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# Cereal Response to Deep Tillage and Incorporated Organic Fertilizer

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**Abstract:** This study examined the effect of stripwise subsoiling and subsoiling combined with the incorporation of organic material on crop development in a two-year field trial with typical weather in the first year and hot, dry weather in the second. Subsoiling and its combination with incorporated organic materials had strong effects on plant development and crop yield of spring barley (2017) and winter wheat (2018). The subsoil was loosened in 30 cm wide furrows down to a depth of up to 60 cm with a tine (DL) or a spader machine (SM) and was compared with the same methods of subsoil loosening combined with the incorporation of compost from biological household wastes (DLB and SMB). Furthermore, green waste compost (SMG), chopped straw (SMCS) and sawdust (SMS) were incorporated with the spader machine only. DL successfully reduced penetration resistance underneath the furrow and enhanced root growth underneath and near the furrow over the whole experimental period. Grain protein content above the furrow was enhanced compared with the untreated control (C) in the first year, but grain yield did not increase. DLB also reduced penetration resistance and increased root growth, but furthermore caused considerable increases in soil mineral nitrogen underneath the furrow throughout the vegetation period. Consequently, both yield and grain protein content above the furrow were tendentially increased as compared with the C. In SMB, grain yield increased even more than in DLB, compared to C, in 2017 (84% for SMB vs. 19% for DLB) and nearly equally in 2018 (65.4% vs. 65.2%) while all other treatments tendentially decreased grain yield above the furrow as compared with C. The results indicate that subsoiling with the introduction of organic material can reduce mechanical impedance and increase soil nitrogen and thereby ensure stable yields during dry periods, which become more frequent under climate change.

**Keywords:** compost; straw; sawdust; sub soiling; mechanical impedance

## 1. Introduction

Tillage is one of the main plant production measures influencing soil conditions. Evaluation and adaptation of tillage practices offers great potential to counteract the effects of climate change on crop growth. If field traffic causes soil compaction leading to a deterioration of topsoil and subsoil [1], crop development is highly affected. Soils respond with reduced permeability to water and air, increased surface runoff, erosion, flooding and reduced groundwater recharge [2]. The trend to warmer summers and the increased risk of heat waves may cause soil moisture deficits, which induce water stress for plants. Water stress is exacerbated in areas of soil compaction since the compacted zone dries out more severely, limiting the plant's ability to take up water and nutrients [3]. Roots are thickened, distorted and retarded in downward growth. In extreme cases, they may run horizontally for the most part. However, the risk of soil compaction strongly depends on soil type and crop rotation. Blanco-Canqui et al. [4] state that different tillage practices can affect the ability of soils to absorb and retain water which is of major importance considering climate change. While 'no-till' has been promoted as the solution of soil protection for more than a decade, current studies indicate that more attention should be drawn to the subsoil. Hartmann et al. [5] state that agronomic intensification has resulted in subsoil degradation and a decline of the productive potential of the soil. Since about 50% of the global soil organic carbon (SOC) is stored in the subsoil, this should not be underestimated [6,7]. This decline in the productive potential is widely recognized as a serious limitation for achieving a sustainable crop production. A recent meta-analysis [8] stated that sub soiling enables tremendous improvements of soil structure and thus plant development in soils with a root-restricting layer and with less than 70% silt. The main effects can be summarized as a reduced bulk density that intensifies overall root development [9,10], an increased infiltration capacity [4] and better access of roots to deeper water and nutrient reservoirs [5,11]. Long-term studies on alternating no-till/subsoiling concepts have shown that biennial subsoiling significantly improved soil physical properties and increased grain yield [12].

Additionally, soil water storage increased during fallow periods [12]. However, on some soils, subsoiling may even reduce crop performance as it may result in a complete collapse of the natural soil structure and thus aggregate compaction [8]. A changing climate implies changing temperatures which affect the subsoil less than the topsoil [7]. Furthermore, Wordell-Dietrich et al. [7] showed that mineralization rates are higher in the subsoil since the soil conditions are more stable compared with the topsoil. Enhanced carbon input into the subsoil is an efficient means to increase C sequestration [12], with the potential effect of both increasing soil fertility and mitigating climate change. Organic amendments are enriched in C, and it is well documented that they increase soil organic matter content [13–15]. According to Freibauer et al. [16], the increase in soil C content should be achieved by the addition of animal manure, crop residues, sewage sludge or compost, as the application of these materials can improve soil microbial activity. Thus, it seems reasonable to combine deep loosening with the incorporation of organic materials to enhance overall soil conditions. Deep soil loosening can counteract negative effects of topsoil and subsoil compaction, increasing the supply of water, nutrients and carbon during dry periods and at important physiological stages, while the organic material will increase carbon input into the subsoil and increase soil microbial activity.

Additionally, it may stabilize the loosened soil structure, thus potentially extending the duration of subsoiling effects and avoiding the observed collapse of natural soil structure with a subsequent compaction in fragile soils. The following study presents the effect of deep subsoil loosening in 30 cm wide furrows with and without the incorporation of organic material on barley and wheat growth. For deep loosening of the soil, two different tools (spader machine and deep working tine) were used. Four different organic materials were incorporated into the subsoil. The aim of this study was to test if (i) different deep loosening tools affect plant development, (ii) different organic materials combined with deep loosening affect plant development and (iii) which organic material influences plant growth the most. We hypothesized that plant growth would significantly increase, compared with the untreated control, because of deep loosening and deep loosening with incorporated organic material.

## 2. Materials and Methods

### 2.1. Experimental Setup

The field experiment was conducted at the 'Campus Klein-Altendorf' experimental research station (50°37′51″N; 6°59′32″E), University of Bonn, Germany. According to the Food and Agriculture Organization of the United Nations FAO standard [17], the soil can be classified as a Luvisol derived from loess. The mean annual air temperature is 9.4 °C and the mean annual precipitation is 603.4 mm. The weather conditions during the experimental period are shown in Figure 1.

