probably resulted from repeated applications of banded fertilizer. Large-scale cyclic trends over distances of 15 to 18 m or a multiple of this distance were probably the result of broadcast fertilization with commercial bulk spreaders.

In our study, the pattern of variation in soil pH differed among the locations (Figures 4–6). In Gränichen (Figure 4) there was a slight trend: pH decreased from the lower left corner to the upper right comer of the field. In Schafisheim the map indicates a patchy distribution with some acidic patches in the middle of the field (Figure 6). The strong trend in the field in Zollikofen (Figure 5) probably resulted from a variation in soil type. Some gleyed positions corresponded with the most acidic positions. Soil pH had a strong spatial dependency only in Zollikofen (Table 2). When strong spatial dependence of pH, P or K exists, there are reasonable prospects of creating site-specific zones of fertilizer management (Pierce, Wamcke, and Everett 1995). The level and structure of such variability may suggest the suitability of creating site specific management zones, with the aim of increasing both crop production and environmental protection (Godwin and Miller 2003; Mzuku et al. 2005). A number of researchers have inferred that soil pH and lime requirements are poorly correlated (Pionke, Corey, and Schulte 1968; Aitken, Moody, and McKinley 1990; Rossel, McBratney, and Stafford 1999). Although pH is used as an indicator of whether or not a soil should be limed, measurements of soil pH and the requirement for lime depend on different soil properties (Wang et al. 2015). Soil pH measures the activity of hydrogen ions in the soil, while requirement for lime depends on the buffering capacity of the soil, its pH and the amount of exchangeable aluminum (Goulding 2016).

The mean level and the spatial variability of SOM content were larger in the field at Gränichen than in those at the other two sites. Its increased SOM content resulted from the long-standing grassland during the last two decades prior the experiments (Table 1). Soil organic carbon content increased by 28% in the topsoil after the conversion of an arable field to grassland for two decades (Van Meirvenne et al. 1996).The highest spatial variation in SOM and total N was detected in Gränichen (Figure 4) in the field that had been fertilized with sewage sludge. Small-scale variation in this field was probably due to heterogeneous application of sewage sludge perpendicular to the traffic direction. Repeated application of sewage sludge in soils leads to an increase in soil fertility but may induce heterogeneity not found initially in the soil (Mondal et al. 2015; Herzel et al. 2016; Rigby et al. 2016); the variability of soil organic C and N was higher in a sewage sludge-amended plot than in a mineral-fertilized plot (Bahri and Berndtsson 1996).

Relationship among soil properties and between soil properties and oat grain yield

Since P is relatively immobile in the soil, it accumulates through adsorption to soil and organic matter particles. In the fields at Gränichen and Schafisheim soil P and SOM content were spatially correlated (Table 3). The congruent trends of soil P, SOM and total N in the field at Gränichen (Figure 4) were probably due to numerous former floodings of a brook that flows along one side of the field. In studies by Schepers, Schlemmer, and Ferguson (2000) and Cahn, Hummel, and Brouer (1994) the available P maps show many similarities with the maps of distribution of SOM.

Soil pH affects the availability of plant nutrients such as N and P (Nordmeyer and Dunker 1999; Bongiovanni and Lowenberg-DeBoer 2000). In Gränichen, the pH was negatively correlated with soil-test P, whereas in Zollikofen and Schafisheim the correlation was positive (Table 3). In a study by Nordmeyer and Dunker (1999) soil pH and plant-available phosphate showed a positive correlation for a pH range of 5.9 to 7.0 and in the study by Reza et al (2017) similar trend was reported for a pH range of 4.4 to 8.4 Strong positional similarities were observed between soil P, calcium (Ca), and pH, which indicates that P available to the plants was strongly influenced by soil Ca and pH (Tsegaye and Hill 1998). The largest amounts of P are available at pH 6.5 in mineral soils (Miller and Donahue 1990). The pattern of variation in pH showed an inverse relation with soil P for a pH range of 6.4 to 7.4 (Frogbrook et al. 2002).

SOM and total N content of the topsoil differed in terms of average level, spatial dependence, and spatial patterns for all three sites (Figures 4–6 and Table 2). However, the maps illustrate some spatial relationships between soil traits, for example between SOM and total N (Table 3) in all three fields. Only at Gränichen did a strong spatial dependence of SOM and total N exist (Table 2).

In Gränichen SOM and total N content were spatially correlated with oat grain yield (Table 3), whereas no spatial relationship between these soil parameters and grain yield was found at Zollikofen. Total soil C and N are generally accepted measures of the potential contribution of SOM to the available N pool; mineralization can provide significant amounts of N to crops during the growing season (Bundy and Meisinger 1994). Selles et al (1999) determined the potential for N mineralization from SOM by soil extraction with hot potassium chloride (KCl). Potassium chloride-N indicated that potentially mineralizable N is directly related to total soil N but inversely related to soil pH and bulk density.

In a study of the spatial variability of early-season N, Lengnick (1997) reported that total soil N exhibited spatial structures very different from those of total organic C, with a much longer range of spatial dependence than that of total organic C. Neither spatial variation in total N nor total organic C corresponded to the spatial variation in maize biomass production (Lengnick 1997). In contrast to the study of Lengnick (1997), total N had a similar spatial structure and similar range of influence as SOM in our investigations; the C_0 for total N was always higher than for SOM (Table 2). In another study of spatial variability at different scales, soil organic C was also more spatially structured than was total soil N, as shown by the components of the semivariogram (Bahri and Berndtsson 1996).

