RESEARCH ARTICLE

Influence of small-scale spatial variability of soil properties on yield formation of winter wheat

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Abstract

Background With the increasing development of sophisticated precision farming techniques, high-resolution application maps are frequently discussed as a key factor in increasing yield potential. However, yield potential maps based on multiple soil properties measurements are rarely part of current farming practices. Furthermore, small-scale differences in soil properties have not been taken into account.

Methods To investigate the impact of soil property changes at high resolution on yield, a field trial has been divided into a sampling grid of 42 plots. The soil properties in each plot were determined at three soil depths. Grain yield and yield formation of winter wheat were analyzed at two sites.

Results Multiple regression analyses of soil properties with yield measures showed that the soil contents of organic carbon, silt, and clay in the top and subsoil explained 45–46% of the variability in grain yield. However, an increasing clay content in the topsoil correlated positively with grain yield and tiller density. In contrast, a higher clay content in the subsoil led to a decrease in grain yield. A cluster analysis of soil texture was deployed to evaluate whether the soil´s small-scale differences caused crucial differences in yield formation. Significant differences in soil organic carbon, yield, and yield formation were observed among clusters in each soil depth.

Conclusion These results show that small-scale lateral and vertical differences in soil properties can strongly impact crop yields and should be considered to improve site-specific cropping techniques further.

Keywords Soil texture · Soil organic carbon · Lateral and vertical small-scale variability · *Triticum aestivum L.* · Yield formation · Precision farming

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Introduction

The impact of global warming, environmental constraints, and increasing demand for food due to a growing world population requires an urgent improvement of crop management, including efficient use of farming resources such as fertilizers and pesticides, while increasing crop yield at the same time (Cassmann 1999; Foley et al. 2011; Gebbers and Adamchuk 2010; Katalin et al. 2014; Kühn et al. 2009; Machado et al. 2000; Mulla 2013; Schimmelpfennig 2018). Besides crop management, the yield formation of crops is mainly driven by abiotic factors such as climate and soil properties. Especially at the field level, the impact of climatic factors on crop growth can be seen as homogeneous. At the same time, small-scale differences in soil properties may provoke heterogeneity in yield formation within a uniformly managed crop stand.

Soil texture, as a fundamental master variable in soils (Ad hoc AG Boden 2005), mainly influences the available water capacity in the effective root space and the air capacity. These properties are directly linked to the crop´s nutrient and water availability (Ad hoc AG Boden 2005; Amelung et al. 2018; Maidl et al. 1999). At most locations, soil texture changes in the landscape and with soil depth, influencing root development, water availability, and soil aeration depending on the geomorphology and the parent material for soil formation (Barraclough and Leigh 1984; Breuning Madsen 1985; Poeplau and Kätterer 2017; Schulte-Eickholt 2009; White and Kirkegaard 2010). Compared to the topsoil, the subsoil´s nutrient content is mostly substantially lower in arable fields if there are no significant changes in soil texture (Crist and Weaver 1924; Kautz et al. 2013). Nevertheless, the subsoil is an essential resource for macro- and micronutrient mining by plant roots in nutrient depletion in the topsoil or topsoil drought (Kautz et al. 2013). A gradient in the nutrient content from the top to the subsoil is mainly driven by plant litter decomposition, surface fertilizer application, topsoil cultivation, and nutrient leakage or dislocation.

In contrast to texture, the soil organic carbon (SOC) content can be influenced by management practices from a medium to long-term perspective (Freibauer et al. 2004; Poeplau et al. 2020, 2021). In the topsoil, SOC can be increased by crop management, for example, through the use of organic fertilizers and the incorporation of plant residues (Guo

et al. 2019; Wuest and Gollany 2013) by including soil organic matter (SOM) preserving crops into crop rotations (Börjesson et al. 2018; Osanai et al. 2021; Šeremešić et al. 2020), or the cultivation of cover crops (Liang et al. 2022; Poeplau et al. 2021). SOC is related to higher water- and nutrient- availability for plants (Ghaley et al. 2018) and is known to have beneficial effects on soil properties, like soil aggregate stability, bulk density, aeration, and soil biological processes, which all affect plant growth (Ghaley et al. 2018; Palmer et al. 2017; Šeremešić et al. 2020; Stein et al. 1997; Yost and Hartemink 2019). However, SOC is not distributed homogeneously either within soil profiles or across fields (Hbirkou et al. 2012; Rentschler et al. 2020), and crop production has the potential even to increase site-specific variations (Conant et al. 2011; Virto et al. 2012).

Due to its high economic value, winter wheat is one of the most important cereals cultivated in temperate regions of Europe (Eurostat 2021). Nevertheless, multiple environmental factors influence individual yield components during different stages of their development. This high responsiveness makes it suitable as a model crop for determining small-scale soil differences. The yield components, plant density, tiller density, spike density, number of grains per spike, and thousand-grain weight, form the winter wheat grain yield. However, the yield components are strongly interrelated and plastic (Slafer and Rawson 1994; Slafer 2003; Roth et al. 1984) so that they can compensate for each other (Bastos et al. 2020).

Under heterogeneous soil conditions in a field, differences in grain yield can be large (Cammarano et al. 2019; Buttafuoco et al. 2017; Taylor et al. 2003). Within a small distance of < 10 m, the variation in winter wheat grain yield can be significant (Crain et al. 2013). Data from several studies suggest that the variability in grain yield is mainly linked to the variability of soil properties (Bölenius et al. 2017; Cox et al. 2003; Gozdowski et al. 2017; Maidl et al. 1999; Rodriguez-Moreno et al. 2014; Wang and Shen 2015). When subdividing a field into management zones, precision agriculture improves the efficient use of pesticides and fertilizers and can help to homogenize the nutrient availability and growth conditions in a field (Argento et al. 2021; Hørfarter et al. 2019; Katalin et al. 2014; Maidl et al. 1999; Nordmeyer 2006; Patzold et al. 2008; Stewart et al. 2002; Wagner and Marz 2017). Site-specific application techniques for sowing, crop protection, N fertilization (Barnes et al.

2019), and irrigation have already been implemented in practical crop production to a certain extent. Especially under highly heterogeneous soil conditions, high-resolution mapping of soil properties is likely to increase the profitability of, for example, site-specific N management compared to coarser mapping approaches (Denora et al. 2022; Späti et al. 2021). However, most field experiments investigating the impact of spatial variability of soil properties on winter wheat yield were performed on larger grid sizes > 0.5 ha (LaRuffa et al. 2001; Mallarino et al. 1999).

Site-specific management at higher resolution can improve resource efficiency and become increasingly crucial for future farming practices (Boenecke et al. 2018; Brogi et al. 2021; LaRuffa et al. 2001; Skakun et al. 2021; Tubaña et al. 2008; Zebarth et al. 2021). In this context, spatial variation in soil properties in combination with soil depth is often not considered (Boenecke et al. 2018; Cammarano et al. 2019). Below 30 cm, variation in soil properties becomes crucial at later development stages of cereals (Kirkegaard et al. 2007). For example, Cammarano et al. (2019) showed that higher clay content in the subsoil led to low and unstable spring barley yields. Steadily evolving high-precision application techniques enhance the resolution of site-specific management. These more precise application techniques will only benefit site-specific management if the field´s lateral and vertical resolution of specific management zones increases. However, site-specific management often considers only two-dimensional lateral differences in soil properties.

