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Seasonal differences in tillage draught on a sandy loam soil with long-term additions of animal manure and mineral fertilizers

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Abstract

Energy requirements for soil tillage are closely linked to soil properties such as contents of clay, water and soil organic carbon (SOC). Long-term application of inorganic and organic fertilizers affects SOC content, but little is known about seasonal differences in tillage draught requirements of soils subject to contrasting fertilization regimes. We assessed autumn and spring tillage draught following harvest of early and timely sown winter wheat grown on a sandy loam in the Askov Long-Term Experiment on Animal Manure and Mineral Fertilizers. Draught force was related to soil texture, soil water and SOC content, shear strength and bulk density, fertilization, and to yields of the preceding winter wheat. Contents of clay and SOC ranged from 8.9 to 10.6 % and from 0.98 to 1.36 %, respectively. In the autumn and spring, SOC normalized to clay content explained 38 and 5 % of the variation in specific draught, respectively. Specific draught did not differ significantly among individual fertilization treatments. SOC was closely correlated with contents of clay and water, with bulk density and with yields of the preceding wheat. Draught force was significantly smaller in the spring than in the autumn. In the autumn when soils were drier (- 700 hPa) tillage draught was correlated with several soil characteristics, whereas water content was the dominating parameter in the spring when soils were more wet (- 100 hPa). The range of SOC contents observed in this study aligns with that observed in Danish sandy loams under intensive cultivation, and within this range SOC *per se* had little effect on draught requirements.

Keywords: Soil Physical Properties, Soil tillage, Energy, Tractor fuel

Highlights

- We assessed seasonal differences in tillage draught of soils subject to contrasting fertilization
- Draught force was significantly smaller in the spring than in the autumn

- In the autumn when soils were drier tillage draught was correlated with several soil characteristics
- Water content was the dominating parameter in the spring when soils were more wet

Introduction

Soil tillage accounts for a significant part of the fuel consumption associated with crop production. Consumption of diesel fuel for temperate zone light to medium-textured soils typically range 20-30 l ha⁻¹ for mouldboard ploughing and 5-20 l ha⁻¹ for harrowing implements (Dalgaard et al., 2001; Bailey et al., 2003). Specific draught for tillage has been related to soil clay and soil organic carbon (SOC) content which together may explain more than 60% of the variation in draught force across a field (Watts et al., 2006; Peltre et al., 2015). Large applications of organic waste inducing high SOC contents may substantially reduce draught force but applications of mineral fertilisers at farm-relevant rates have also been shown to moderate draught force requirements (Watts et al., 2006; Liang et al., 2013; Peltre et al., 2015). Inputs of above- and belowground crop residues and organic amendments affect soil bulk density, tensile strength, clay dispersibility and soil cohesion (Schjønning et al., 1994, 2012; Munkholm et al., 2002) and thereby also tillage draught. However, soil water content is known to play a key role for soil friability and draught force requirements (Watts and Dexter, 1994; Perfect et al., 1997; Arvidsson et al., 2004; Munkholm, 2011).

Long-term field experiments are indispensable for studies on management impacts on SOC and draught force requirements, because changes in SOC develop slowly and over long periods. Studies of soil tillage draught requirements under contrasting and long-term management are rare, with draught force being measured on a single occasion (Watts et al., 2006; Peltre et al., 2015) or in the autumn across several years (McLaughlin et al., 2002; Liang et al., 2013). In the temperate zone, soil mechanical properties show substantial seasonal changes due to cycles of

organic inputs, drying-rewetting, freeze-thaw, and fluctuations in soil moisture and biological activity (Kay and Dexter, 1992; Munkholm et al., 2003). Although differences in draught requirements between autumn and spring are of particular interest for temperate soils because most tillage operations are performed during these periods, field studies of seasonal differences in tillage draught force could not be traced. We hypothesized that tillage draught force changes over-winter and that the relationships between draught force and above-mentioned soil parameters also differ between autumn and spring.