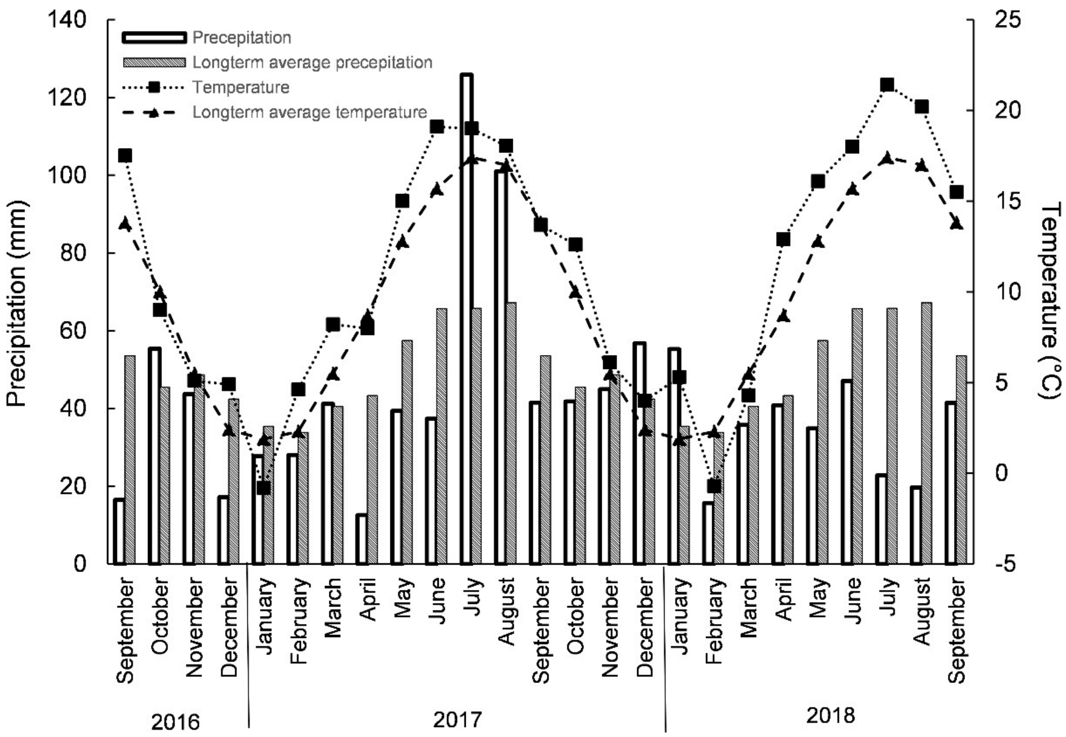


**Figure 1.** Overview of weather data during the vegetation period (2016–2018).

The experiment consisted of control plots and deep tillage plots using different tools and incorporated materials. In fall of 2016, all plots were tilled using a rotary harrow (Lemken Zirkon 300; 5 cm working depth) for seedbed preparation. The deep tilled plots additionally received a subsoil loosening in three steps (see Table 1). In the first step, a furrow of 30 cm width and depth was created using a one share plough. The furrow was created centered within the plot width of 3 m.

**Table 1.** Overview of tillage operations for subsoiling with and without organic material. DL: deep loosening with tine, SM: spader machine, DLB: deep loosening with tine and bio compost, SMB: spader machine and bio compost, SMS: spader machine and sawdust, SMCS: spader machine and chopped straw.

| Operation | Aim | Machinery | Treatments |
|---|---|---|---|
| Removal of A-horizon (0–30 cm) | Creation of a furrow (centered within 3 m; 30 cm × 30 cm; width × depth) | One plough share | DL, SM, DLB, SMB, SMS and SMCS |
| Loosening of the B-horizon (30–60 cm) | Subsoiling | Deep working tine<br>Spader machine | DL<br>SM |
| Deposition of organic material within the furrow | Fresh matter incorporation | Fodder mixer | DLB, SMB, SMS and SMCS |
| Mixing of B-horizon and organic material | Subsoiling with organic material | Deep working tine<br>Spader machine | DLB<br>SMB, SMS and SMCS |
| Passage with depth wheel | Recompaction of B-horizon | Depth wheel | DL, SM, DLB, SMB, SMS and SMCS |
| Passage with leveling panel | Return of A-horizon and closing of furrow | Leveling panel | DL, SM, DLB, SMB, SMS and SMCS |

For deep loosening and incorporation of material, two different strategies were used. In a first approach, a spader machine was used and in a second approach, a tine was used to incorporate the material into the B-horizon. Both tools worked within the furrow and the target working depth was set up to 60 cm, thus working within the soil depth 30–60 cm. However, the spader machine could not intermix the biocompost up to this depth and it just reached a working depth up to 45 cm. Furthermore, the incorporation of the different materials was very heterogenous. Thus, further soil analyses (including penetration resistance measurements and root analysis) were not undertaken for these treatments. After this, the soil was reconsolidated using a depth wheel and the A-horizon was laid back into the furrow using a leveling panel. Regular tillage followed, using a rotary harrow for seedbed preparation. Mustard was sown as a catch crop during the fall term. Mustard was mulched in spring of 2017 and the field was chisel ploughed (15 cm) twice before the rotary harrow (10 cm) with seedbed preparation took place. The experimental field received 70 kg $ha^{-1}$ of calcium ammonium nitrate as general fertilization at the end of March 2017 and 100 kg $ha^{-1}$ at the end of March 2018. Spring barley (330 seeds $m^{-2}$) was sown at the end of March 2017 and harvested in August. Mustard was sown at the beginning of September 2017 and winter wheat (300 seeds $m^{-2}$) was sown at the end of October 2017 and harvested in July 2018.

The complete experiment consisted of eight treatments in a threefold replication, with plots of 3 m × 15 m (width × length). The experiment was designed as a complete randomized block design. An overview of the different treatments is given in Table 2. It should be noted that only a small portion of the total nitrogen applied with the incorporated materials became plant available each year.