This study aims to evaluate the impact of small-scale vertical and lateral soil heterogeneity in two typical locations in Germany on the yield formation of winter wheat. Therefore, we (i) assessed the lateral and vertical small-scale variability of soil properties, (ii) analyzed the influence of soil properties in different soil depths on winter wheat grain yield and its components at a small-scale level, and (iii) identified clusters of soil texture and their influence on yield components and grain yield.

Materials and methods

Locations

The field experiment was conducted from autumn 2015 to summer 2016 at two locations in Germany:

Triesdorf is located in Northern Bavaria (450 m a.s.l., 49°12'36.5"N 10°38'33.9"E) on a Stagnic Cambisol (IUSS Working Group WRB 2015). The area with a mean annual air temperature of 8.7 °C and annual precipitation of 674 mm (2005–2015) is characterized by a warm, fully humid climate with warm summer (Kottek et al. 2006). The second location is Asendorf in Ems-Hunte-Geest (Lower Saxony, 49 m a.s.l., 52°45'48.4"N 9°01'24.3"E). The climatic conditions are similarly warm and humid, with a mean annual air temperature of 8.9 °C and annual precipitation of 705 mm (2005–2015) (Kottek et al. 2006). The soil is also described as a Stagnic Cambisol (IUSS Working Group WRB 2015).

Experimental design

At both locations, a subarea of a field was selected for the field trial with a size of 2 areas of 63.0 m x 34.5 m separated by a tramline and divided into a sampling grid of 42 squares to assess the effects of spatial variability of soil properties on crop yield and the structure of its components. The plot size was 10.5 m x 9.0 m each.

Plant material and growth conditions

On both sites, the field experiment started with the harvest of the previous crop, spring wheat, in 2015. Tillage and seedbed preparation was performed with conservation tillage. On 13th October 2015 in Triesdorf and on 21st October 2015 in Asendorf, winter wheat (cultivar "Patras") was sown with a sowing rate of 345 grains per m². During the vegetation period, crop management followed common local practices adapted to the two regions. The crop protection strategy was based on a homogeneous growth regulator application at the beginning of stem elongation and a fungicide application at the flag leaf stage. In total, 220 kg ha^{-1} in Triesdorf and 160 kg ha^{-1} in Asendorf of nitrogen were applied according to the different yield potentials of the locations. The fertilizer was applied in three partial doses during winter wheat´s tillering, stem elongation, and grain filling phase.

Analysis of soil measures

Soil samples for bulk density were taken manually from an open pit in depths of 0–10, 10–30, and 30–60 cm before sowing in autumn 2015 at both locations. The soil texture was analyzed according to DIN ISO 11,277. The pH value was quantified in soil suspension with water at a solid-to-solution ratio of 1:2.5, with 10 g of dry soil in 25 ml H_2O. A stainless-steel cutter (100 cm³) was used for sampling bulk density. Samples were dried at 105 °C, and bulk density was determined gravimetrically (Rawls 1983). SOC content was measured with an EA system (Elementar Analysesysteme GmbH, Hanau, Germany). Traces of carbonates ($< 0.5\%$) were removed by acid fumigation, according to Harris et al. (2001), and subsequent neutralization was carried out over NaOH pellets, 48 h for each sample.

Analysis of plant measures

The plant development of winter wheat was monitored in each plot over the growing period following the BBCH code (Hess et al. 1997). Stand density was assessed by counting the number of tillers per m² at the beginning of stem elongation (BBCH 31). Spike density was determined before harvest (BBCH 79) based on one square meter per plot. Winter wheat was harvested on 4th August 2016 in Triesdorf and 27th September 2016 in Asendorf. Plots were harvested with the plot combine Hege 140 (Hege Saatzuchtmaschinen, Hohebuch, Germany) for the exact quantification of grain yield. Only the score area of the plots was harvested to minimize border effects. The total plot area was divided into three repetitions of 15.75 m² each, so yield components could be determined in three replicates per plot. Grain samples were dried for 24 h at 65 °C to determine grain dry matter yield gravimetrically. Postharvest, the thousand-grain weight was determined by counting 500 grains per sample and quantified weight gravimetrically based on 14.0% moisture (Pfeufer Contador, Germany). Additionally, grain protein content was determined with near-infrared spectroscopy using the DA 7250 At-line NIR Instrument (PerkinElmer, Waltham, United States).

Statistical analysis

In the first step, data were analyzed with descriptive statistics like minimum and maximum values, mean, standard deviation (SD), and coefficient of variation (CV), and the dataset was analyzed for distribution. Statistical analysis was performed using the R program (R Core Team 2021). Variations of soil texture of all soil layers were visualized in the soil triangle according to the German soil classification system (Ad hoc AG Boden 2005) using the R package "soil texture" (Moey 2018). Further, as a measure of linear correlation, Pearson's correlation coefficients (*r*) between soil measures and plant measures were calculated, which is recommended for sampling numbers < 50 points (Leroux and Tisseyre 2019). To investigate soil properties´ influence on winter wheat yield and its yield components, we performed a stepwise multiple regression analysis using the Akaike information criterion (AIC) as a selection criterion for removing or adding variables of soil properties against the plant properties (Bozdogan 1987). Distributions of the experimental errors were tested for normality by executing Shapiro-Wilk's test for each regression.

Variance inflation factor (VIF) was used to test multiple regression models on collinearity (Manly and Navarro Alberto 2004; Miles 2014). To visualize the influence of the soil texture (especially for silt and clay) in different soil depths on the development of yield and yield components, the R-package "Akima" (Version 0.6–2.1) was used to create linear interpolated contour plots (Akima et al. 2020).

An additional approach for data analysis was clustering the dataset. Clustering by soil properties is common practice in site-specific farming approaches and is done by zoning (Taylor et al. 2003). Soil texture is a constant physical soil measure that barely changes over time. To distinguish subsets in the data set characterized by minimized intra-cluster variation, a k-means cluster analysis was performed (Hartigan and Wong 1979). Based on this analysis, clusters have been identified, mainly based on the measures of sand and clay (Fig. 1). For comparison of the mean values of these clusters, a two-way analysis of variance (ANOVA) was conducted. To check the basic assumptions for an ANOVA, the homogeneity of variances was tested using the Levene test (Schultz 1985).

Fig. 1 Schema of clustering the dataset by measures of the soil texture in Triesdorf
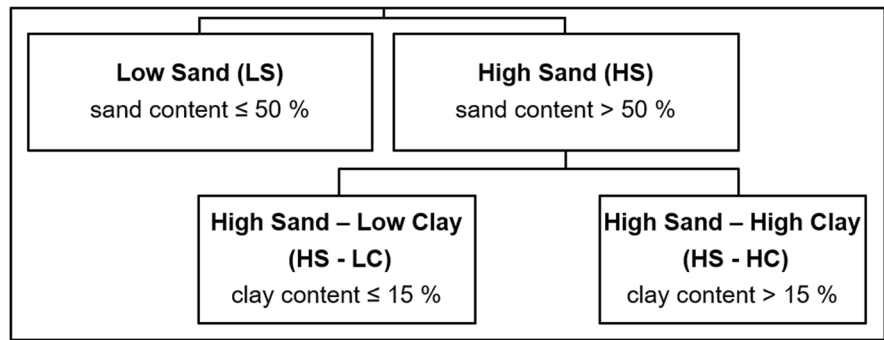
The normal distribution of the residuals was verified using the Shapiro-Wilk test. When needed, data were transformed (log8 or exponential), and a one-way analysis of means (not assuming equal variances) was executed (Welch 1951), followed by a multi-comparison of means with Tukey's honestly significant difference (HSD) test with $p < 0.05$. A multiple comparison of means calculating the least significant difference (LSD) on all measures with $p < 0.05$ was calculated using the R-package "Agricolae" (Mendiburu 2021).