In this study we focused on the spatial variability of soil chemical and biological (SOM) properties. This variation explained only a small part of the variation in the grain yield of oats (Table 3). This is to be expected because crop yields under field conditions are a combination of both positive and negative effects of soil factors, weather conditions, management practices and different spatial distribution patterns of soil properties and crop yields. The data of Pierce, Wamcke, and Everett (1995) indicates that soil physical properties or landscape, particularly with regard to their effect on water relations, may be more important than soil chemical properties in explaining yield variation. Similar conclusions were drawn by Usowicz and Lipiec (2017) who found that management to increase water storage and use by cereal crops especially in sandy soils is particularly critical to increase crop productivity. Other studies (Froment et al. 1995; Lord, Shepherd, and Dampney 1997) concluded that the supply of soil water is the most common factor determining yield variation in arid and semi-arid environments. It is expected that the frequency of wet days in summer will decrease in Europe in the next 50 to 100 years (Fuhrer et al. 2006). Thus, water deficits during the vegetation period will increasingly limit crop productivity in humid temperate environments as well (Lavalle et al. 2009; Mendelsohn and Massetti 2017).

Frogbrook et al. (2002) found clear correlations among the spatial patterns of wheat yield, leaf chlorosis, weed population and soil pH, whereas the relationships between soil nutrient contents and yield were very poor. In agreement with Frogbrook et al. (2002), the relation between yield and the measured soil properties appeared to be generally weak. However, the range of spatial correlation of yield, as shown in the variogram, was similar to that of the soil chemical properties in Gränichen but not in Zollikofen (Table 2). The spatial variation of soil structure and of other soil physical properties, which were not measured in our study, probably contribute to the variation in grain yield in combination with the variation in weed infestation. Weed density (data not shown) varied considerably in the fields in Gränichen and Zollikofen with CVs of 58 and 63%, respectively.

Conclusions

This analysis of the spatial variation in the grain yield of oats in small fields indicates that yield variations cannot be explained simply by the spatial pattern of a limited set of soil parameters. Nevertheless, the spatial distribution of SOM and total N content in the topsoil had some influence on the spatial pattern of the grain yield of oats in the field at Gränichen. Some soil chemical properties were strongly spatially dependent; therefore a site-specific fertilizer application could be beneficial. This is particularly true for lime and P in Zollikofen but could also be advantageous for P, K and, to a lesser extent, N in the field at Gränichen. The spatial patterns of soil chemical traits suggest that former fertilization and cropping practices (i.e. anthropogenic spatial variation) strongly affect the spatial distribution of these soil parameters. Spatial distribution maps developed for soil properties could be the primary guide for site-specific nutrient management and designing future soil sampling strategies in the intensively cultivated cropping systems.

Abbreviations

SOM	soil organic matter
P	phosphorus
K	potassium
N	total nitrogen
SD	standard deviation
CV	coefficient of variation
S-W statistic	Shapiro-Wilk statistic

Acknowledgements

The authors acknowledge support from the Alliance for Global Sustainability (AGS) as a partner of the project (http://globalsustainability.org/).

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Christos Noulas http://orcid.org/0000-0002-1087-2203

References

Aitken, R. L., P. W. Moody, and P. G. McKinley. 1990. Lime requirement of acidic Queensland soils. II. Comparison of laboratory methods for predicting lime requirement. *Australian Journal of Soil Research* 28(5): 703–15. https://doi.org/10.1071/SR9900703

Bahri, A., and R. Berndtsson. 1996. Nitrogen source impact on the spatial variability of organic carbon and nitrogen in soil. *Soil Science* 161(5):288–97.

Basso, B., D. Cammarano, C. Fiorentino, and J. T. Ritchie. 2013. Wheat yield response to spatially variable nitrogen fertilizer in mediterranean environment. *European Journal of Agronomy* 51:65–70. https://doi.org/10.1016/j.eja.2013.06.007

Basso, B., B. Dumont, D. Cammarano, A. Pezzuolo, F. Marinello, and L. Sartori. 2016. Environmental and economic benefits of variable rate nitrogen fertilization in a nitrate vulnerable zone. *Science of the Total Environment* 545-546:227–35. https://doi.org/10.1016/j.scitotenv.2015.12.104

Basso, B., J. T. Ritchie, D. Cammarano, and L. Sartori. 2011. A strategic and tactical management approach to select optimal N fertilizer rates for wheat in a spatially variable field. *European Journal of Agronomy* 35(4): 215–22. https://doi.org/10.1016/j.eja.2011.06.004

Behera, S. K., K. Suresh, B. N. Rao, R. K. Mathur, A. K. Shukla, K. Manorama, K. Ramachandrudu, P. Harinarayana, and C. Prakash. 2016. Spatial variability of some soil properties varies in oil palm (*Elaeis guineensis* jacq.) plantations of west coastal area of India. *Solid Earth* 7(3):979–93. doi:10.5194/se-7-979-2016

Bhatti, A. U., A. Bakhsh, M. Afzal, and A. H. Gurmani. 1999. Spatial variability of soil properties and wheat yields in an irrigated field. *Communications in Soil Science and Plant Analysis* 30(9–10):1279–90. doi:10.1080/00103629909370284

Blackmore, S., R. J. Godwin, J. C. Taylor, N. D. Cosser, G. A. Wood, R. Earl, and S. Knight. 1999. Understanding variability in four fields in the United Kingdom, In *Proceedings of the 4th international conference on precision agriculture: 19–22 July, 1998 St. Paul, MN*, ed. P. C. Robert, R. H. Rust, and W. E. Larson, 3–18. Madison: ASA, CSSA, and SSSA.