**Table 2.** Overview of the different treatments with amounts of incorporated materials in t $ha^{-1}$ and. incorporated nitrogen in kg $ha^{-1}$. C: control, SMG: spader machine and green waste compost.

| Treatment | Tillage Operation | Incorporated Material | Fresh Matter Incorporated (t $ha^{-1}$) | N Incorporated (kg $ha^{-1}$) |
|---|---|---|---|---|
| C | no deep tillage | no material | - | - |
| DL | tine | no material | - | - |
| SM | spader machine | no material | - | - |
| SMB | spader machine | bio compost | 50 | 641 |
| SMG | spader machine | green waste compost | 50 | 355 |
| SMS | spader machine | sawdust | 50 | 58 |
| SMCS | spader machine | chopped straw | 50 | 246 |
| DLB | tine | bio compost | 50 | 641 |

The field site was used for nutrient depletion experiments in the years before establishing the field trial. Nutrient depletion started in 2013 with a soil composition of 26 mg $K_2O$, 26 mg $P_2O_5$, 7 mg MgO, pH value of 6.7 and humus content of 1.7%. Crop rotation included winter barley (2014 and 2015) and winter wheat (2016). Fertilization started again after the harvest of 2016 with a soil composition of 10 mg $K_2O$, 20 mg $P_2O_5$, 7 mg MgO, pH value of 6.5 and humus content of 1.3%. After fertilization (2017) the soil had nutrient contents of 18 mg $K_2O$, 22 mg $P_2O_5$, 8 mg MgO, a pH value of 6.9 and humus content of 1.6%. Primary soil tillage including ploughing and seedbed preparation was undertaken after the harvest of 2016 using a rotary harrow. A disc cultivator was used for stubble incorporation.

*2.2. Characterization of Material*

The four materials were chosen based on their accessibility and economic feasibility for farmers. The biocompost was a fresh compost, which means that the rotting process was not finished, and was based on kitchen wastes from private households. The green waste compost was a finished compost based on trees, bushes and shrubs from public green spaces and parkland. Sawdust was based on soft wood (from pine trees) and chopped straw consisted of wheat straw. Table 3 shows the sieving analysis and compounds of the materials.

**Table 3.** Sieving analysis and dry matter content, C %, N%, P%, K% and C:N of incorporation material.

| Material | Sieving Analysis (%) | | | | | | | | Dry Matter (%) | Total C (%) | Total N (%) | Total P (%) | Total K (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | <3 mm | 3–6 mm | 6–10 mm | 10–15 mm | 15–20 mm | 20–25 mm | >25 mm | C:N | | | | | |
| Chopped straw [1] | 5 | 10 | 7 | 5 | 3 | 2 | 68 | 78:1 | 89.5 | 42.84 | 0.55 | 0.22 | 1.3 |
| Sawdust [1] | 15 | 20 | 62 | 2 | 1 | - | - | 370:1 | 90.4 | 50.23 | 0.13 | 0.01 | 0.06 |
| Green compost [2] | 58 | 14 | 12 | 8 | 4 | 3 | 1 | 24:1 | 60.7 | 48.00 | 1.17 | 0.44 | 0.92 |
| Bio compost [2] | 71 | 11 | 7 | 7 | 2 | 2 | - | 13:1 | 66.8 | 41.80 | 1.92 | 0.75 | 1.50 |

[1] Analysis of components and C:N: external lab analysis. [2] Analysis of components and C:N: quality certification of composting plant.

### 2.3. Plant Development and Grain Quality

To determine the impact of subsoiling and deep incorporation of organic materials, standard plant observations were undertaken. Measurements were made centered in each plot in a twofold repetition. For each repetition, data from one meter was recorded. Thus, in total, two meters per plot were recorded in three field replicates. The number of plants (after crop emergence) and the number of ears (after flowering) were counted. Plant height was measured at the final plant height (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie-BBCH 87 according to the standard system of German 'Bundessortenamt' [18]). At the time of threshing ripeness (BBCH 99), the two meters were harvested manually. Dry matter yield, straw yield and grain yield were determined following the standard plant observation system of the German 'Bundessortenamt' [18]. Thousand kernel weight (TKW) was calculated, grains were sieved and near-infrared technology (Perten DA7250TM NIR analyzer) was used to determine protein and starch content.

### 2.4. Penetrometer Measurements

Penetration resistance was measured shortly after crop emergence, after the harvesting of spring barley and after the harvesting of winter wheat. The C (control), and treatments DL (deep loosening with tine) and DLB (deep loosening with tine and bio compost) were measured. The penetration resistance curve equaled the average values of $n$ = 9 measurements in the center of the plot. A penetrometer that equaled the standard of the American Society of Association Executives (ASAE) norm was used [19,20], with a cone size of 1 cm in diameter and an angle of 30°.

### 2.5. Soil Sampling for Monitoring Soil Mineral Nitrogen ($N_{min}$) and Gravimetric Soil Water Content

Soil samples were taken 9 May and 21 July, 2017, and 25 April, 28 May and 31 July, 2018 using a Pürckhauer auger. All three field replicates were sampled ($n$ = 3), except for 9 May, 2017 when only two field replicates were sampled and 31 July where, because of very time-consuming sampling in very dry soil, the number of samples was reduced to two per plot and thus samples from all three field replicates were merged to gain enough material for analysis. In each plot, five samples from 0 to 100 cm soil depth (directly divided into samples 0–30 cm, 30–50 cm, 50–60 cm, 60–70 cm, 70–100 cm according to soil horizons and melioration depth) and additionally four samples from 0–30 cm depth (due to larger heterogeneity in the topsoil) were taken in the area of the furrow. The soil samples were cooled directly after sampling, then frozen at −18 °C and, after extraction with potassium sulfate, analyzed for $NO_3^-$ and $NH_4$+ using a continuous flow analyzer (wavelengths 540 nm and 660 nm, Verband deutscher landwirtschaftlicher Untersuchungs- und Forschungsanstalten e.V.-VDLUFA 1991). $NO_3^-$ and $NH_4$+ were summarized as plant-available soil nitrogen [21]. Gravimetric soil water content was analyzed from 50 g of soil per sample. The treatments C, DL and DLB were measured.

### 2.6. Analysis of Root-length Density (RLD)

Root-length density (RLD) of spring barley and winter wheat was quantified with the profile wall method [22] on 6 July 2017 and from 4–6 June 2018 during anthesis. In 2017 two field replicates were sampled and in 2018 three field replicates ere sampled within the treatments C, DL and DLB. An excavator was used to install a trench with a depth of 130 cm (2017) or 230 cm (2018) at the front end of each plot. After flattening a 100 cm wide vertical profile wall transversely to the plant rows, 0.5 cm of soil was rinsed off with tap water from a crop sprayer, with simultaneous scratching by use of a fork. Afterwards, a 100 × 60 cm length times width counting frame was placed on the profile wall. In 2017, the frame was adjusted with the left side in the middle of the furrow, with the aim to assess the RLD gradient from underneath the furrow towards the undisturbed soil. However, since this resulted in a larger area covered for the undisturbed soil than for the treatment, in 2018 this procedure was changed, and the counting frame was centered over the furrow. Root length was quantified by visual estimation of the length (cm) in 240 squares of 5 cm × 5 cm size in a range of 100 cm width, from surface soil until 135 cm depth (spring barley 2017) or 180 cm depth (winter wheat 2018). Roots in holes were not considered.