We assessed autumn and spring tillage draught requirements following harvest of early and timely sown winter wheat. The wheat was grown at the Lermarken site of the Askov Long-Term Experiment on Animal Manure and Mineral Fertilizers (Askov-LTE), a sandy loam soil first cultivated around year 1800 and with widely different fertilisation since 1894. The Askov-LTE includes unmanured plots and plots receiving different rates of nitrogen (N), phosphorus (P) and potassium (K) in animal manure and in mineral fertilizer. Subsidiary treatments are mineral fertilizer N, P and K, added individually or in combinations of two. Draught force was related to soil texture, soil water and SOC content, shear strength and bulk density, fertilization, and to grain and straw yields of the preceding winter wheat.

Materials and Methods

The Askov Long-Term Experiment (Askov-LTE)

The Askov Long-Term Experiments on Animal Manure and Mineral Fertilizers (Askov-LTE) was established in 1894 at Askov Experimental Station, Denmark (55°28'N, 09°07'E; elevation 63 m a.s.l.). Annual average precipitation and potential evapotranspiration is 862 mm and 543 mm, respectively, and mean annual temperature is 7.7 °C (1961-1990 averages; Christensen et al., 2006). The Askov-LTE Lermarken site consists of four blocks termed B2-, B3-, B4- and B5-field and is

cropped with a four course rotation of winter wheat, silage maize, spring barley, and a grass-clover mixture used for cutting. Thus, each crop is present every year in a separate field. The soil is a light sandy loam derived from Weichselian glacial deposits and classified as Typical Hapludalf according to the USDA Soil Taxonomy System. Soil pH is maintained in the range 5.5 – 6.5 by addition of magnesium-enriched lime every four years.

The main treatments of the Askov-LTE are unfertilized plots (Unf) and plots amended with different levels ($\frac{1}{2}$, 1, $1\frac{1}{2}$ and 2 times the standard rate for a given crop) of nitrogen (total-N), phosphorus (P) and potassium (K) in animal manure (AM) or in mineral fertilizers (NPK). Subsidiary treatments are mineral fertilizer N, P and K, added individually (1 N, 1 P and 1 K) or in combinations of two (1 NP, 1 NK and 1 PK). Mineral fertilizer N, P and K are given in calcium-ammonium-nitrate, triple-super-phosphate and potassium-chloride, respectively. The manure has been cattle slurry since 1973 with an average of 5 % dry matter and with 60 % of the total-N being on ammoniacal form. Not all treatments are present in all fields and the number of treatment replicates within each field differs. Averaged across the rotation, fertilization level 1 corresponds to an annual input of 100 kg total-N ha^{-1} , 20 kg P ha^{-1} and 80 kg K ha^{-1} . For cattle slurry, the fertilization level 1 typical corresponds to the addition of 25 t slurry (fresh weight) ha^{-1} . Further details are given by Christensen et al. (2006) and Christensen and Johnston (1997).

The present study was embedded in the B5-field (fertilization level 2 not present) following harvest of winter wheat. For wheat, 1 AM and 1 NPK corresponds to 150 kg total-N ha^{-1} , 30 kg P ha^{-1} and 120 kg K ha^{-1} . The wheat crop had been established after ploughing of the grass-clover sward on 22 August 2013. Subsequently, each field plot was divided into two subplots (each $11.7 \times 4.7 \text{ m}^2$). One subplot was sown to wheat on 23 August 2013 (early sown wheat; 225 seeds m^{-2}), while the other subplot was sown to wheat one month later on 23 September 2013 (timely sown wheat; 350 seeds m^{-2}). The harvest took place on 5 August 2014 using a plot combiner that

allowed separate determination of grain and straw yields and left 5 cm of wheat stubbles. Wheat grain and straw was removed from the plots immediately upon harvest. The field was treated with a broad-spectrum weed killer (glyphosate) to eliminate any effect of volunteer plants on subsequent draught force recordings.