Blackmore, B. S., P. N. Wheeler, J. Morris, R. M. Morris, and R. J. A. Jones. 1995. The role of precision farming in sustainable agriculture: A European perspective, In *Site-specific management for agricultural systems*, ed. P. C. Robert, R. H. Rust, and W. E. Larson, 777–793. Madison: ASA, CSSA, SSSA. doi:10.2134/1995.site-specificmanagement.c60

Bogunovic, I., M. Mesic, Z. Zgorelec, A. Jurisic, and D. Bilandzija. 2014. Spatial variation of soil nutrients on sandy-loam soil. *Soil and Tillage Research* 144:174–83. https://doi.org/10.1016/j.still.2014.07.020

Bogunovic, I., S. Trevisani, M. Seput, D. Juzbasic, and B. Durdevic. 2017. Short-range and regional spatial variability of soil chemical properties in an agro-ecosystem in Eastern Croatia. *Catena* 154:50–62. https://doi.org/10.1016/j.catena.2017.02.018.

Bone, J., M. Head, D. Barraclough, M. Archer, C. Scheib, D. Flight, and N. Voulvoulis. 2010. Soil quality assessment under emerging regulatory requirements. *Environment International* 36(6):609–22.

Bongiovanni, R., and J. Lowenberg-DeBoer. 2000. Economics of variable rate lime in Indiana. *Precision Agriculture* 2:55–70. https://doi.org/10.1016/j.envint.2010.04.010

Bundy, L. G., and J. J. Meisinger. 1994. Nitrogen availability indices. In *Methods of soil analysis. Part 2: Microbiological and biochemical properties*. ed. R.W. Weaver, 951–984. Madison: SSSA.

Cahn, M. D., J. W. Hummel, and B. H. Brouer. 1994. Spatial analysis of soil fertility for site specific crop management. *Soil Science Society of America Journal* 58(4):1240–8. doi:10.2136/sssaj1994.03615995005800040035x

Cambardella, C. A., and D. L. Karlen. 1999. Spatial analysis of soil fertility parameters. *Precision Agriculture* 1(1): 5–14. https://doi.org/10.1023/A:1009925919134

Cambardella, C. A., T. B. Moorman, T. B. Parkin, D. L. Karlen, J. M. Novak, R. F. Turco, and A. E. Konopka. 1994. Field-scale variability of soil properties in Central Iowa soils. *Soil Science Society of America Journal* 58(5): 1501–11. doi:10.2136/sssaj1994.03615995005800050033x

Chancellor, W. J., and M. A. Goronca. 1994. Effects of spatial variability of nitrogen, moisture and weeds on the advantages of site-specific application for wheat. *Transactions of the American Society of Agricultural Engineers (ASAE)* 37:717–24.

Cressie, N. A. C. 1991. *Statistics for spatial data*. New York: John Wiley & Sons.

Cressie, N. A. C. 1993. *Statistics for spatial data*. Revised ed. New York: John Wiley & Sons.

Dampney, P. M. R., G. Goodlass, A. E. Riding, and M. A. Froment. 1997. The spatial variation of soil mineral nitrogen in two arable fields in England, and the implications for decision processes on nitrogen fertilizer use. In Proceedings of the 11th world fertilizer congress, fertilization for sustainable plant production and soil fertility, Gent, Belgium, September 7–13, Vol. 3, pp. 155–162.

Diacono, M., P. Rubino, and F. Montemurro. 2013. Precision nitrogen management of wheat. A review. *Agronomy for Sustainable Development* 33(1):219–41. https://doi.org/10.1007/s13593-012-0111-z

Dirks, B., and F. Scheffer. 1930. Der kohlensäure-bikarbonatauszug und der wasserauszug als grundlage zur ermittlung der phosphorsäurebedürftigkeit der böden (The carbonic acid-bicarbonate extract and the water extract as a basis for determining the phosphoric acid need of the soil). *Landwirtschaftliche Jahrbcher* 71:73–99.

Domsch, H., and O. Wendroth. 1997. On-site diagnosis of soil structure for site specific management. In *Proceedings of the 1st European conference on precision agriculture*. ed. J V Stafford, 95–102. Warwick, UK: BIOS Scientific Publishers Ltd.

European Commission 2006. *Communication from the commission to the council, the European parliament, the European economic and social committee and the committee of the regions. Thematic strategy for soil protection COM (2006) 231*. Brussels, Belgium: European Commission.

FAO 1988. *Soil map of the world: Revised legend*, World soil resources report 60. Rome, Italy: FAO-UN.

Franzen, D. W., and T. R. Peck. 1995. Field soil sampling density for variable rate fertilization. *Journal of Production Agriculture* 8(4):568–74.