Results

Lateral and vertical variability of soil properties

Small-scale lateral variability of soil properties was analyzed using a grind of 10.5 m x 9.0 m plots at two locations. Samples were also taken in three soil depths to define the vertical variability. Firstly a plot-wise classification of the prevailing soil type according to Ad hoc AG Boden (2005) was performed to get an idea of soil variability at both locations (Fig. 2a). The observed soil types in Triesdorf ranged from medium loamy sand (Sl3), strong loamy sand (Sl4) over medium sandy loam (Ls3) to strong sandy loam (Ls4) in the topsoil containing two upper analyzed soil layers (0–10 cm and 10–30 cm). In the subsoil (30–60 cm), the soil type Sl3 was present in 19% of the plots, while Sl4 characterized 33%, Ls 24%, Ls 19%, partly silty loamy sand (Slu) only 2%, an sandy clay loam (Lts) 2% of the plots in Triesdorf (Fig. 2b). So, clay content showed a higher coefficient of variation (CV) in each soil layer compared to the fractions of silt and sand. The values range from 12.5 to 23.9%, with the highest CV in the subsoil layer (30–60 cm) (Table S1).

At the second location Asendorf, the soil was generally characterized on average by 12% points smaller clay and 43% points higher silt contents than at Triesdorf. So, the observed soil types are sandy silt (Us), pure silt (Uu), sandy clayey silt (Uls), and slight clayey silt (Ut2) (Fig. 2a). Also, the soil texture's variability was low in the subsoil, with 83.3% of the soil samples being classified as sandy silt (Us) (Fig. 2c). Hence, the two locations showing different soil types, and Asendorf delivered more homogenous conditions in small-scale variability for the field trials compared to Triesdorf.

As expected, the SOC content decreased from the topsoil to the subsoil. In Triesdorf, on average, 14.5 mg g^{-1} SOC was observed in the first soil layer of 0–10 cm, 12.4 mg g^{-1} SOC in 10–30 cm soil depth, and 6.5 mg g^{-1} SOC in the subsoil (30–60 cm) (Table 1). A similar gradient in SOC over soil depth was observed in Asendorf too. Nevertheless, in contrast to bulk density, high lateral variability of SOC content was observed in all three soil layers, indicated by CV values ranging from 16.1 to 32.9% at both sites. Bulk density increased with soil depth with a mean of 1.3 g cm^{-3} in the topsoil, 1.5 g cm^{-3} in 10–30 cm, and 1.7 g cm^{-3} in the subsoil, and minor variations of the pH value were observed in Triesdorf. Similar vertical variations of the measured soil properties could be observed in the soil profile of the second location Asendorf (Table 1). Nevertheless, compared to soil texture, the lateral variability in SOC and bulk density were nearly comparable in Triesdorf and Asendorf (Table 1).

Variability of grain yield and yield components

In order to characterize the impact of the presented small-scale lateral and vertical soil variability on yield formation, winter wheat was cultivated, and
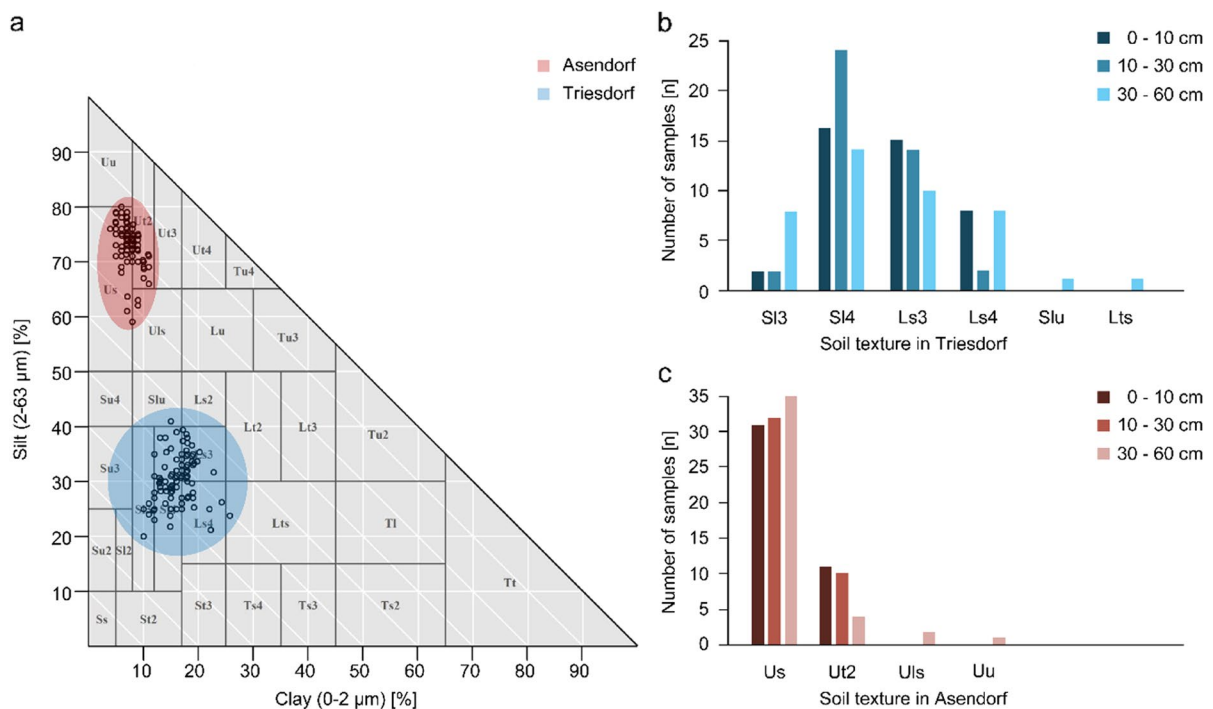
Fig. 2 Soil texture in the soil layers of 0–10 cm, 10–30 cm, and 30–60 cm (**a**) and the number of soil samples that could be assigned to individual soil texture classes [n] to soil depths in Triesdorf (**b**) and Asendorf (**c**), following the German soil classification system (Ad hoc AG Boden 2005)

yield components were analyzed in each plot. A sowing rate of 345 grains m^{-2} was applied homogeneously over all plots, and in the field emergence rate (72.8%), no statistically significant differences were observed. Wheat plants tillered differently in the plots during the vegetative development (until BBCH 31), so a variation of 367 to 591 tillers per m² with a CV of 10.8% was observed in Triesdorf (Table 2). The variation of tiller density between plots decreased even during the tiller reduction phase, resulting in 388 and 538 spikes m^{-2} and a CV of 7.5% at BBCH 79. Lateral differences between plots were not only observed in the spike density. Also, the number of grains per spike and the single spike weight showed a CV of 10.7% and 9.5%, respectively. While the measures representing organ setting were strongly influenced by soil´s inhomogeneity, like spike density and numbers of grains per spike, resulting in a high grain density range from 17,313 to 22,107 grains m^{-2}, grain weight was not strongly influenced. In Triesdorf, the thousand-grain weight ranged from 48.7 to 57.3 g, and the soil's small-scale differences caused a

CV of 3.5%. Likewise, the CV of 4.1% was relatively low for the grain yield. Nevertheless, the mean grain yield was 10.4 t ha^{-1} ranging from 9.6 to 11.2 t ha^{-1}, and soil's small-scale effects on grain protein content with values between 12.9 and 13.8% and a CV of only 1.6% were low.