Measurement of draught force

Draught force was determined on 23 September 2014 (autumn campaign) and again on 12 March 2015 (spring campaign) with no tillage or weed re-growth in between the two campaigns. The measurement setup consisted of three spring tines (model: Kongskilde Vibro Flex, Kongskilde Industries A/S, Skælskørvej 64, DK-4180 Sorø, Denmark) spaced 45 cm apart on a purpose-build toolbar (see Nyord et al., 2010). The toolbar was attached to the three-point linkage of a 48.5 kW (65 hp) Massey Ferguson 365 2WD tractor. The tines were 65 mm wide (w) with a rake angle of 22° related to the horizontal plane, and the working depth (d) was 12 cm below the soil surface. Each tine was connected to an extended octagonal ring transducer (EORT) (Godwin, 1975) measuring the horizontal force and recording the draught force at a frequency of 200 Hz. The tractor was driven along the plots at a nominal speed of 4 km h⁻¹ (actual ground speed being recorded by geo-radar mounted on the toolbar) with two replicate runs in the autumn and one run in the spring. Specific draught force (SDfr) was calculated according to:

$$SDfr = \frac{Dfr}{3wd} \quad [1]$$

where Dfr is in kN and the width of the tines (w) and implement depth (d) of the tines are in metres. Only recordings from the central 4 m of each plot were used in the calculations. Soil cross-section disturbance area was measured in randomly selected plot according to Chen et al. (2013) and showed no significant difference among treatments.

Soil characterization

Bulk soil (0-12 cm depth) was sampled next to the tine tracks in all plots in autumn 2014 and again in spring 2015 immediately following the draught force recordings. Gravimetric water content was determined after drying the soil at 105 °C for 24 hours. SOC content and soil texture were determined only on soil sampled in the autumn. Texture was determined using wet sieving and the hydrometer method after dispersing soil in 0.1 M sodium pyrophosphate solution (Gee and Bauder, 1986). Concentrations of SOC were determined on ball-milled subsamples using dry combustion (Thermo Flash 2000 NC Soil Analyzer, Thermo Scientific).

For determination of autumn and spring soil bulk density, six intact soil cores (100 cm³) were sampled in 5-10 cm depth in each of three replicate plots of the treatments: Unf, ½ NPK, 1 NPK, and 1 ½ AM.

Determination of in-situ soil cohesion relied on different vane shear tools in the autumn and spring campaigns. In the autumn, the vane shear (diameter 33 mm and height 50 mm) was inserted 75 mm into the soil before the shear test while in the spring, the vane shear (diameter 100 mm and height 50 mm) was placed 50 mm below soil surface. The average cohesion values are based on ten separate recordings in each plot, taken in undisturbed soil near the tine tracks.

Statistical analyses

Linear mixed effect models were used to test the significance of soil parameters applying the *lmer* function of the *lme4* package in R software version 3.1.0. Soil parameters were set as fixed effects while plot position (plot row and column) in the B5-field was set as random effects. This allowed us to account for the unbalanced design of the field experiment with different treatments having different number of replicates. The significance of soil parameters were assessed using ANOVA comparing models including a fixed effect to a model including only random effects (i.e. plot rows

and columns). Multiple pairwise comparisons were calculated ~~in order~~ to isolate differences between treatments using the general linear hypotheses (*glht*) function implemented in the *multcomp* package in R. Linear regressions were performed using SigmaPlot V.13.

Results

Soil characteristics

On average, the soil in the Askov-LTE B5-field held 10 % clay (< 2 µm), 11 % silt (2-20 µm), 12 % coarse silt (20-63 µm), 26 % fine sand (63-200 µm) and 39 % coarse sand (200-2000 µm) with no significant differences among fertilization treatments and 2 % organic matter. Plots situated to the east side of the field tended to be slightly enriched in clay and clay+silt compared with plots situated to the west side of the field (Figure 1). The SOC content (Figure 2) was smallest in the Unf (unfertilized) and 1 NP treatments (0.98 and 1.00 % C, respectively) and highest in the 1 ½ AM treatment (1.36 % C).