Frogbrook, Z. L., M. A. Oliver, M. Salahi, and R. H. Ellis. 2002. Exploring the spatial relations between cereal yield and soil chemical properties and the implications for sampling. *Soil Use and Management* 18(1):1–9. https://doi.org/10.1111/j.1475-2743.2002.tb00043.x

Froment, M., P. M. R. Dampney, G. Goodlass, C. J. Dawson, and J. Clarke. 1995. *A review of spatial variation of nutrients in soil. MAFF final report for project CE0139, ministry of agriculture*. London, UK: Fisheries and Food.

Fu, W., H. Tunney, and C. Zhang. 2010. Spatial variation of soil nutrients in a dairy farm and its implications for site-specific fertilizer application. *Soil and Tillage Research* 106(2):185–93. https://doi.org/10.1016/j.still.2009.12.001.

Fuhrer, J., M. Beniston, A. Fischlin, F. Ch, S. Goyette, K. Jasper, and P. Ch. 2006. Climate risks and their impact on agriculture and forests in Switzerland. In *Climate variability, predictability and climate risks*, ed. H. Wanner, M. Grosjean, R. Röthlisberger, and E. Xoplaki, 79–102. Dordrecht, The Netherlands: Springer. https://doi.org/10.1007/978-1-4020-5714-4_5.

Funk, R., and F. X. Maidl. 1997. Heterogeneity of yield formation of winter wheat in fields of the Tertiärhügelland (Upper Bavaria) considering site-specific crop management. *Pflanzenbauwissenschaften* 1:117–26.

García-Gil, J. C., C. Plaza, N. Senesi, G. Brunetti, and A. Polo. 2004. Effects of sewage sludge amendment on humic acids and microbiological properties of a semiarid mediterranean soil. *Biology and Fertility of Soils* 39(5): 320–8. https://doi.org/10.1007/s00374-003-0709-z

Gee, G., and J. Bauder. 1986. Particle size analysis. In *Methods of soil analysis, part 2. Agronomy monograph 9*, ed. A. Klute, 383–411. Madison, WI: ASA, SSSA.

Geesing, D., M. Diacono, and U. Schmidhalter. 2014. Site-specific effects of variable water supply and nitrogen fertilization on winter wheat. *Journal of Plant Nutrition and Soil Science* 177(4):509–23. doi:10.1002/jpln.201300215.

Geypens, M., L. Vanongeval, N. Vogels, and J. Meykens. 1999. Spatial variability of agricultural soil fertility parameters in a *gleyic* podzol of Belgium. *Precision Agriculture* 1:319–26. https://doi.org/10.1023/A:1009977109430

Gisi, U., R. Schenker, R. Schulin, F. X. Stadelmann, and H. Sticher. 1990. *Bodenokölogie*, 304. Stuttgart, Germany: Georg Thieme Verlag.

Godwin, R. J., and P. C. H. Miller. 2003. A review of the technologies for mapping within-field variability. *Biosystems Engineering* 84(4):393–407. https://doi.org/10.1016/S1537-5110(02)00283-0

Goovaerts, P. 1997. *Geostatistics for natural resources evaluation. Applied geostatistics series*. Oxford: Oxford University Press.

Goulding, K. W. T. 2016. Soil acidification and the importance of liming agricultural soils with particular reference to the United Kingdom. *Soil Use and Management* 32(3):390–9. http://doi.org/10.1111/sum.12270.

Gozdowski, D., E. Leszczyńska, M. Stępień, J. J. Rozbicki, and S. Samborski. 2017. Within-field variability of winter wheat yield and grain quality versus soil properties. *Communications in Soil Science and Plant Analysis* 48(9): 1029–41. doi: 10.1080/00103624.2017.1323091

Heisel, T., A. K. Ersbøll, and C. Andreasen. 1999. Weed mapping with co-kriging using soil properties. *Precision Agriculture* 1(1):39–52. https://doi.org/10.1023/A:1009921718225

Hergert, G. W., R. B. Ferguson, C. A. Shapiro, E. J. Penas, and F. N. Anderson. 1995. Classical statistical and geostatitical analysis of spatial variability of soil nitrate-N. In *Proceedings of the 2nd international conference on site-specific management for agricultural systems, Minneapolis, MN, 27–30 March 1994*, ed. P. C. Robert, R. H. Rust, and W. E. Larson, 175–186. Madison: ASA, CSSA, and SSSA.

Herzel, H., O. Kruger, L. Hermann, and C. Adam. 2016. Sewage sludge ash-a promising secondary phosphorus source for fertilizer production. *Science of the Total Environment* 542:1136–43. https://doi.org/10.1016/j.scitotenv.2015.08.059

Heuvelink, G. B. M., D. J. Brus, and J. J. de Gruijter. 2006. Chapter 11. Optimization of sample configurations for digital soil mapping with universal kriging. In *Developments in soil science*. eds. P. Lagacherie, A. B. McBratney, and M. Voltz, vol. 31, 137–151. Amsterdam, The Netherlands: Elsevier B. V. https://doi.org/10.1016/S0166-2481(06)31011-2.

Hupet, F., and M. Vanclooster. 2002. Intraseasonal dynamics of soil moisture variability within a small agricultural maize cropped field. *Journal of Hydrology* 261(1–4):86–101. https://doi.org/10.1016/S0022-1694(02)00016-1.

Isaaks, E. H., and R. M. Srivastava. 1989. *An introduction to applied geostatistics*. New York: Oxford University Press.