In Asendorf, vegetative development was much more substantial and led to more tillers. On average, 816 tillers per m² were observed at the end of tillering period (BBCH 31), and the CV of 3.7% was low (Table 2). However, tiller reduction during booting led to a mean of 543 spikes per m², and variability between plots increased to a CV of 7.7% before harvest. Due to elevated spike density, the crop stand was characterized by a mean number of 31.1 grains per spike and 16,820 grains per m². Hence, the grain setting was much lower in comparison to Triesdorf. Even though fewer grains were created per m^{-2}, grain weight was relatively low in Asendorf compared to Triesdorf. Hence, thousand-grain weight ranged from 28.1 to 44.2 g with a CV of 7.2%, indicating that small-scale differences in soil properties influenced

Table 1 Descriptive statistics of soil properties SOC, bulk density, and pH-value according to different soil depths at the field sites in Triesdorf and Asendorf in 2016, including minimum, maximum, mean, standard deviation, and the coefficient of variation in % (CV); $n=42$ for each location

Soil depth [cm]	Soil properties	Minimum	Maximum	Mean	Standard deviation	CV [%]
Triesdorf						
0–10	Soil organic carbon [mg g−1]	4.9	19.2	14.5	3.5	23.7
	Bulk density [g cm^{-3}]	1.0	1.6	1.3	0.1	10.3
	pH value	6.8	7.9	7.5	0.4	
10–30	Soil organic carbon [mg g^{-1}]	7.8	17.1	12.4	2.3	18.2
	Bulk density [g cm^{-3}]	1.3	1.8	1.5	0.1	7.0
	pH value	6.8	7.9	7.5	0.3	
30–60	Soil organic carbon [mg g^{-1}]	3.8	9.1	6.5	1.3	20.2
	Bulk density [g cm^{-3}]	1.5	1.9	1.7	0.1	4.3
	pH value	7.0	7.9	7.5	0.2	
Asendorf						
0–10	Soil organic carbon [mg g^{-1}]	8.8	23.5	18.0	3.0	16.4
	Bulk density [g cm^{-3}]	1.1	1.3	1.2	0.1	4.4
	pH value	5.3	6.6	6.1	0.3	
10–30	Soil organic carbon [mg g^{-1}]	13.8	24.9	17.9	2.9	16.1
	Bulk density [g cm^{-3}]	1.2	1.4	1.3	0.1	4.3
	pH value	5.5	6.8	6.2	0.3	
30–60	Soil organic carbon [mg g^{-1}]	4.4	20.8	9.8	3.2	32.9
	Bulk density [g cm^{-3}]	1.4	1.8	1.7	0.1	6.6
	pH value	5.9	6.9	6.4	0.2	

Table 2 Descriptive statistics of the yield components and measures tiller density, spike density, grain per spike, single spike weight, grain density, thousand-grain weight, grain yield, and grain protein content in Triesdorf and Asendorf in 2016, including minimum, maximum, mean, standard deviation, and the coefficient of variation [%], $n=42$ for each location

Plant properties	Minimum	Maximum	Mean	SD	CV [%]
Triesdorf					
Tillers density [tillers m-2]	367	591	485	52.84	10.8
Spikes density [spike m^{-2}]	388	538	468	35.38	7.5
Grains per spike [n]	34	53	42	4.6	10.7
Single spike weight [g]	1.87	2.80	2.24	0.22	9.5
Grain density [grains m^{-2}]	17,313	22,107	19,608	1,130	5.7
Thousand-grain weight [1000 grains g^{-1}]	48.7	57.3	53.3	1.9	3.5
Grain yield [t ha^{-1}]	9.6	11.2	10.4	0.43	4.1
Protein content [%]	12.9	13.8	13.4	0.2	1.6
Asendorf					
Tillers density [tillers m^{-2}]	725	885	816	31	3.7
Spikes density [spike m^{-2}]	461	676	543	41	7.7
Grains per spike	25	43	31	2.9	9.4
Single spike weight [g]	1.00	1.50	1.23	0.11	9.1
Grain density [grains m^{-2}]	14,894	22,753	16,820	1,228	7.3
Thousand-grain weight [1000 grains g^{-1}]	28.1	44.2	39.6	2.8	7.2
Grain yield [t ha^{-1}]	5.8	7.2	6.6	0.31	4.8
Protein content [%]	10.9	12.3	11.6	0.3	2.4

yield formation much stronger in the later stages compared to the vegetative growth in this location. As a result, grain yield ranged from 5.8 to 7.2 t ha^{-1} with a mean yield of 6.6 t ha^{-1}. Even though the lower yield level in Asendorf, the grain protein content was only 11.6%, with a small CV of 2.4%.

In summary, the two sites' different growing conditions and soil properties had contrasting impacts on plant development. While vegetative development was retarded and showed high variations due to soil properties in Triesdorf, the later-formed yield components compensate for the limited vegetative development. Thus, the influence of soil differences became less important at later developmental stages. In contrast, the solid vegetative development was hardly influenced by soil differences in Asendorf. However, the impact of soil properties increased during the generative developmental stages but could not be associated with plant properties like in Triesdorf, showing higher soil heterogeneity (Fig. S2).

Influence of soil properties on yield formation

To further assess the relationship between plant measures and soil properties, Pearson's correlation coefficients (r) were calculated. In Triesdorf, the soil's small-scale variability was much more pronounced than in Asendorf. Grain yield correlated positively with clay and silt in the topsoil (0–30 cm). The correlation coefficient ranged from 0.32 to 0.39, $p < 0.05$ (Table 3). In contrast, the correlation with

sand showed negative values in all three tested soil layers. Interestingly, clay content was negatively associated with grain yield in the subsoil (r = -0.31, $p < 0.05$). While thousand-grain weight showed no significant correlation with any measure of the soil texture, tillering showed a clear positive association with clay content (r = 0.44, $p < 0.01$) and a negative with sand (r = -0.36, $p < 0.05$ and −0.44, $p < 0.01$) in the topsoil down to 30 cm. Nevertheless, spike density strongly based on tillering showed no significant association with any measure of the soil texture in the first tested layer (0–10 cm). In the second layer of the topsoil (10–30 cm), the correlation for clay (r = 0.34, $p < 0.05$) was significantly positive, while sand (r = -0.31, $p < 0.05$) was negative. No significant correlations were observed in the subsoil. Grain protein content was only significantly correlated with silt content (r = 0.32, $p < 0.05$) and clay content (r = -0.42, $p < 0.01$) in the subsoil, indicating the importance of the subsoil during grain filling, even if this was not observable for the thousand-grain weight.