Significant positive correlation was found between contents of clay and SOC (P=0.016, Table 1, Figure 3a) while the correlation between clay+silt and SOC content was on the fringe of significance (P=0.053, Table 1, Figure 3b). The gravimetric water content was greater in the spring (average; 15.2 % water) than in the autumn (average; 11.5 % water) and showed a positive and significant relationship with clay content in the autumn (P=0.048, Table 1, Figure 3c) but not in the spring (P=0.078). However, soil water was positively related to clay+silt content in autumn (P=0.042) as well as in spring (P=0.033; Figure 3d). Soil water content showed a strong positive correlation with SOC in the autumn and spring (P<0.0001, Table 1, Figure 3e). SOC showed a negative correlation with shear strength in the autumn and with bulk density in autumn as well as spring, and a positive correlation with straw and grain yields (Table 1).

Effects of fertilization treatments on draught

Average draught force in the autumn campaign ranged from 1.48 kN in the 1½ AM treatment to 1.81 kN in the 1 P treatment, representing specific draughts of 63.2 and 77.4 kPa, respectively (Figure 4). In the spring campaign average draught force ranged from 1.34 kN for 1 NK to 1.64 kN for 1 P, corresponding to specific draughts of 57.1 and 70.1 kPa. However, the specific draught did not differ significantly among individual fertilization treatments, neither in the autumn nor in the spring.

Effects of soil characteristics on draught

Linear regression analyses revealed that specific draught tended to be positively related to clay content in the autumn ($r=0.31$, $P=0.073$, Table 1, Figure 5a) but not in the spring ($P=0.524$), the relationship being weaker for clay+silt than for clay content (Figure 5b). SOC content was significantly negatively correlated with specific draught in the autumn ($P=0.035$, Figure 5c), and this correlation became stronger when specific draught was normalized to clay content ($P<0.001$, Figure 5d). These relationships were not significant in the spring campaign (Figure 5c and d). However, seen across the whole dataset, SOC content did not explain much of the variation in specific draught. Clay/SOC and Clay+Silt/SOC ratios were significantly positively correlated with specific draught measured in the autumn but not in spring (Table 1).

The correlation between specific draught and gravimetric soil water content was not significant when autumn and spring data were considered separately whereas a significant negative correlation was seen when autumn and spring data were pooled ($P=0.001$, Figure 5e). When specific draught was normalized to clay content (SDfr/Clay), the negative correlation with water content became significant for autumn data ($P=0.048$, Figure 5f), and for autumn and spring data analysed together ($P<0.001$).

Specific draught measured in the autumn was also positively correlated with bulk density but this is mainly due to differences in SOC, soil bulk density being tightly correlated with SOC content (Table 1). A significant positive relation between specific draught and shear strength ($r=0.74$, Table 1) was seen in the spring ~~campaign~~ while a weaker and non-significant relationship was observed in the autumn ($r=0.30$, Table 1).

Effect of fertilization regimes and grain yield

The nutrient treatments were grouped into three fertilization regimes: animal manure, balanced mineral NPK fertilizers, and unbalanced fertilization (unfertilized treatment and treatments with mineral fertilizer N, P and K added individually or in combinations of two). Using this approach, specific draught normalized to clay content (SDfr/Clay) was significantly lower for manured soil than for soils subject to unbalanced fertilization ($P=0.022$) but only in the autumn (Figure 6). The SDfr/Clay ratios for balanced NPK fertilization and unbalanced fertilization tended to be smaller in spring than in autumn, while similar autumn and spring ratios were found for the animal manure regime.