Jones, C. A., A. N. Sharpley, and J. R. Williams. 1984. A simplified soil and plant phosphorus model: III. Testing. *Soil Science Society of America Journal* 48(4):810–3. doi:10.2136/sssaj1984.03615995004800040022x

Juang, K., D. Liou, and D. Lee. 2002. Site-specific phosphorus application based on the kriging fertilizer-phosphorus availability index of soils. *Journal of Environment Quality* 31(4):1248–55. doi:10.2134/jeq2002.1248

Kitanidis, P. K. 1997. *Introduction to geostatistics: Applications to hydrogeology*, 249. New York: Cambridge University Press.

Lan, Y., S. J. Thomson, Y. Huang, W. C. Hoffmann, and H. Zhang. 2010. Current status and future directions of precision aerial application for site-specific crop management in the USA. *Computers and Electronics in Agriculture* 74(1):34–8. https://doi.org/10.1016/j.compag.2010.07.001.

Lauzon, J. D., I. P. O'Halloran, D. J. Fallow, A. P. von Bertoldi, and D. Aspinall. 2005. Spatial variability of soil test phosphorus, potassium, and pH of Ontario soils. *Agronomy Journal* 97(2):524–32. doi:10.2134/agronj2005.0524

Lavalle, C., F. Micale, T. D. Houston, A. Camia, R. Hiederer, C. Lazar, C. Conte, G. Amatulli, and G. Genovese. 2009. Climate change in Europe. 3. Impact on agriculture and forestry. A review. *Agronomy for Sustainable Development* 29(3):433–46. https://doi.org/10.1051/agro/2008068

Lengnick, L. L. 1997. Spatial variability of early season nitrogen availability indicators in corn. *Communications in Soil Science and Plant Analysis* 28(19–20):1721–36. https://doi.org/10.1080/00103629709369912

Li, Y., Z. Shi, C. F. Wu, H. X. Li, and F. Li. 2007. Improved prediction and reduction of sampling density for soil salinity by different geostatistical methods. *Agricultural Sciences in China* 6(7):832–41.

Limpert, E., and W. A. Stahel. 2011. Problems with using the normal distribution – and ways to improve quality and efficiency of data analysis. *PLoS One* 6(7):e21403. https://doi.org/10.1371/journal.pone.0021403.

López-Granados, F., M. Jurado-Expósito, S. Atenciano, A. García-Ferrer, M. Sánchez de la Orden, and L. García-Torres. 2002. Spatial variability of agricultural soil parameters in Southern Spain. *Plant and Soil* 246(1):97–105. https://doi.org/10.1023/A:1021568415380

Lord, E. I., M. A. Shepherd, and P. M. R. Dampney. 1997. Yield variation and crop water use: Cause or effect? In *Precision agriculture '97: Technology, IT and management*, ed. J. V. Stafford, vol. 2, 243–251. London, UK: Society of Chemical Industry.

Mallarino, A. P. 1996. Spatial variability patterns of phosphorus and potassium in no tilled soils for two sampling scales. *Soil Science Society of America Journal* 60(5):1473–81. doi:10.2136/sssaj1996.03615995006000050027x

Matheron, G. 1971. *The theory of regionalized variables and its applications. Les cahiers du Centre de morphologie mathematique 5*. Paris, France: Centre de Géostatistique, Fontainebleau. 211 p.

Mendelsohn, R. O., and E. Massetti. 2017. The use of cross-sectional analysis to measure climate impacts on agriculture: Theory and evidence. *Review of Environmental Economics and Policy* 11(2):280–98. https://doi.org/10.1093/reep/rex017

Miller, R. W., and R. L. Donahue. 1990. *Soils: An introduction to soils and plant growth*. 6th ed. Englewood Cliffs, NJ: Prentice Hall. 768 p.

Mohanty, B. P., and R. S. Kanwar. 1994. Spatial variability of residual nitrate-nitrogen under two tillage systems in Central Iowa: A composite three-dimensional resistant and exploratory approach. *Water Resources Research* 30(2):237–51. doi:10.1029/93WR02922

Momtaz, H. R., N. Ghasemi, E. Sepehr, and S. M. Mousavifard. 2017. Spatial distribution of soil-available phosphorus and single-point phosphorus buffering index in the Khoy region, Iran. *Soil Use and Management* 33(1): 13–24. doi:10.1111/sum.12318.

Mondal, S., R. D. Singh, A. K. Patra, and B. S. Dwivedi. 2015. Changes in soil quality in response to short-term application of municipal sewage sludge in a *typic haplustept* under cowpea-wheat cropping system. *Environmental Nanotechnology, Monitoring and Management* 4:37–41. https://doi.org/10.1016/j.enmm.2014.12.001.

Mulla, D., and M. Hammond. 1988. Mapping of soil test results from large irrigation circles. In *Proceedings of 39th annual regional fertilizer conference, Bozeman, Montana, 11–13 July 1988*, 169–176. ed. J. S. Jacobsen. Pasco, WA: Far West Fertilizer and Agrichemical Association.

Murphy, J., and J. P. Riley. 1962. A modified single solution method for the determination of phosphate in natural water. *Analytica Chimica Acta* 27:31–6.

Muschietti-Piana, M. D. P., P. A. Cipriotti, S. Urricariet, N. R. Peralta, and M. Niborski. 2018. Using site-specific nitrogen management in rainfed corn to reduce the risk of nitrate leaching. *Agricultural Water Management* 199:61–70. https://doi.org/10.1016/j.agwat.2017.12.002.