In summary, wheat yield formation in Triesdorf profited from higher clay contents in the topsoil, while larger sand contents were counterproductive to form yield components. In contrast, the subsoil silt content was the most decisive for yield formation.

A stepwise multiple regression analysis was performed to understand the functional relationship between grain yield and the yield components as the dependent and the soil properties as the independent variables. Additionally, soil measures were expanded to include SOC and bulk density.

Table 3 Pearson's correlation coefficient (r) and p-value (p) of soil texture divided into clay (0–2 μm), silt (2–63 μm), and sand (63–200 μm), as well as the plant measures tiller density, spike density, grain yield, thousand-grain weight, and grain protein content in Triesdorf, 2016

Soil depth [cm]	Soil texture	tiller density [tillers m^{-2}]		spike density [spike m^{-2}]		grain yield [t ha^{-1}]		thousand-grain weight [1000 grains g^{-1}]		protein content [%]	
		r²	p	r²	p	r²	p	r²	p	r²	p
0–10	Clay	0.44	***	0.27	n.s.	0.36	*	0.14	n.s.	0.05	n.s.
	Silt	0.23	n.s.	0.14	n.s.	0.39	*	0.04	n.s.	-0.01	n.s.
	Sand	-0.44	**	-0.27	n.s.	-0.41	**	-0.12	n.s.	-0.02	n.s.
10–30	Clay	0.44	**	0.34	*	0.32	*	0.11	n.s.	0.01	n.s.
	Silt	0.27	n.s.	0.26	n.s.	0.32	*	0.1	n.s.	0.02	n.s.
	Sand	-0.36	*	-0.31	*	-0.34	*	-0.11	n.s.	-0.01	n.s.
30–60	Clay	-0.28	n.s.	0.27	n.s.	-0.31	*	0.03	n.s.	-0.42	**
	Silt	0.34	*	0.13	n.s.	0.49	***	-0.08	n.s.	0.32	*
	Sand	-0.11	n.s.	-0.27	n.s.	-0.22	n.s.	0.05	n.s.	-0.01	n.s.

Significance at different probability levels (p) is indicated as "***" ≤ 0.001, "**" ≤ 0.01, "*" ≤ 0.05, n.s. = non-significant, $n = 42$

Table 4 Stepwise multiple regression relationships relating tiller density [tillers m^{-2}], spike density [spikes m^{-2}], grain yield [t ha^{-1}], and grain protein content [%] to soil properties in different soil depths in Triesdorf 2016

Soil depth [cm]	Dependent variable	Regression relationship	R^2	p
0–10	Tiller density	51.66 ± 29.43 (SOC) $+ 8.68 \pm 4.75$ (Clay)	0.43	< 0.001
	Spike density			n.s.
	Grain yield	10.94 ± 2.48 (SOC) $+ 0.52 \pm 0.18$ (Silt) $- 0.99 \pm 0.44$ (Clay)	0.46	< 0.001
	Protein content			n.s.
10–30	Tiller density	127.36 ± 30.70 (SOC)	0.30	< 0.001
	Spike density	9.89 ± 3.26 (Clay) $- 95.34 \pm 46.63$ (BD) $- 55.61 \pm 29.43$ (SOC)	0.24	< 0.01
	Grain yield	11.30 ± 2.42 (SOC)	0.35	< 0.001
	Protein content			n.s.
30–60	Tiller density	224.28 ± 52.34 (SOC) $- 5.97 \pm 1.77$ (Clay)	0.37	< 0.001
	Spike density			n.s.
	Grain yield	0.26 ± 0.11 (Silt) $- 0.46 \pm 0.14$ (Clay) $+ 13.09 \pm 4.40$ (SOC)	0.45	< 0.001
	Protein content	-0.02 ± 0.01 (Clay) $+ 0.01 \pm 0.01$ (Silt)	0.27	< 0.01

The regression relationship shows coefficients with standard error of the factors included in the multiple regression

SOC = Soil organic carbon (mg g^{-1}); Silt = Silt content (%); Clay = Clay content (%); BD = Bulk density (g cm^{-3})

Together the soil measures SOC and clay content in the topsoil (0–10 cm) explained 43.0% ($p < 0.001$) of the variability in tiller density (Table 4) in Triesdorf. Plotting the influence of clay and silt content on tiller formation until BBCH 31 in a contour plot clarified that increasing clay content promotes tiller density (Fig. 3a), especially if clay content reaches levels above 16%. A clear impact of silt content on tillering could not be observed. Notably, data for these graphics have not been corrected for outliers and smoothened by moving averages. While it is common practice in precision farming to generate maps from higher numbers of data points showing smooth gradients (Joernsgaard and Halmoe 2003; Karampoiki et al. 2021), this study deliberately avoids doing so. Therefore, single values not fitting into the gradients became visible and impeded uniform slopes. In contrast to tillering, soil properties did not significantly affect spike density and protein content. In 0–10 cm soil depth, SOC, silt plus clay content explained 46.0% of the variance in grain yield of winter wheat (p 0.001) (Table 4). However, the contour plot conveys that silt content influenced grain yield much more than the soil´s clay content (Fig. 3c).

In contrast, in the subsoil (30–60 cm), higher clay content was associated with a reduced tiller density, especially under silt concentrations < 30% (Fig. 3b). Areas with higher silt content showed no adverse effects

of increasing clay contents on tillering. Despite this, the variance in tiller density was explained to 37.0% by SOC plus clay ($p < 0.001$) (Table 4). Unexpectedly, the variation in spike density could not be significantly related to any subsoil´s measures, even so rooting depth usually reached its maximum during this developmental period (Rasmussen and Thorup-Kristensen 2016). In contrast, subsoil´s SOC, silt plus clay explained 45.0% of the variability in grain yield (< 0.001) (Table 4). A reduced grain yield was observed whenever clay content was higher than 12% paired with a silt content below 25% (Fig. 3d). The variables clay and silt could explain the variance in grain protein content to 27.0% ($p < 0.01$).

In Asendorf, tiller and spike density and grain protein content were explained by the same variables in a multiple regression analysis, but the effects were far less pronounced (Table S3). No regression relationships existed between soil properties and grain yield and its components, tiller density, spike density, or grain protein content in the topsoil.