Root length (cm) from the soil profile wall was converted into root length density (RLD) (cm cm$^{-3}$) by dividing by 12.5 cm$^{-3}$ (soil volume: 5 cm (height) × 5 cm (width) × 0.5 cm (depth) = 12.5 cm$^{-3}$). Data were evaluated for three (2017) or four soil depth classes (2018) in three distance classes: underneath the furrow (3 or 6 squares, respectively), near the furrow (4 or 8 squares, respectively) and away from the furrow (13 or 6 squares, respectively) (Table 4). This procedure was not applied for control plots; here, all 20 squares entered into the analysis. In 2018, one field replicate of the DL treatment was not considered for data analysis because it deviated strongly from all other plots with only very few roots present.

**Table 4.** Distance classes on the profile wall 2017 and 2018, showing the three categorized distances classes underneath the furrow, near the furrow and away from the furrow and the four depth classes of 0–30, 30–60, 60–120 and 120–180 cm.

| **2017** | **Underneath Furrow (15 cm)** | | | **Near Furrow (20 cm)** | | | | **Away from Furrow (65 cm)** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Depth (cm)** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 0–30 | | | | | | | | | | | | | | | | | | | | |
| 30–60 | | | | | | | | | | | | | | | | | | | | |
| 60–135 | | | | | | | | | | | | | | | | | | | | |
| **2018** | **Away from Furrow (15 cm)** | | | **Near Furrow (20 cm)** | | | | **Underneath Furrow (30 cm)** | | | | | | **Near Furrow (20 cm)** | | | | **Away from Furrow (15 cm)** | | |
| **Depth (cm)** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 12 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 0–30 | | | | | | | | | | | | | | | | | | | | |
| 30–60 | | | | | | | | | | | | | | | | | | | | |
| 60–120 | | | | | | | | | | | | | | | | | | | | |
| 120–180 | | | | | | | | | | | | | | | | | | | | |

### *2.7. Statistical Analysis*

Statistical analysis of variance of data was conducted using IBM SPSS 20 for Microsoft Windows. A one-way ANOVA followed by Tukey's significant difference test was conducted to figure out the significant effects of each treatment on the development of spring barley and winter wheat. RLD was statistically tested for treatment, depth and distance effects. The nonparametric Kruskal–Wallis test followed by Dunn–Bonferroni correction with a significance level of 0.05 was performed using IBM SPSS Statistics version 24. Nonparametric tests were used because the normal distribution of data was not always provided.

## 3. Results

### 3.1. Effects on Yield Formation

Single subsoiling and subsoiling combined with deep incorporation of organic material impacted on plant development in different ways was compared with the untreated control treatment for both years. The number of plants was not affected in both years. The number of ears was higher under SMB (spader machine and bio compost) compared with C in 2017, while in 2018 it was higher than under DL, SM (spader machine), SMG (spader machine and green waste compost) and SMS (spader machine and sawdust) but not higher than C (Table 5). Concerning yield (Figure 2) SMB showed the highest dry matter yield in both years. However, these differences were not statistically significant. In 2017, the dry matter yields of SMG, SMS and SMCS (spader machine and chopped straw) were lower than SMB but not lower than C. Straw yield and grain yield was lowest for SMG in 2017 and for SMS in 2018. No significant differences in grain yield compared to C were detected in both years. The treatments SMB and DLB had higher straw yields than C in 2017 and 2018.

Maximum plant height of SMB and DL was significantly higher than C under spring barley and winter wheat. Plants under SMS were the smallest (63 cm and 50 cm). The 1000-kernel weight (TKW) differed only for spring barley, with the highest TKW under SMB and the lowest under SMG, which was significantly lower than the control.

**Table 5.** Yield parameters of spring barley (2017, year 1) and winter wheat (2018, year 2). Different letters indicate significant differences between the treatments in each year ($p < 0.05$, Tukey's test), C: control, DL: deep loosening with tine, SM: spader machine, SMB: spader machine and bio compost, SMG: spader machine and green waste compost, SMS: spader machine and sawdust, SMCS: spader machine and chopped straw, DLB: deep loosening with tine and bio compost. [1] 1000-kernel weight (TKW).

| Crop | Treatment | Number of Plants ($m^{-2}$) | Number of Ears ($m^{-2}$) | Maximum Plant Height (cm) | TKW [1] (g) | Protein Content (%) | Starch Content (%) |
|---|---|---|---|---|---|---|---|
| Spring barley | C | 143 | 551 a | 73 cd | 48.3 bc | 11.1 ab | 54.7 abc |
| | DL | 147 | 897 ab | 76 de | 49.0 bc | 12.8 c | 54.0 ab |
| | SM | 123 | 801 ab | 74 de | 45.3 abc | 11.1 b | 55.2 bcd |
| | SMB | 152 | 1123 b | 78 ef | 49.5 c | 14.2 cd | 53.9 a |
| | SMG | 143 | 564 a | 67 b | 41.7 a | 9.7 a | 55.7 cd |
| | SMS | 129 | 548 a | 63 a | 43.5 ab | 9.8 ab | 55.8 d |
| | SMCS | 143 | 576 a | 70 bc | 45.5 abc | 10.2 ab | 55.9 d |
| | DLB | 140 | 708 ab | 80 f | 45.0 abc | 14.6 d | 54.0 a |
| Winter wheat | C | 255 | 301 abc | 54 a | 28.7 | 9.8 a | 74.3 |
| | DL | 229 | 263 a | 56 a | 27.2 | 10.2 ab | 74.0 |
| | SM | 267 | 288 ab | 54 a | 27.2 | 10.5 abc | 73.3 |
| | SMB | 243 | 444 c | 68 b | 29.0 | 13.0 c | 72.7 |
| | SMG | 207 | 268 a | 52 a | 28.2 | 10.5 a | 74.0 |
| | SMS | 244 | 267 a | 50 a | 25.3 | 10.3 ab | 73.5 |
| | SMCS | 229 | 311 abc | 52 a | 29.5 | 9.8 a | 74.0 |
| | DLB | 263 | 425 bc | 67 b | 29.0 | 12.2 bc | 73.2 |