Mzuku, M., R. Khosla, R. Reich, D. Inman, F. Smith, and L. MacDonald. 2005. Spatial variability of measured soil properties across site-specific management zones. *Soil Science Society of America Journal* 69(5):1572–9. doi: 10.2136/sssaj2005.0062

Nakamoto, T., J. Yamagishi, H. Oyaizu, T. Funahashi, and W. Richner. 2002. Spatial variability patterns of wheat growth and soil properties in a small field as affected by tillage intensity. *Plant Production Science* 5(2):175–83. https://doi.org/10.1626/pps.5.175

Nanni, M. R., F. P. Povh, J. A. M. Demattê, R. B. Oliveira, M. L. Chicati, and E. Cezar. 2011. Optimum size in grid soil sampling for variable rate application in site-specific management. *Scientia Agricola* 68(3):386–92. https://doi.org/10.1590/S0103-90162011000300017

Navas, A., F. Bermúdez, and J. Machín. 1998. Influence of sewage sludge application on physical and chemical properties of *Gypsisols*. *Geoderma* 87(1–2):123–35. https://doi.org/10.1016/S0016-7061(98)00072-X

Nelson, D. W., and L. E. Sommers. 1982. Total carbon, organic carbon and organic matter. In *Methods of soil analysis. Part 2: Chemical and microbiological properties*, ed. A. L. Page, 2nd ed., 539–580. Madison: SSSA.

Nordmeyer, H., and M. Dunker. 1999. Variable weed densities and soil properties in a weed mapping concept for patchy weed control. In *Precision agriculture '99, paper presented at the 2nd European conference on precision agriculture. Odense, Denmark, 11-15 July 1999. Part 1*, 453–462. Sheffield, UK: Sheffield Academic Press.

Parkin, T. B., and J. A. Robinson. 1992. Analysis of lognormal data. In *Advances in soil science*. ed. B.A. Stewart, vol 20, 193–235. New York: Springer. https://doi.org/10.1007/978-1-4612-2930-8_4.

Pierce, F. J., D. D. Wamcke, and M. W. Everett. 1995. Yield and nutrient variability in glacial soils of Michigan. In *Second international conference of site-specific management for agricultural systems, Minneapolis, MN, March 27-30, 1994*, 133–150. Madison: ASA-CSSA-SSSA.

Pionke, H. B., R. B. Corey, and E. E. Schulte. 1968. Contributions of soil factors to lime requirement and lime requirement tests. *Soil Science Society of America Journal* 32(1):113–7. doi:10.2136/sssaj1968.03615995003200010030x

Reuss, J. O., P. N. Soltanpour, and A. E. Ludwick. 1977. Sampling distributions of nitrates in irrigated fields. *Agronomy Journal* 69(4):588–92.

Reza, S. K., D. C. Nayak, S. Mukhopadhyay, T. Chattopadhyay, and S. K. Singh. 2017. Characterizing spatial variability of soil properties in alluvial soils of India using geostatistics and geographical information system. *Archives of Agronomy and Soil Science* 63(11):1489–98. doi:10.1080/03650340.2017.1296134

Rigby, H., B. O. Clarke, D. L. Pritchard, B. Meehan, F. Beshah, S. R. Smith, and N. A. Porter. 2016. A critical review of nitrogen mineralization in biosolids-amended soil, the associated fertilizer value for crop production and potential for emissions to the environment. *Science of the Total Environment* 541:1310–38. https://doi.org/10.1016/j.scitotenv.2015.08.089

Robertson, M. J., R. S. Llewellyn, R. Mandel, R. Lawes, R. G. V. Bramley, L. Swift, N. Metz, and C. O. Callaghan. 2012. Adoption of variable rate fertilizer application in the Australian grains industry: Status, issues and prospects. *Precision Agriculture* 13(2):181–99. https://doi.org/10.1007/s11119-011-9236-3

Robertson, M. J., G. Lyle, and J. W. Bowden. 2008. Within-field variability of wheat yield and economic implications for spatially variable nutrient management. *Field Crops Research* 105(3):211–20. doi:10.1016/j.fcr.2007.10.005.

Rosemary, F., U. W. A. Vitharana, S. P. Indraratne, R. Weerasooriya, and U. Mishra. 2017. Exploring the spatial variability of soil properties in an *Alfisol* soil catena. *CATENA* 150:53–61. https://doi.org/10.1016/j.catena.2016.10.017.

Rossel, R. A. V., A. B. McBratney, and J. V. Stafford. 1999. Calibration of a lime requirement buffer for site-specific lime applications in south-eastern Australia. In *Precision agriculture '99, paper presented at the 2nd*

European conference on precision agriculture. Odense, Denmark, 11-15 July 1999. Part 1, 429–440. Sheffield, UK: Sheffield Academic Press.

Royston, P. 1992. Approximating the Shapiro-Wilk W-test for non-normality. *Statistics and Computing* 2(3):117–9.