Summing up, the less pronounced impact of soil measures on wheat yield and its yield components can be attributed to the lower variability of the soil measures at Asendorf (Fig. S2). These results indicate that small-scale differences in a subsite of a field of 4200 m^2 caused a difference in wheat grain yield of 1.6 t ha^{-1} in Triesdorf and 1.4 t ha^{-1} in Asendorf (Table 2). Interestingly, when the soil variability
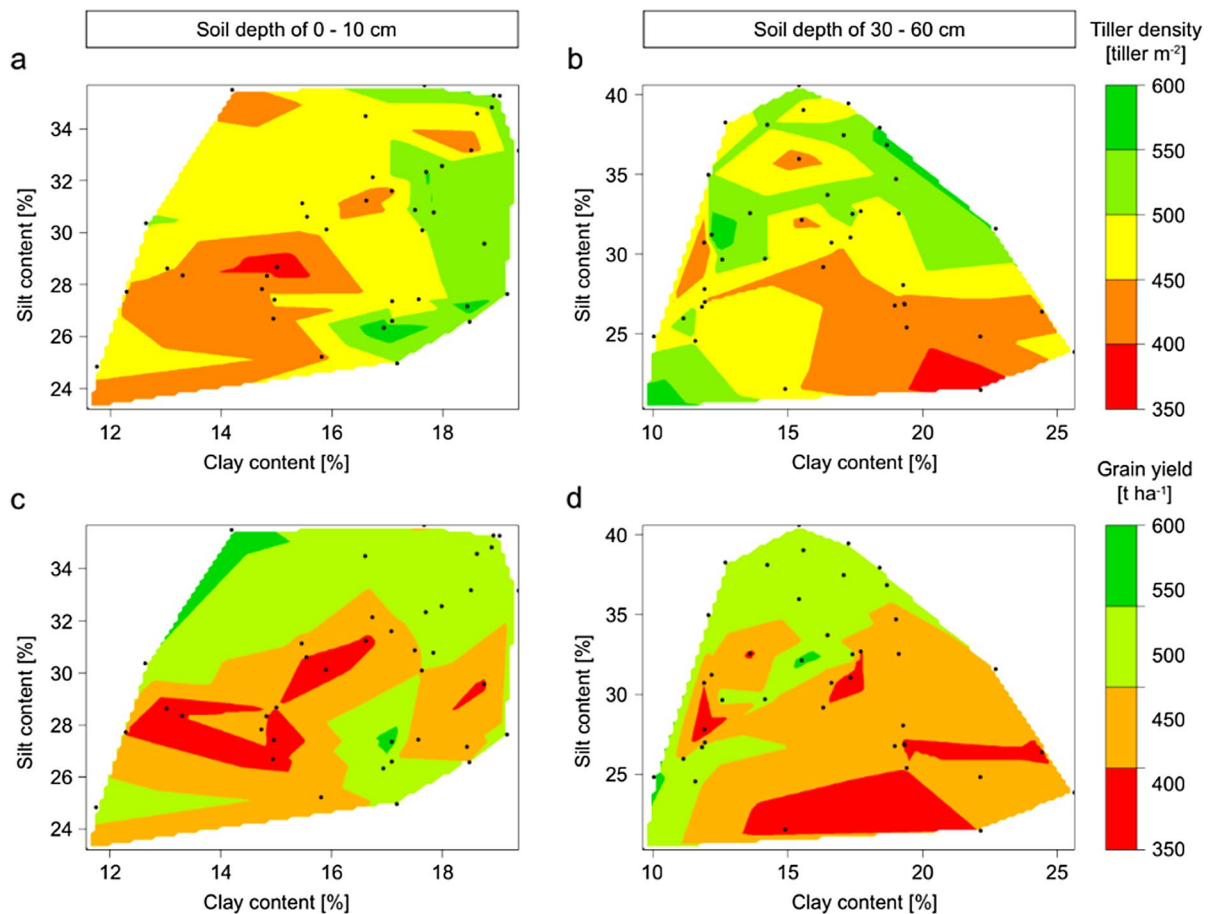
Fig. 3 Influence of silt and clay content in the soil depth of 0–10 cm (**a** & **c**) and 30–60 cm (**b** & **d**) on tiller density [tillers m^{-2}] in BBCH 31 (**a** & **b**) and on grain yield [t ha^{-1}] of winter wheat (**c** & **d**) in Triesdorf, 2016

was high, as in Triesdorf, 35 to 46% of the variance in grain yield could be explained by only a few soil measures depending on soil depth (Table 4). However, no interaction was observed under more homogeneous conditions, as in Asendorf (Table S3).

Impact of small-scale differences in soil properties on yield components

To analyze if our approach of evaluating yield formation in response to vertical and lateral small-scale variations in soil properties is relevant for the practical application of site-specific crop production, we first clustered the dataset by soil texture. Farm practice typically uses this method to develop application maps based on large-scale soil differences, such as for fertilization approaches. Therefore, the Triesdorf

dataset was clustered by soil properties in different depths. Because clusters were mainly described by sand and clay content, the 3 clusters were named low sand (LS) with a sand content ≤ 50%, high sand, and low clay (HS-LC) characterized by a sand content > 50% in combination with clay content ≤ 15%, and high sand and high clay (HS-HC) with sand content > 50% and clay content > 15% (Fig. 1).

All 3 clusters showed significant differences in sand content in every tested soil depth, with consistently smallest sand contents in LS and highest in HS-LC (Table 5). The highest clay content of the topsoil layers (0–30 cm), with around 18%, was observed in the LS cluster. In comparison, clay content decreased over HS-HC to around 14% in HS-LC. In contrast, the highest clay contents in the subsoil were recorded in the HS-HC cluster.

Table 5 Soil texture of the 3 clusters characterized by low sand (LS), high sand & low clay (HS-LC), and high sand & high clay (HS-HC) (clay, silt, sand [%], and soil organic carbon (SOC) content [mg g^{-1}]) and their impact on the plant measures grain yield [t ha^{-1}], tiller density [tillers m^{-2}], spike density [spike m^{-2}], thousand-grain weight [1000 grains g^{-1}]g, rain per spike [n], grain density [grains m^{-2}], single spike weight [g], grain density [grains m^{-2}], thousand-grain weight [1000 grains g^{-1}], and grain protein content [%] at Triesdorf in 2016

Soil depth [cm]	0–10 cm			10–30 cm			30–60 cm		
	LS	HS		LS	HS		LS	HS	
Cluster names		LC	HC		LC	HC		LC	HC
	(n = 11)	(n = 15)	(n = 15)	(n = 11)	(n = 16)	(n = 15)	(n = 11)	(n = 16)	(n = 15)
Soil measures									
Sand	47.8 c	57.9 a	53.7 b	47.0 c	57.2 a	53.4 b	45.7 c	59.0 a	52.5 b
Silt	34.3 a	27.9 b	28.7 b	34.9 a	27.3 c	29.5 b	36.7 a	28.6 b	28.0 b
Clay	18.0* a	14.1* b	17.6* a	18.1 a	13.9 c	16.6 b	17.5 b	12.3 c	19.5 a
SOC	16.4* a	10.9* b	16.4* a	14.0 a	10.9 b	12.8 a	7.6 a	5.9 b	6.5 b
Plant measures									
Grain yield	10.8 a	10.1 c	10.4 b	10.8 a	10.2 b	10.4 b	10.7 a	10.5 a	10.2 b
Tillers density	508 a	444 b	508 a	516 a	461 b	511 ab	513 a	494 a	454 b
Spikes density	475 a	465 a	469 a	482 a	459 b	477 ab	483 a	456 a	471 a
Thousand-grain weight	53.5 a	53.6 a	53.0 a	53.2 a	53.1 a	53.7 a	53.1 a	53.3 a	53.4 a
Grains per spike	42.7 a	41.1 a	42.3 a	42.1 a	42.7 a	40.5 a	42.0 a	43.5 a	40.8 a
Grain density	20,253 a	18,909 b	19,730 b	20,229 a	19,416 b	19,303 ab	20,213 a	19,716 ab	19,048 b
Single spike weight	2.3 a	2.2 a	2.2 a	2.2 a	2.3 a	2.2 a	2.2 a	2.3 a	2.2 a
Protein content	13.4 a	13.3 a	13.4 a	13.4 a	13.3 a	13.3 a	13.4 ab	13.4 b	13.3 b

Values representing means and different letters indicate significant differences among clusters at $p \leq 0.05$ by Fisher-LSD test or (*) Tukey HSD test

Irrespective of the soil depth, the highest SOC content was observed in the LS cluster with 16.4 mg g^{-1}, 14.0 mg g^{-1}, and 7.6 mg g^{-1} from the topsoil to the subsoil and lowest in HS-LC with 10.9 mg g^{-1}, 10.9 mg g^{-1}, 5.9 mg g^{-1}.