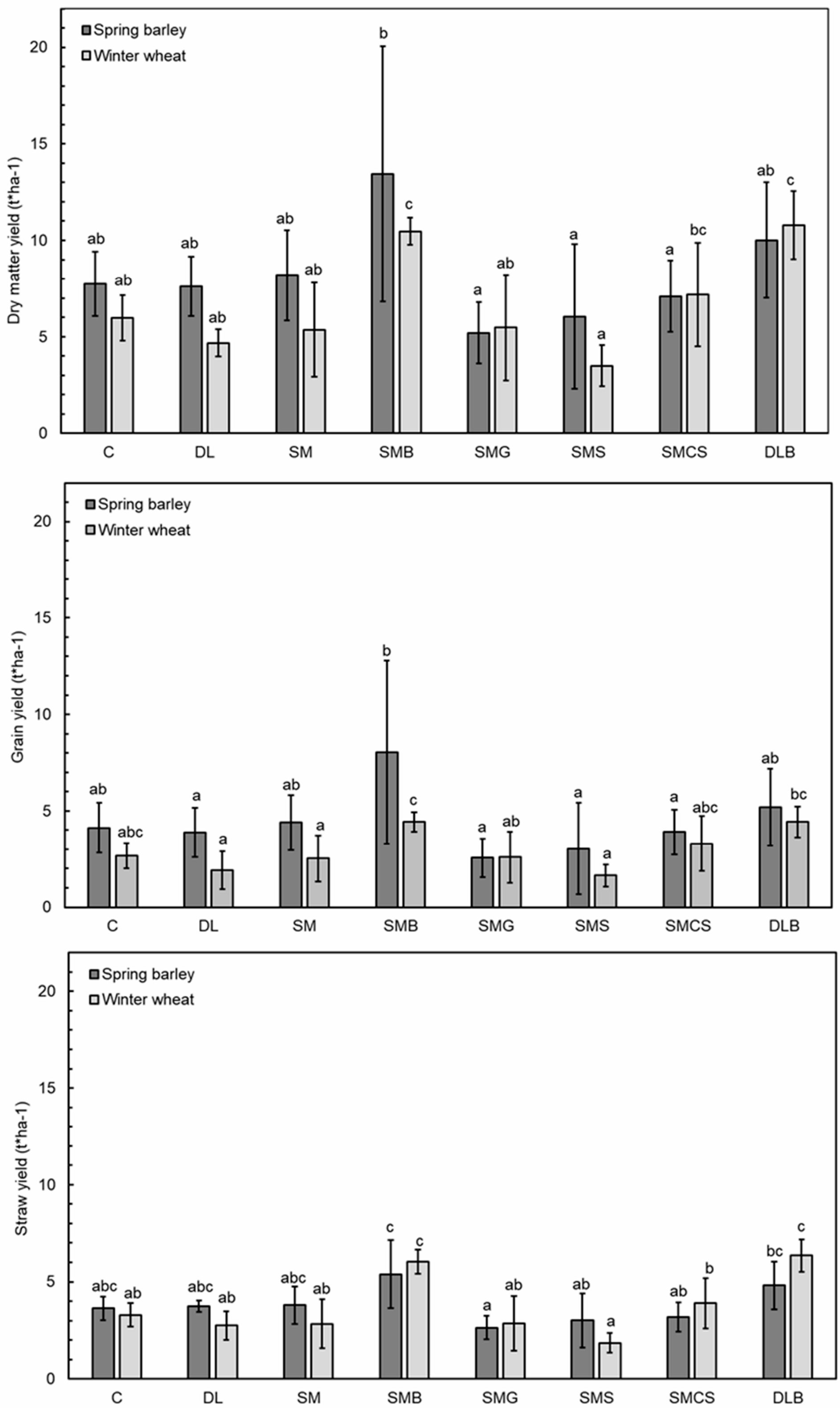


**Figure 2.** Dry yield, grain yield and straw yield of spring barley (2017) and winter wheat (2018). Different letters indicate significant differences between the treatments in each year ($p < 0.05$, Tukey's test), error bars represent ± SD ($n = 6$). C: control, DL: deep loosening with tine, SM: spader machine, SMB: spader machine and bio compost, SMG: spader machine and green waste compost, SMS: spader machine and sawdust, SMCS: spader machine and chopped straw, DLB: deep loosening with tine and bio compost.

### 3.2. Effects on Root Development

RLD was measured directly underneath the furrow, near the furrow and away from the furrow. In 2017 (spring barley) the soil was classified into three layers, while in 2018 (winter wheat) it was classified into four layers because of higher rooting depth of the winter cereal. In 2017 the RLD of DL and DLB was significantly higher underneath the furrow, up to 60cm soil depth (Figure 3). Moreover, the RLD of DLB was increased up to 135cm soil depth. While these differences persisted near the furrow, being away from the furrow at only 30–60 cm soil depth DL resulted in higher RLD as compared with the other two treatments. In 2018, the RLD underneath the furrow of both DL and DLB was increased with up to 60 cm soil depth, but was different from 2017 below this depth, with only DL resulting in higher RLD. Near the furrow and away from the furrow, the differences in the topsoil and in the 30–60 cm layer persisted, but below 60 cm DLB also had higher RLD in deeper soil layers.