Ryan, J., M. Singh, S. Masri, and H. Ibrikci. 2012. Spatial variation in soil organic matter, available phosphorus, and potassium under semi-arid conditions: Research station management implications. *Communications in Soil Science and Plant Analysis* 43(21):2820–33. https://doi.org/10.1080/00103624.2012.716126

Sadler, E. J., W. J. Busscher, P. J. Bauer, and D. L. Karlen. 1998. Spatial scale requirements for precision farming: a case study in the southeastern USA. *Agronomy Journal* 90(2):191–7. doi:10.2134/agronj1998.00021962009000020012x

Sawyer, J. E. 1994. Concepts of variable rate technology with considerations for fertilizer application. *Journal of Production Agriculture* 7:95–201. doi:10.2134/jpa1994.0195

Schepers, J. S., M. R. Schlemmer, and R. B. Ferguson. 2000. Site-specific considerations for managing phosphorus. *Journal of Environment Quality* 29(1):125–30. doi:10.2134/jeq2000.00472425002900010016x

Schimmelpfennig, D., and R. Ebel. 2011. On the doorstep of the information Age: Recent adoption of precision agriculture, EIB-80, U.S. Dept. of Agriculture, Economic Research Service, Washington, DC.

Schimmelpfennig, D., and R. Ebel. 2016. Sequential adoption and cost savings from precision agriculture. *Journal of Agricultural and Resource Economics* 41(1):97–115.

Schmidt, J. P., R. K. Taylor, and G. A. Milliken. 2002. Evaluating the potential for site specific phosphorus applications without high-density soil sampling. *Soil Science Society of America Journal* 66(1):276–83. doi:10.2136/sssaj2002.2760

Selles, F., C. A. Campbell, B. G. McConkey, S. A. Brandt, and D. Messer. 1999. Relationships between biological and chemical measures of N supplying power and total soil N at field scale. *Canadian Journal of Soil Science* 79(2):353–66. https://doi.org/10.4141/S98-035

Sharmasarkar, F. C., S. Sharmasarkar, R. Zhang, G. F. Vance, and S. D. Miller. 1999. Micro-spatial variability of soil nitrate following nitrogen fertilization and drip irrigation. *Water, Air, and Soil Pollution* 116(3/4):605–19. https://doi.org/10.1023/A:1005188827642

Sharpley, A. N., C. A. Jones, C. Gray, and C. V. Cole. 1984. A simplified soil and plant phosphorus model. II. Prediction of labile, organic and sorbed phosphorus. *Soil Science Society of America Journal* 48(4):805–9. doi:10.2136/sssaj1984.03615995004800040021x

Shukla, A. K., S. K. Behera, N. K. Lenka, P. K. Tiwari, C. Prakash, R. S. Malik, N. K. Sinha, V. K. Singh, A. K. Patra, and S. K. Chaudhary. 2016. Spatial variability of soil micronutrients in the intensively cultivated Trans-Gangetic plains of India. *Soil and Tillage Research* 163:282–9. https://doi.org/10.1016/j.still.2016.07.004

Singh, R. P., and M. Agrawal. 2008. Potential benefits and risks of land application of sewage sludge. *Waste Management* 28(2):347–58. https://doi.org/10.1016/j.wasman.2006.12.010

Srinivasarao, C., B. Venkateswarlu, R. Lal, A. K. Singh, S. Kundu, K. P. R. Vittal, J. J. Patel, and M. M. Patel. 2014. Long-term manuring and fertilizer effects on depletion of soil organic carbon stocks under pearl millet-cluster bean-castor rotation in Western India. *Land Degradation & Development* 25(2):173–83. doi:10.1002/ldr.1158

Starr, J. L., J. J. Meisinger, and T. B. Parkin. 1992. Sample size consideration in the determination of soil nitrate. *Soil Science Society of America Journal* 56(6):1824–30. doi:10.2136/sssaj1992.03615995005600060029x

Surfer for Windows (Version 7). 1999. 2D and 3D Mapping, Modeling, and Analysis Software. USA: Golden Software, LLC Colorado Inc. 1999.

Sylvester-Bradley, R., E. Lord, D. L. Sparkes, R. K. Scott, J. J. J. Wiltshire, and J. Orson. 1999. An analysis of the potential of precision farming in Northern Europe. *Soil Use and Management* 15(1):1–8. doi:10.1111/j.1475-2743.1999.tb00054.x

SYSTAT for Windows (version 10). 2000. San Jose, CA: Systat Software, Inc. www.sigmaplot.com.

Tagarakis, A. C., and Q. M. Ketterings. 2018. Proximal sensor-based algorithm for variable rate nitrogen application in maize in northeast U.S.A. *Computers and Electronics in Agriculture* 145:373–8. https://doi.org/10.1016/j.compag.2017.12.031

Timlin, D. J., Y. Pachepsky, V. A. Snyder, and R. B. Bryant. 1998. Spatial and temporal variability of com grain yield on a hillslope. *Soil Science Society of America Journal* 62(3):764–73. doi:10.2136/sssaj1998.03615995006200030032x

Tsegaye, T., and R. L. Hill. 1998. Intensive tillage effects on spatial variability of soil test, plant growth, and nutrient uptake measurements. *Soil Science* 163(2):155–65.

Uprety, D., M. Hejcman, J. Száková, E. Kunzová, and P. Tlustoš. 2009. Concentration of trace elements in arable soil after long-term application of organic and inorganic fertilizers. *Nutrient Cycling in Agroecosystems* 85(3):241–52. https://doi.org/10.1007/s10705-009-9263-x

Usowicz, B., and J. Lipiec. 2017. Spatial variability of soil properties and cereal yield in a cultivated field on sandy soil. *Soil and Tillage Research* 174:241–50. https://doi.org/10.1016/j.still.2017.07.015.