The grain yield of wheat responded significantly to differences in the soil texture of the 3 clusters. With 10.7 to 10.8 t ha^{-1}, grain yield was highest in the LS cluster in all soil layers (Table 5). Only HS-LC in the subsoil reached nearly the same yield level with 10.5 t ha^{-1}. At the high grain yield level of average 10.4 t ha^{-1} in our study, the soil´s small-scale differences caused only a maximum span of 10.1 to 10.8 t ha^{-1} between different clusters but still caused a max variation in grain yield of 6.9%.

Interestingly, variations in yield between clusters in all tested soil layers were neither related to the thousand-grain weight nor the number of grains per spike or single-spike weight. Nevertheless, grain density showed significant differences between clusters. Similar to the findings in grain yield, the highest grain density was observed in the LS cluster for all 3 soil layers with a range of 20,213 to 20,253 grains m^{-2}. A significantly smaller grain number was observed in the topsoil´s HS-LC cluster, with 18,909 (0–10 cm) and 19,416 grains m^{-2} (10–30 cm). Only in the subsoil, the HS-HC cluster with 19,048 grains m^{-2} led to the lowest grain setting. Interestingly, yield components formed during vegetative plant development responded stronger to differences in soil texture than those formed during the generative phase. In fact, tillering in the clusters followed the same pattern as grain density. Even the levels of significance were the same. Moreover, the tiller number was relatively low, with values between 444 and 516 tillers m^{-2}, compared to other experiments reaching a high grain yield (Sieling et al. 2005; Zhang et al. 2020). The only drawback was that the tiller density was not transferred to spike density in the 0–10 cm and the subsoil layer. Therefore, only the clusters of the second topsoil layer (10–30 cm) showed the same patterns as grain density and grain yield. Grains´ protein content was the only measure during the grain-filling phase, which was influenced by the soil differences represented by the clusters. Nevertheless, only the clustering in the subsoil led to significant effects in which HS-LC, with 13.4%, reached the highest protein content. At the same time, HS-HC resulted in only an infinitesimal reduction of 0.1% points to the smallest value in this analysis.

Summing up, the impact of soils´ small-scale differences at Triesdorf was prominent on tillering, spike density, grain density, grain yield, and even grain protein content employing the zoning technique as common practice in site-specific farming. At Asendorf, the cluster approach did not lead to statistically significant differences in plant measures due to a less pronounced small-scale variability of soil parameters (Table 1).

Discussion

Defining the appropriate resolution of sensor data, application maps, and the section size of agricultural machinery is an important step toward improving crop production systems through site-specific farming approaches. Especially when the economic value added is limited or even absent in practice, a higher resolution is often cited to improve the benefit of site-specific application strategies (Katalin et al. 2014; Späti et al. 2021). Indeed, this approach works well, especially in image-based decision systems, such as herbicide applications with single nozzle switching (Hørfarter et al. 2019; Kämpfer and Nordmeyer 2021; Oerke et al. 2010) or in the evaluation of canopy shapes and above-ground biomass, especially in multi-species cover crops (Kümmerer et al. 2023). In practice, however, high resolution is still limited, especially for soil data, like for variable-rate application in seeding (Šarauskis et al. 2022) and in nitrogen (Argento et al. 2021) or basic fertilization (Wagner and Marz 2017).

To tackle whether an increase in resolution can improve yield or resource efficiency, we did not conduct seeding or fertilization experiments to evaluate the performance of treatments under different soil conditions. Instead, we chose an inverse approach and evaluated the plant development under a regime of homogeneous crop production by different soil conditions. For this purpose, the small-scale variability of soil in the lateral and vertical dimensions was detected, and grain yield, its yield components, and quality measures were analyzed at two locations.

Spatial variability of small-scale differences in soil properties

In common practice, the site-specific variability of soil is detected laterally and vertically by electromagnetic resistivity (André et al. 2012; Basso et al.

2010; Boenecke et al. 2018) or soil conductivity (Cossel et al. 2019; Kühn et al. 2009; Stadler et al. 2015). The resolution of these methods is limited more by sampling grid and application conditions than by the limitations of the technology itself (André et al. 2012). Nevertheless, the exact composition of soil properties that trigger the signal, and thus the exact impact on plant growth, remains to be determined.

Soil texture variability increased from the topsoil with four to subsoil with six texture classes according to German soil classification in the field trials (Fig. 2), representing one factor for inhomogeneous growing conditions in Triesdorf. In Asendorf, soil conditions were more homogeneous. Here, the topsoil was represented by only two different soil texture classes, with the majority of 74–76% classified as Us. The homogeneity was even more pronounced in the subsoil, where 35 of the 42 plots were classified as Us (Fig. 2c).

At the Triesdorf field site, geological clay lenses resulted in a CV of 23.9% of the clay content, indicating a high variability of 9.6 to 25.6% clay in the subsoil (Table S1). Studies reported similar CV in subsoil's soil texture with larger grid sizes on experimental sites of 11–30 ha with 20 soil sampling points (Boenecke et al. 2018; Cammarano et al. 2019). Thus, there is clear evidence that small-scale variability can typically be as large as observed across the entire field site. This is also supported by other studies that report similar small-scale differences in soil textures as identified in our experiment (Grote et al. 2010; Martinez-Turanzas et al. 1997), and recent studies have shown that heterogeneous soil texture is common in arable fields and that higher resolution is beneficial (Boenecke et al. 2018; Bölenius et al. 2017; Mallarino et al. 1999; Stadler et al. 2015; Usowicz and Lipiec 2017; van Meirvenne 2003). To our knowledge, no studies have combined high-resolution sampling (9.0 m x 10.5 m grid size) of soil properties at lateral and vertical scales with yield measures in European environments.