The correlation between wheat grain yields and specific draught was tested as crop vigor and especially root growth could influence soil physical properties. Wheat grain yields correlated with SDfr/Clay ratios determined in the autumn ~~campaign~~ when all treatment plots were taken together, plots with greater yields having lower SDfr/Clay values (Figure 7a). There was no significant correlation in the spring (Figure 7b). In the autumn, the SDfr/Clay values in manured plots tended to be negatively correlated with grain yield ($r=-0.60$, $P=0.068$) while the NPK and unbalanced fertilization regimes ~~plots~~ showed no such relationship (Figure 7a). This finding became clearer when grain yield of early sown and timely sown wheat and the associated measurements of SDfr/Clay in the autumn were considered separately (Figure 8). Grain yield was correlated with

SDfr/Clay for the early sown wheat only and not for the timely sown wheat. When only yields of early sown wheat were considered (Figure 8a), the manure ~~fertilization~~ regimes now showed a significant negative correlation between grain yield and SDfr/Clay ($r=-0.69$, $P=0.027$). ~~It is noted that wheat grain and straw yields are~~ closely correlated (Table 1).

Seasonal differences in draught force

The draught force values were significantly smaller in the spring than in the autumn ($P<0.001$; Figure 5). The average gravimetric soil water content was greater ($P<0.0001$) in the spring (15.2 %) than in the autumn (11.5 %). These gravimetric water contents correspond to matric potentials of c. -100 hPa and -700 hPa, respectively. When specific draught force were grouped into ~~fertilization~~ regimes (Figure 6), autumn and spring values were similar for the manure treatments, ~~while~~ draught force decreased from autumn to spring in soil under NPK and unbalanced ~~fertilization~~ regimes. The relative difference in specific draught between autumn and spring ~~campaigns~~ could be partly explained by the difference in soil water content (Figure 9a). The seasonal variation in draught force was correlated with the Clay/SOC ratio in different ways for the different ~~fertilization~~ regimes (Figure 9b). For unbalanced ~~fertilization~~, the relative seasonal differences in SDfr was negatively correlated with the Clay/SOC ratio; for the balanced NPK regime the correlation was positive ~~while~~ no correlation was found for manure.

Discussion

Effect of texture and soil organic matter

The clay content in the B5-field used for tillage draught measurements ranged from 8.9 to 10.6 % and clay+silt from 19.5 to 22.0 %. This variation in soil texture is considerably smaller than reported in previous studies on more clayey soils (Arvidsson et al., 2004; Watts et al., 2006; Liang

et al., 2013; Peltre et al., 2015), and the lighter texture may explain the lower specific draught values found in our study. The narrow range in texture allowed for detailing the effect of small differences in SOC on draught force. SOC *per se* explained only 13% of the variation in specific draught in the autumn and 6 % in the spring. When specific draught was normalized to clay content (SDfr/clay) SOC explained 38% and 5%, respectively. Although results from the autumn campaign confirmed that SOC affects specific draught force, the correlation was much weaker than reported in studies involving large organic amendments (Watts et al., 2006; Peltre et al., 2015). In these studies, SOC and clay contents together explained more than 60% of the variance in specific draught. This difference is ascribed to a much smaller range in clay and SOC contents in the present study. Noticeably, we observed a strong influence of season on draught force requirements. In contrast to the autumn campaign, results from the spring campaign showed insignificant effects of SOC on draught force. Seasonal effects have not previously been reported and are discussed below.

Influence of water content and shear strength

Our results show a negative correlation between specific draught/clay and water content for the autumn but not for the spring measurements, and the spring results show a positive correlation between specific draught and shear strength. Similar relationships are reported by Arvidsson et al. (2004) and Peltre et al. (2015). The stronger correlation in the spring than in the autumn could be due to difference in especially water content, although the different vane shear equipment applied for spring and autumn measurements may also have played a role.