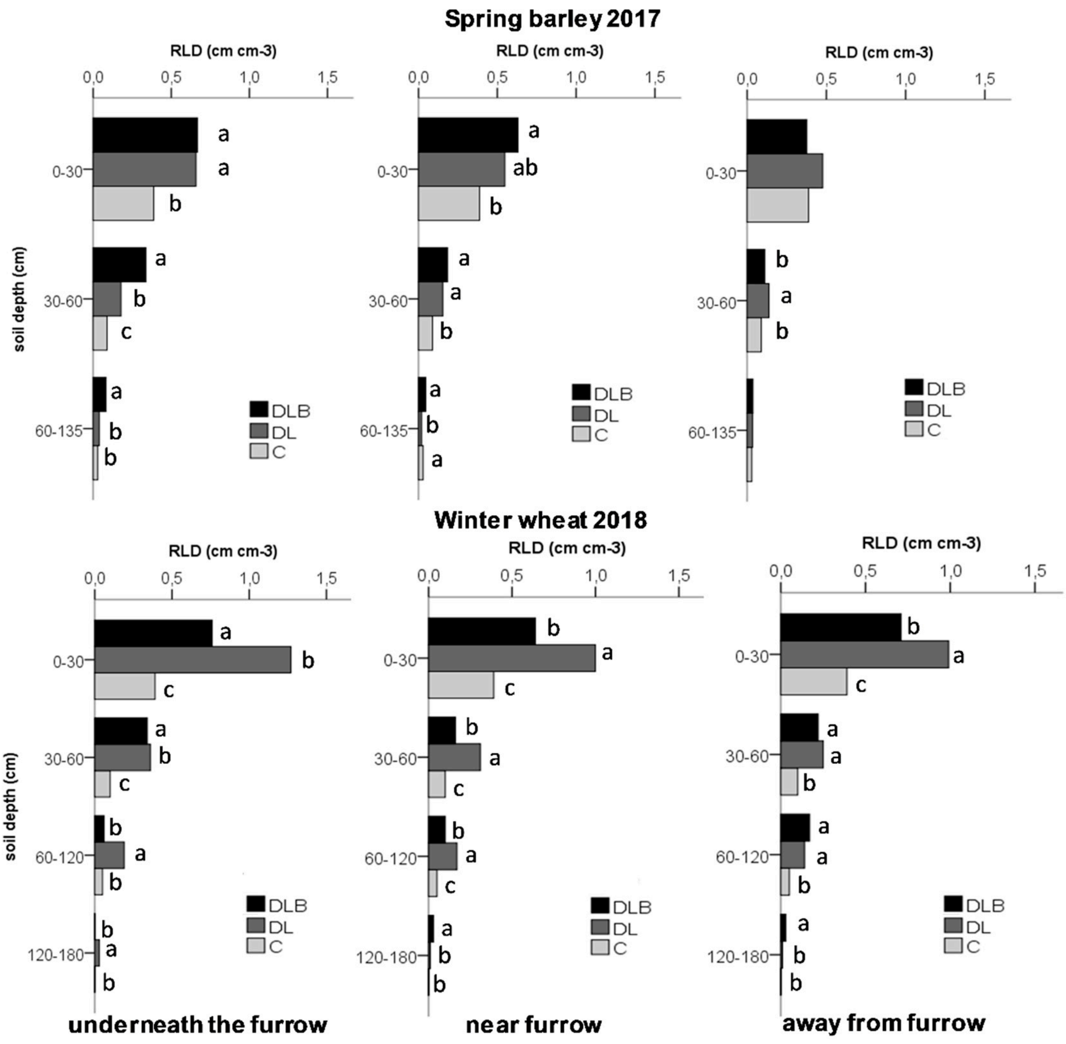


**Figure 3.** Mean root-length density of three soil depth classes (2017) and four soil depth classes (2018). From left to right: directly underneath the furrow, near the furrow (up to 20 cm distance) and away from the furrow (2017: 20–85 cm distance, 2018: 20–35 cm distance). Different letters indicate significant differences (Kruskal–Wallis test followed by Dunn–Bonferroni correction, $p < 0.05$). C: control, DL: deep loosening with tine, DLB: deep loosening with tine and bio compost, RLD: root-length density.

### 3.3. Effects on Soil $N_{min}$ and Soil Dry Matter

The deep loosening of the soil and deep loosening combined with the introduction of organic material caused changes in soil mineral nitrogen ($N_{min}$) content. Figure 4 shows the concentration of $N_{min}$ over the experimental period. The introduction of biocompost clearly increased $N_{min}$. After the dry April 2017, $N_{min}$ was high in all treatments in May 2017, however, in DLB, it was about twice that of C and DL, with 130 kg ha-1 below 30 cm soil depth. In July 2017, $N_{min}$ was strongly reduced in all treatments and the major part of $N_{min}$ could be found in the topsoil up to 30 cm. Until April 2018, $N_{min}$ was increased in deeper soil layers in all treatments. This effect was highest under DLB. Differences between C and DL were negligible up to a depth of 60 cm. However, $N_{min}$ of DLB was constantly approximately twice as high as C and DL. Furthermore, in July 2018 an increase in $N_{min}$ was observed compared with July 2017 and May 2018, especially up to 60 cm.

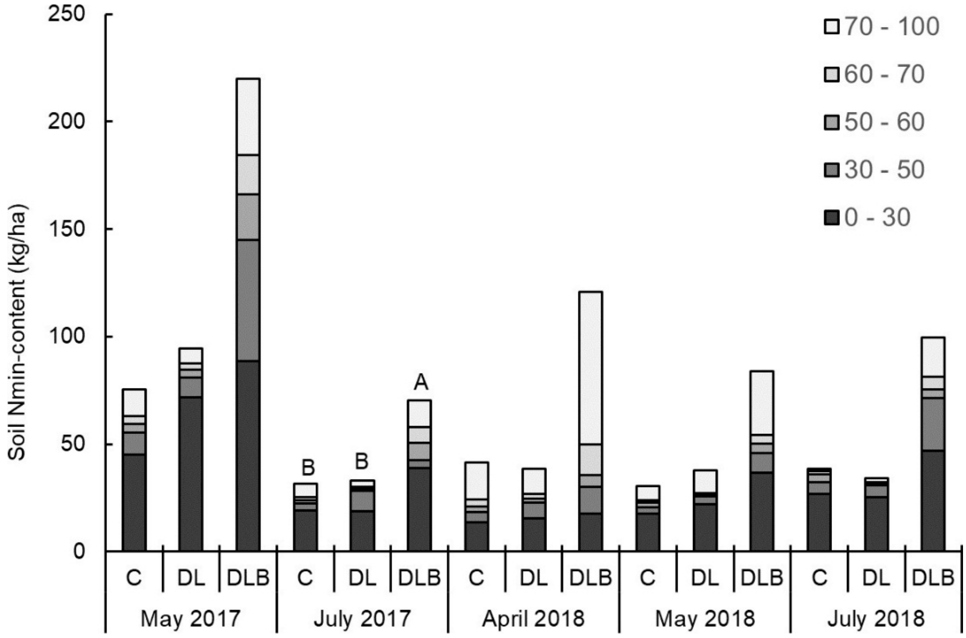


**Figure 4.** Soil mineral nitrogen at five sampling dates in five soil depth classes, respectively. Different letters indicate significant differences of within one sampling date (Tukey's test, $p < 0.05$). In May 2017 (only two field replicates sampled) and July 2018 (samples from three field replicates merged) statistical evaluation was not possible. C: control, DL: deep loosening with tine, DLB: deep loosening with tine and bio compost.