Van Meirvenne, M., and G. Hofman. 1989. Spatial variability of soil nitrate nitrogen after potatoes and its change during winter. *Plant and Soil* 120(1):103–10. https://doi.org/10.1007/BF02370296

Van Meirvenne, M., J. Pannier, G. Hofman, and G. Louwagie. 1996. Regional characterization of the long-term change in soil organic carbon under intensive agriculture. *Soil Use and Management* 12(2):86–94. doi:10.1111/j.1475-2743.1996.tb00964.x

Vašák, F., J. Černý, Š. Buráňová, M. Kulhánek, and J. Balík. 2015. Soil pH changes in long-term field experiments with different fertilizing systems. *Soil and Water Research* 10(1):19–23. doi:10.17221/7/2014-SWR

Veeresh, H., S. Tripathy, D. Chaudhuri, B. Ghosh, B. Hart, and M. Powell. 2003. Changes in physical and chemical properties of three soil types in India as a result of amendment with fly ash and sewage sludge. *Environmental Geology* 43(5):513–20. https://doi.org/10.1007/s00254-002-0656-2

Verhagen, J. 1997. Modeling soil and crop responses in a spatially variable field. In *Proceedings of the 1st European conference on precision agriculture*. ed. J V Stafford. 197–204. Warwick, UK: BIOS Scientific Publishers Ltd.

Vieira, S. R., and A. P. Gonzalez. 2003. Analysis of the spatial variability of crop yield and soil properties in small agricultural plots. *Bragantia* 62(1):127–38. https://doi.org/10.1590/S0006-87052003000100016

Von Moos, A. 1942. *Die Geologie der Schweiz und deren Beziehung zur Bautechnik [The geology of Switzerland and its relationship to construction technology]*. Zürich, Switzerland: Verlag Hoch- und Tiefbau, 52 p.

Wang, G., G. Gertner, V. Singh, S. Shinkareva, P. Parysow, and A. Anderson. 2002. Spatial and temporal prediction and uncertainty of soil loss using the revised universal soil loss equation: A case study of the rainfall - runoff erosivity R factor. *Ecological Modelling* 153(1–2):143–55. https://doi.org/10.1016/S0304-3800(01)00507-5

Wang, X., C. Tang, S. Mahony, J. A. Baldock, and C. R. Butterly. 2015. Factors affecting the measurement of soil pH buffer capacity: Approaches to optimize the methods. *European Journal of Soil Science* 66(1):53–64. doi:10.1111/ejss.12195

Webster, R. 1985. Quantitative spatial analysis of soil in the field. In *Advances in soil science*. ed. B. A. Stewart, vol. 3, 1–70. New York: Springer. https://doi.org/10.1007/978-1-4612-5090-6_1

Webster, R., and M. A. Oliver. 1992. Sample adequately to estimate variograms of soil properties. *Journal of Soil Science* 43(1):177–92. doi:10.1111/j.1365-2389.1992.tb00128.x

Webster, R., and M. A. Oliver. 2007. Characterizing spatial processes: the covariance and variogram. In *Geostatistics for environmental scientists*. 2nd ed., 47–73. Chichester, UK: Wiley.

Webster, R., M. A. Oliver, and R. Webster. 1990. *Quantitative and numerical methods in soil classification and survey. Statistical methods in soil and land resource survey*. Oxford, UK: Oxford University Press.

Weisz, R., R. Heiniger, J. G. White, B. Knox, and L. Reed. 2003. Long-term variable rate lime and phosphorus application for piedmont no-till field crops. *Precision Agriculture* 4:311–30. doi:10.1023/A:1024908724491.

Wibawa, W. D., D. L. Dludlu, L. J. Swenson, D. G. Hopkins, and W. C. Dahnke. 1993. Variable fertilizer application based on yield goal and soil map unit. *Journal of Production Agriculture* 6(2):255–61. doi:10.2134/jpa1993.0255

Wollenhaupt, N. C., R. P. Wolkowski, and M. K. Clayton. 1994. Mapping soil test phosphorus and potassium for variable-rate fertilizer application. *Journal of Production Agriculture* 7(4):441–8. doi:10.2134/jpa1994.0441

Wollenhaupt, N. C., R. P. Wolkowski, and H. F. Reetz. 1993. Variable-rate fertilizer application: Update and economics. In *Proceedings of the 23rd North Central Extension-Industry soil fertility conference, St. Louis, MO, 27-28 October 1993*, 139–151. Manhattan, KS: Potash and Phosphate Institute.

Wu, J., W. A. Norvell, D. G. Hopkins, and R. M. Welch. 2002. Spatial variability of grain cadmium and soil characteristics in a durum wheat field. *Soil Science Society of America Journal* 66(1):268–75. doi:10.2136/sssaj2002.2680

Yang, C., J. H. Everitt, and J. M. Bradford. 2001. Comparisons of uniform and variable rate nitrogen and phosphorus fertilizer applications for grain sorghum. *Transactions of the American Society of Agricultural Engineers* 44(2):201–9.

Zicker, T., S. von Tucher, M. Kavka, and B. Eichler-Löbermann. 2018. Soil test phosphorus as affected by phosphorus budgets in two long-term field experiments in Germany. *Field Crops Research* 218:158–70. https://doi.org/10.1016/j.fcr.2018.01.008.