Influence of crop yield

Interestingly, SDfr/clay determined in the autumn displayed a negative correlation to grain yield for the manure treated soil although only significant for soil after early sown wheat. Yields of wheat

dressed with animal manure was more responsive to benefits derived from early sowing than wheat grown with mineral NPK fertilizers, the average grain yield for early sown wheat grown with manure being 1 Mg ha^{-1} higher than that for timely sown wheat. For wheat grown with mineral NPK fertilizers the difference was 0.5 Mg ha^{-1} . Watts et al. (2006) found that increasing applications of mineral fertilizer N caused a relatively small increase in SOC but a relatively large decrease in specific draught. They proposed that a larger return of stubble and root material associated with increased fertilization could have a disproportionately large effect on the soil physical parameters. Our study supports this view. Due to its higher yield, early sown wheat may have left more stubble and root-derived residues with a positive effect on draught requirements. However, any superior effect on draught force associated with early sown wheat is likely to diminish from autumn to spring as the decay of residues advances over-winter. Thus, McLaughlin et al. (2004) ascribed reductions in tillage draught following use of glyphosate to breakdown of root tissue structures and an associated loss of mechanical strength of the plant roots.

According to Table 1, high SDfr/clay levels correlates with high bulk density levels, i.e. poor soil structure, suggesting a vicious circle (Kay and Munkholm, 2004) where low nutrient input decrease grain yields, the low grain yields (i.e. low inputs of labile organic matter to the soil) decrease soil structural stability, and the poor structural stability cause high degree of compaction. The latter will then amplify the negative effect of low nutrient input on crop growth. It is not surprising that crop yields do not correlate with SDfr/clay for the unbalanced treatments as lack of one or more nutrients will be the most yield-limiting factor for those treatments. On the other hand it is interesting that there was no correlation for the NPK treatments either.

Seasonal variation

Overall, a decrease in draught force from autumn to spring occurred for the balanced NPK and unbalanced fertilization regimes (unfertilized, one or two nutrients only) but not for the manured treatments (Figure 6). This could to a large extent be explained by a larger increase in soil water content for the NPK and unbalanced regimes than for the manured soil (Figure 9a). In the spring with soil water contents around -100 hPa, the specific draught correlated significantly with shear strength and bulk density only while there was no effect of SOC and clay contents. Under the drier conditions in the autumn (c. -700 hPa), specific draught correlated not only with bulk density but also with SOC and Clay/SOC. This aligns with previous studies showing that the influence of clay and SOC on soil strength depends on water regime. In the review of Schjønning et al. (2015) clay was found to play an insignificant role on soil strength at -100 hPa matric potential but a very significant role at drier conditions. Further, the effect of water regime on soil strength is smaller for soils high in SOC than for soils low in SOC (Munkholm and Kay, 2002; Munkholm et al., 2002), soil strength increased more with decreasing water contents for soils low in SOC content.

For the unbalanced fertilization regime, the seasonal difference in specific draught increased with increasing Clay/SOC ratio (Figure 9b). This indicates that soils with unbalanced fertilization and Clay/SOC near 10 might be more susceptible to structure degradation and drying/rewetting events than soils with smaller Clay/SOC ratios (Kay and Dexter, 1992; Schjønning et al., 2012; Getahun et al., 2016; Jensen et al. Submitted). The balanced NPK treatments showed, surprisingly, the opposite trend as the unbalanced treatments, i.e. significantly decreasing seasonal difference with increasing clay/SOC ratio (Figure 9b). This is not readily explained but it is noted that this correlation strongly depends on three data points with a Clay/SOC ratio <8. Field studies on soils with larger gradients in SOC but little in-field variation in texture are needed to identify the effect of organic matter on draught force at different water regimes and to recommend the ideal range in water content for soil tillage (Munkholm, 2011). Further research is required to elucidate

seasonal annual patterns in tillage draught across several years as these are influenced by specific weather conditions.

Conclusions

Our study was based on a well-controlled field experiment on sandy loam with little spatial variation in soil texture (8.9 to 10.6 % clay). The contrasting fertilization treatments maintained for > 120 years allowed us to examine the long-term effects of fertilizer type and rate on tillage draught requirements avoiding confounding effects of clay and SOC contents. Contents of SOC ranged from 0.98 to 1.36 % C. In the autumn and spring, SOC normalized to clay content explained 38 % and 5 % of the variation in specific draught, respectively. Specific draught did not differ significantly among individual fertilization treatments, neither in the autumn nor in the spring. SOC was found to be closely correlated to contents of clay and soil water, and to bulk density and yields of the previous wheat crop. Draught force values were significantly smaller in the spring than in the autumn. While tillage draught in the autumn at a water content corresponding to – 700 hPa was found to be correlated with several soil characteristics, the higher soil water content in the spring (corresponding to – 100 hPa) was found to be the dominating parameter at this time. Our findings are important when evaluating the energy required for soil tillage and to evaluate the optimal soil status for tillage operations. The range of SOC aligns with that observed in sandy loams under intensive cultivation, and within this range SOC *per se* appears to have little effect on tillage draught.