Soil water content was generally lower in the unusually dry year of 2018 than in 2017 (Table 6). Furthermore, in 2018, soil water content decreased with soil depth and throughout the cropping season. At all sampling dates in both years, DLB had the lowest water content in 70 cm soil depth, i.e., directly underneath the compost deposit. In April 2018, this difference was significant.

**Table 6.** Gravimetric soil water content in five soil depth classes. Different letters indicate significant differences within one sampling date (Tukey's test, $p < 0.05$). In May 2017 (only two field replicates sampled) and July 2018 (samples from three field replicates merged) statistical evaluation was not possible. C: control, DL: deep loosening with tine, DLB: deep loosening with tine and bio compost.

| Date | Treatment | Gravimetric Water Content (%) of Soil Depth Classes | | | | |
|---|---|---|---|---|---|---|
| | | 0–30 cm | 30–50 cm | 50–60 cm | 60–70 cm | 70–100 cm |
| May 2017 | C | 16.3 | 15.8 | 16.6 | 16.7 | 16.8 |
| | DL | 16.5 | 16.6 | 16.9 | 17.2 | 17.0 |
| | DLB | 19.0 | 17.6 | 16.4 | 16.8 | 17.4 |
| July 2017 | C | 13.6 | 8.9 | 10.4 | 11.7 | 13.6 |
| | DL | 14.3 | 10.2 | 11.3 | 12.0 | 13.1 |
| | DLB | 14.6 | 9.2 | 10.5 | 11.1 | 13.0 |

**Table 6.** *Cont.*

| Date | Treatment | Gravimetric Water Content (%) of Soil Depth Classes | | | | |
|---|---|---|---|---|---|---|
| | | 0–30 cm | 30–50 cm | 50–60 cm | 60–70 cm | 70–100 cm |
| April 2018 | C | 14.4 | 15.9 | 16.3 | 17.0 b | 17.6 |
| | DL | 15.0 | 15.8 | 16.6 | 17.0 b | 17.3 |
| | DLB | 14.9 | 16.0 | 16.2 | 16.4 a | 17.3 |
| May 2018 | C | 11.6 | 13.9 | 15.3 | 16.0 | 16.1 |
| | DL | 12.7 | 12.8 | 14.6 | 16.4 | 15.9 |
| | DLB | 12.2 | 13.5 | 14.2 | 14.8 | 16.0 |
| July 2018 | C | 9.5 | 12.6 | 12.3 | 14.7 | 15.1 |
| | DL | 8.4 | 12.2 | 14.4 | 15.3 | 15.0 |
| | DLB | 8.5 | 11.8 | 14.2 | 13.2 | 14.8 |

### *3.4. Effects on Penetration Resistance*

Measurements of penetration resistance (Figure 5) showed that after crop emergence in 2017, penetration resistance was lower in DL and DLB compared to Cup to 60 cm soil depth. These differences persisted until the harvest of 2017, but after the harvest of 2018, only DL had lower penetration resistance as compared with the control.

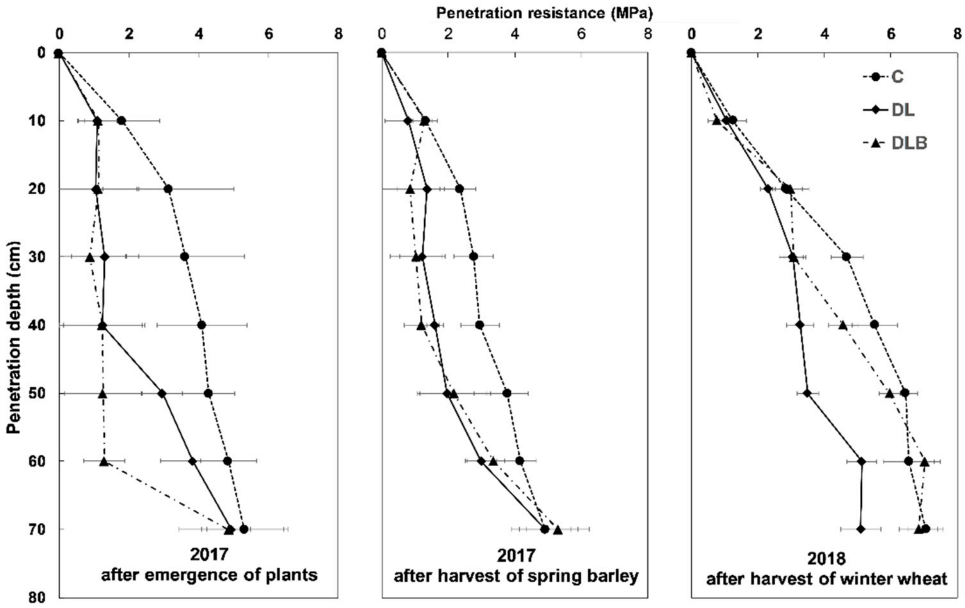


**Figure 5.** Measurements of penetration resistance. Measurements represent average values of $n = 9$ measurements. Error bars represent ± SD ($n = 9$). C: control, DL: deep loosening with tine, DLB: deep loosening with tine and bio compost.

## 4. Discussion

### *4.1. Effect of Sub Soiling and Incorporation of Organic Material on Yield and Root Development*

The results of this study show that deep soil loosening or deep soil loosening with the incorporation of organic material can affect plant development. Generally, single deep soil loosening (subsoiling) reduces bulk density and deepens the active soil layer, thus promoting root growth into deeper soil layers, as roots are more prone to grow downwards with deeper subsoil tillage [9]. Ghosh et al. [10] associated this effect with improved water storage and a higher root-length density. A meta-analysis comparing different deep tillage options by Schneider et al. [8] concluded that deep tillage causes on average a 20% increase in crop yield at sites with root-restricting layers. However, the individual response depends on the soil type and ranges from slight increases in yield up to large yield depressions.

Statistical analyses of the treatments in comparison to the control allowed a separation into two groups—those treatments that increased yield and those that decreased yield, as compared to the control. The treatments SM, SMB and DLB increased yield, while SMG, SMS and SMCS decreased yield in 2017. Under the treatment DL, only some yield parameters decreased, while others increased. In 2018, only the treatments SMB and DLB increased yield parameters in comparison to C. Treatments DL, SMG, SMS and SMCS showed no significant differences as compared to C.