Benefit of considering small-scale variability on plant properties

At the two field sites, fundamental differences in yield formation were observed due to different soil properties and climatic differences (Fig. S3), such as a milder winter and a more extended period for tillering in Asendorf. Although leaf appearance and tillering are strongly influenced by temperature and photoperiod (Ochagavía et al. 2017), this could not be the only explanation for the enormous tiller formation in Asendorf compared to Triesdorf (Table 2). Of course, the seeding time differs in agricultural practice between different sites, but increased vegetative development cannot explain differences in tillering between the northern and southern locations (Budzyński et al. 2018). Therefore, the main driver for the increased tillering in Asendorf must be the different soil textures (Fig. 2). Several studies have shown the impact of soil clay content, in particular, on the formation of yield components such as tillering in cereals (Bölenius et al. 2017; Dou et al. 2016; Gozdowski et al. 2017; Yunusa and Sedgley 1992). Nevertheless, the effect of soil texture on tiller number could only be observed in tendency in the stepwise multiple regression analysis for Asendorf (Table S3), and the tiller number only ranged from 725 to 855 tillers m^{-2} (Table 2). However, other studies have observed the impact of soil texture on wheat development and grain yield under similar climatic conditions (Johnen et al. 2014) or in general (Carvalho Mendes et al. 2021; Pan et al. 2020). On the other hand, the influence of soil texture on tillering was present in Triesdorf and was mainly determined by clay and SOC content in the top and subsoil (Table 4).

Interestingly, although the site-specific differences by soil types are at first sight more heterogeneous in Triesdorf (Fig. 2), the CV for clay, silt, and sand were at a similar level as in Asendorf (Tables S1, S2). Nevertheless, the variation in Asendorf caused a variation in tillering and resulted in a CV for tiller density of 3.7% compared to 10.8% for Triesdorf. As an explanation for this phenomenon, high silt concentrations (Watson et al. 2002), as observed in Asendorf, are often mentioned in the literature.

However, the high tiller density in Asendorf, where site-specific variation was low, did not result in similarly high yields as in Triesdorf (Table 2), even though the site is generally considered to have higher yield potential due to favorable climatic conditions for winter wheat (Lüttger and Feike 2018). Nevertheless, the tiller density in Asendorf was too

high compared to Triesdorf, which is indicated by an average of 9 fewer grains per spike, resulting in a decrease in grain density by 2788 grains m^{-2}. In addition, the grain filling was also negatively influenced by the elevated tiller density, so the single spike weight was reduced by approximately 1.0 g compared to Triesdorf. The thousand-grain weight reached only 39.6 g compared to 53.3 g in Triesdorf (Table 2). The observation of decreased grain filling under a high organ setting, e.g., tillering under the condition of a specific location, is consistent with the findings of other studies (Slafer et al. 2014; Berry et al. 2003; Langridge 2017). Besides the general differences in yield formation between the two contrasting sites, the influence of small-scale variability in soil properties on yield was evident on both sites. It strongly depended on lateral soil texture differences across the field site and on vertical differences along the soil depth profile, especially under the condition of the soil properties in Triesdorf (Fig. 2). Subsoil conditions, which are important for water and nutrient availability (Kautz et al. 2013; Kuhlmann and Baumgärtel 1991; Kuhlmann 1990; Kuhlmann et al. 1989; Zheng et al. 2023), explain the differences in yield formation, especially during generative development. In another study, small-scale variability in subsoil texture was observed to influence water and nutrient fluxes (Leinemann et al. 2016).

However, the influence of small-scale soil texture differences in different soil layers on tiller density was rarely investigated. Interestingly, the soil measures SOC and clay in the first soil layer of 0–10 cm explained 43.0% of the variability in tiller density (Table 4) and decreased to 30% in the subsoil. At Asendorf, soil properties had little or no significant impact on tillering, regardless of which soil layer was analyzed. Previous studies have shown that winter wheat roots reach the subsoil before tillering (Hodgkinson et al. 2017; Zhou et al. 2022). Increasing clay content was associated with increased tiller density in the topsoil layer, while opposite effects occurred in the subsoil (Fig. 3; Table 4). An explanation for this observation is provided by Coelho Filho et al. (2013), who suggested that increasing soil impedance due to changes in soil texture negatively affects tiller density. At Triesdorf, 46.0% of the yield variability was explained by soil properties of the first layer (0–10 cm), 35.0% of the 10–30 cm layer, and 45.0% of the subsoil (Table 4). Similar observations of small-scale lateral differences

in soil texture and chemical soil properties linked to grain yield were reported in former studies (Hausherr Lüder et al. 2018; Maidl et al. 1999). Nevertheless, under the conditions of Asendorf, no significant impact of soil properties on yield variability has been observed (Table S3).

Taken together, we suggest a smaller grid size for site-specific crop management beyond the current standard grid size of approx. 20 m to 20 m, derived from satellite-based remote sensing, can increase grain yield, especially on sites with highly inhomogeneous soil properties. Based on our results, we recommend using a higher resolution of at least 10.5 m to 9.0 m as the grid size.

SOC is relevant at all soil depths

In addition to soil texture, the wheat yield was strongly determined by SOC, which explained 45–46% of the yield variability in Triesdorf, irrespective of the soil depth studied (Table 4). This is consistent with previous findings of increased grain yield at higher subsoil SOC (Usowicz and Lipiec 2017). In line with other studies, SOC content decreased with soil depth and was associated with the soil type (Börjesson et al. 2018; Poeplau et al. 2020). In Asendorf, no relationships between soil SOC and grain yield were observed (Table S3). This could be explained by a combination of non-limited precipitation (Fig. S3), less pronounced subsoil heterogeneity (Fig. 2c), and a generally lower yield level (Table 2), which did not fully exploit the yield potential. In previous studies, SOC increased nitrogen use efficiency (Oelofse et al. 2015) and had a positive influence on cereal grain yield (Šeremešić et al. 2020; Stein et al. 1997), even under soil conditions similar to the present study, as reported in Poland on sandy soils in a coarse sampling grid (Usowicz and Lipiec 2017). In addition, a previous study by Cammarano et al. (2019) on winter barley highlighted the importance of soil texture and bulk density, closely related to SOC, on the vertical distribution of nitrogen below 30 cm soil depth and showed an impact on crop yield stability. In general, the need for nutrient and water uptake from the subsoil is closely related to the topsoil conditions (Engels et al. 1994; Jin et al. 2015), such that nutrient uptake from the subsoil does not necessarily result in higher grain yield (Hodgkinson et al. 2017). Thus, in Asendorf, non-limiting precipitation may have reduced the impact of the soil properties on grain yield.

Our data support the view that SOC provides a valuable indication of growing conditions and can benefit site-specific management decisions. Because site-specific yield potential and mineralization patterns are closely related to soil properties, variable-rate mineral fertilizer application will likely improve nitrogen use efficiency. High-resolution information on soil properties is essential to achieve this efficiency (Argento et al. 2021; Tubaña et al. 2008). However, despite the environmental benefits, the economic value of the technology for smaller farms is still questionable (Späti et al. 2021).

Conclusion

The present study shows lateral and vertical soil property variations significantly influence winter wheat development and grain yield, even at small field scales. The approach to defining clusters of physical soil properties within different soil depths is suitable for quantifying the effect of soil heterogeneity on yield patterns and assessing the impact and reliability for practical use. The described approach is particularly relevant whenever soils show small-scale soil texture or SOC differences. Future studies should define the optimal grid size for site-specific crop production strategies by considering soil heterogeneity to improve grain yield, yield stability, and input efficiency for sustainable crop production.

Data availability The Datasets from the current study are available in the zenodo database, https://doi.org/10.5281/zenodo.8245951.

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