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For Peer Review

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Figure captions:

Figure 1. Spatial distribution of clay ($< 2 \mu\text{m}$) and silt+clay ($< 20 \mu\text{m}$) across plots in the B5-field of the Askov-LTE.

Figure 2. Boxplot with median and quartiles for SOC content for individual fertilization treatments in the B5-field. Different letters indicate significant differences in SOC content at $P < 0.05$.

Figure 3. Relationships between soil texture, SOC and water content in soil sampled in the B5-field at the autumn and spring measurement campaigns.

Figure 4. Boxplot with median and quartiles for specific draught measured in the autumn and spring in individual fertilization treatments of the B5- field.

Figure 5. Relationships between specific draught and soil texture, SOC content and water content in soil from the B5-field at the autumn and spring measurement campaigns.

Figure 6. Specific draught normalized to clay content (SDfr/Clay) for different fertilization regimes in the B5-field at the autumn and spring campaigns. Letters denote significant difference in the autumn campaign at $P < 0.05$; no significant differences were observed in the spring measurement campaign. The fertilization regimes are: manure (all treatments given animal manure), NPK (all treatments with balanced addition of mineral fertilizer N, P and K) and unbalanced fertilization (unfertilized and all treatments with mineral fertilizer N, P and K added individually or in combinations of two).

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Figure 7. Relationships between grain yields of the previous winter wheat crop and specific draught normalized to clay content ($SD_{fr}/Clay$) for the autumn (a) and spring (b) measurement campaigns. For definition of fertilization regimes see legend in Figure 6.

Figure 8. Relationships between grain yield of the previous winter wheat crop (a, early sown; b, timely sown) and specific draught normalized to clay content ($SD_{fr}/Clay$) at the autumn measurement campaign. For definition of fertilization regimes, see legend in Figure 6.

Figure 9. Relationships between interseasonal difference in specific draught (SD_{fr}) and in water content (a) and Clay+silt/SOC ratio (b). Two outliers (plot 551 Unf; plot 522 NK) were removed from the dataset for the unbalanced fertilization regime. For definition of fertilization regimes, see legend in Figure 6.

Table 1. Pearson correlation table for the autumn results and for the spring result (in italic font). ‡ denotes variables varying between autumn and spring (i.e. measured in the autumn and in the spring).

	Clay	Silt	Silt+Clay	Coarse silt	Fine sand	Coarse sand	Water content	SOC	Clay/SOC	Clay+Silt/SOC	Shear strength	Straw Yield	Grain Yield	Bulk density	Specific draught
Clay		0.14	0.80****	-0.12	0.00	-0.35*	0.30	0.40*	0.02	-0.20	0.09	0.16	0.22	-0.14	0.11
Silt	0.14		0.71****	0.30	0.32	-0.68****	0.24	0.07	-0.03	0.13	-0.15	0.10	0.06	0.22	0.08
Silt+Clay	0.80****	0.71****		0.10	0.19	-0.67****	0.36*	0.33	0.00	-0.06	-0.03	0.17	0.20	0.00	0.13
Coarse silt	-0.12	0.30	0.10		0.05	-0.65****	-0.14	-0.29	0.25	0.33	0.09	-0.10	-0.11	0.15	0.26
Fine sand	0.00	0.32	0.19	0.05		-0.58***	-0.03	-0.25	0.28	0.33	0.05	-0.25	-0.32	-0.03	0.07
Coarse sand	-0.35*	-0.68****	-0.67****	-0.65****	-0.58***		-0.16	0.00	-0.16	-0.20	-0.09	0.03	0.05	0.04	-0.25
Water content‡	0.34*	0.17	0.35*	-0.05	0.18	-0.31		0.69****	-0.60***	-0.61***	0.26	0.38*	0.37*	-0.37*	0.20
SOC	0.40*	0.07	0.33	-0.29	-0.25	0.00	0.62****		-0.90****	-0.95****	0.13	0.53**	0.60***	-0.65****	-0.07
Clay/SOC	0.02	-0.03	0.00	0.25	0.28	-0.16	-0.51**	-0.90****		0.96****	-0.12	-0.51**	-0.57***	0.67****	0.11
Clay+Silt/SOC	-0.20	0.13	-0.06	0.33	0.33	-0.20	-0.54***	-0.95****	0.96****		-0.17	-0.52**	-0.59***	0.67****	0.09
Shear strength‡	-0.23	-0.03	-0.18	-0.19	0.06	0.25	-0.36*	-0.49**	0.44**	0.48**		0.17	0.20	-0.54***	0.74****
Straw Yield	0.16	0.10	0.17	-0.10	-0.25	0.03	0.34*	0.53**	-0.51**	-0.52**	0.00		0.98****	-0.42*	-0.15
Grain Yield	0.22	0.06	0.20	-0.11	-0.32	0.05	0.34*	0.60***	-0.57***	-0.59***	-0.10	0.98****		-0.48**	-0.13
Bulk density‡	-0.25	0.34*	-0.03	0.09	0.29	-0.01	-0.57***	-0.80****	0.80****	0.83****	0.88****	-0.61***	-0.64****		-0.45**
Specific draught‡	0.31	0.07	0.26	0.31	-0.02	-0.25	-0.25	-0.36*	0.57***	0.49**	0.30	-0.23	-0.26	0.55***	

*: p<0.05, **: p<0.01, ***: p<0.001, ****: p<0.0001

Figure 1. Spatial distribution of clay (< 2 μm) and silt+clay (< 20 μm) across plots in the B5-field of the Askov-LTE.
120x184mm (150 x 150 DPI)

Figure 2. Boxplot with median and quartiles for SOC content for individual fertilization treatments in the B5-field. Different letters indicate significant differences in SOC content at P<0.05.
146x146mm (150 x 150 DPI)

Figure 3. Relationships between soil texture, SOC and water content in soil sampled in the B5-field at the autumn and spring measurement campaigns. 322x483mm (300 x 300 DPI)

Figure 4. Boxplot with median and quartiles for specific draught measured in the autumn and spring in individual fertilization treatments of the B5- field.
229x117mm (150 x 150 DPI)

Figure 5. Relationships between specific draught and soil texture, SOC content and water content in soil from the B5-field at the autumn and spring measurement campaigns.
320x480mm (300 x 300 DPI)

Figure 6. Specific draught normalized to clay content (SDfr/Clay) for different fertilization regimes in the B5-field at the autumn and spring campaigns. Letters denote significant difference in the autumn campaign at $P < 0.05$; no significant differences were observed in the spring measurement campaign. The fertilization regimes are: manure (all treatments given animal manure), NPK (all treatments with balanced addition of mineral fertilizer N, P and K) and unbalanced fertilization (unfertilized and all treatments with mineral fertilizer N, P and K added individually or in combinations of two).

141x132mm (300 x 300 DPI)

Figure 7. Relationships between grain yields of the previous winter wheat crop and specific draught normalized to clay content (SDfr/Clay) for the autumn (a) and spring (b) measurement campaigns. For definition of fertilization regimes see legend in Figure 6.

Figure 8. Relationships between grain yield of the previous winter wheat crop (a, early sown; b, timely sown) and specific draught normalized to clay content (SDFr/Clay) at the autumn measurement campaign. For definition of fertilization regimes, see legend in Figure 6.

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