The main differences between the different treatments were (i) the working depth of the deep loosening tool, with effects on penetration resistance and (ii) C:N ratio and structure of the filling material, affecting N supply to the crops throughout the vegetation period. With respect to the latter, our results clearly show that bio compost as the material with the lowest C:N ratio and the finest structure was the only material with yield increasing effects, while all other materials decreased yield. Diacono et al. [14] argue that the prompt availability of N, introduced from compost application, is very low since the majority is bound to the organic N-pool. This contrasts with the significantly taller plants in SMB and DLB as compared to C in both years in our study and is presumably due to the effect of extra N from compost, as the plant height of DL and SM was not significantly higher, thus the subsoil loosening tool was not the deciding factor. Moreover, the organic matter may have improved soil physical properties, e.g., the water holding capacity. The incorporation of bio compost is accompanied by the introduction of microorganisms. This stimulates plant growth and ensures proper N supply during the early growth stages and after pollination [23]. Abiven et al. [15] and Diacono et al. [14] summarized that easily decomposable products have an intense and transient effect on aggregate stability (bio compost) while more recalcitrant products have a less pronounced but longer lasting effect (sawdust and chopped straw, and in our study also green waste compost). The presence of sawdust can increase soil acidity and affect plant growth negatively because of competition for nutrients [24]. In contrast, cereal straw can improve soil quality and productivity [25]. Negative effects on plant germination were expected for plants under SMCS. Procházková et al. [26] stated that straw is a main source of essential organic matter supplied to the soil, but its incorporation into the soil can affect germination and plant establishment negatively. However, these expected differences were not observed. The lowest number of ears and the smallest maximum plant height occurred under SMS in both years. SMS and SMCS decreased yield compared with C. Plants of SMS were the smallest of all treatments and produced fewer ears than C in both years. Wei et al. [24] summarized that straw incorporation can restock the soil organic matter by enhanced carbon input, which has a positive effect on the accumulation and utilization of nutrients. Even though Procházková et al. [25] also designate straw to be an essential pool of organic matter to the soil, their studies show that straw incorporation results in a significant reduction of yields, which is consistent with our results. The authors argue that this was based on physical and biochemical effects. These effects include water consumption for straw decomposition and the release and production of phytotoxic substances from straw during decomposition. Furthermore, with sawdust, a highly-lignified product is incorporated into the soil, which causes an increase in the population of soil microorganisms, thereby immobilizing N [27]. This explanation is supported by the very large C:N ratio of SMS and significant smaller plants compared to C.

With respect to the different loosening tools, results are more complex. Our study identified that the two deep loosening tools affected plant development differently. The tine breaks up the soil structure and creates a new microstructure of the subsoil. This microstructure consists of soil aggregates which are differently sized. The working depth is around 60 cm. In contrast, the spader machine, with its rotary motion, creates a new microstructure with nearly uniform soil aggregates, and the working depth was clearly lower than 60 cm. However, when applied without incorporation of any material, the two loosening tools resulted in similar yield parameters in both years—the only difference was higher grain protein content in DL in 2017. Plants of DL and SM produced more ears than C (Table 4) but grain yield was only slightly increased for SM in 2017. Ji et al. [28] showed that deep tillage (up to 30 cm) increased RLD at the soil layer by 10–40 cm on loamy soils and by 0–30 cm on clayey soils. Furthermore, they demonstrated that bulk density was reduced, and soil water content increased. Similarly, in our study, in DL and presumably also in SM, reduced penetration resistance allowed deeper rooting of plants, thus the possibility to access water stored in deeper soil layers at important physiological stages. The studies of Kirkegaard et al. [11] demonstrated that under conditions of drought, water stored deeply in the soil profile is highly valuable to crop yield as it becomes available during grain filling. Presumably, in our study, crops of DL benefitted from subsoil water used before anthesis in 2017 more than crops of SM, since TKW was tendentially higher. Concerning yield formation in 2018, the impact of weather was a major parameter. After abundant rainfall in winter and spring, summer was extremely dry. These weather conditions were reflected in much lower ear numbers, TKW and grain yield over all treatments as compared with 2017. Muñoz-Romero [29] pointed out that rainfall is one of the main determining factors for RLD. Under these weather conditions, RLD in DL was two to three times higher than in the control throughout all distance classes and soil depths, which, however, did not result in higher yield parameters and grain yield. Thus, the high investment of assimilates into roots was obviously not compensated by higher nutrient and water uptake in this treatment. Since, at the site under study, no root-restricting layer was present before subsoiling, these results are in line with the meta-analysis by Schneider et al. [8].

The differences between the two working tools also influenced the results of SMB and DLB. The two deep loosening tools with incorporation of bio compost (SMB and DLB) also resulted in similar yield parameters in both years—in contrast to mere deep loosening (SM and DL), both had clear differences as compared with the control. Surprisingly, crop performance in SMB increased even more as compared with DLB, with a much higher ear number (77% higher than C in SMB vs. 11% higher than C in DLB), tendentially higher TKW and much higher grain yield (84% vs. 19% higher than C) in 2017. In 2018, only grain protein content was slightly higher in SMB than in DLB. We assume that the fertilizing effect of the incorporated compost was probably higher in SMB in both years, since the spader machine mixed bio compost and subsoil more evenly than the tine in the areas of the plot where the target working depth was reached. Thus, plants of SMB could translocate extra N from compost directly into grain development. However, we could also observe that the total distribution of bio compost mixed in by the spader machine was heterogeneous throughout the whole furrow since the machine could not reach the target working depth. This was reflected by very high SD in yields of SMB. In contrast, in DLB the crops presumably profited more from reduced penetration resistance in deeper soil layers. This assumption is supported by the fact that only in 2017 was grain yield higher in SMB as compared with DLB, while in 2018 it was similar, i.e., the deeper subsoil loosening in DLB may have compensated for by the higher fertilizer effect in SMB. However, as the data on water content and penetration resistance show, in DLB the loosening effect also did not persist throughout the dry season in 2018—below 50 cm soil depth, penetration resistance in DLB was not any more lower than in C, and the water content in 70 cm soil depth was significantly or tendentially lower in DLB as compared with the control at all sampling dates in 2018. As a consequence, root growth underneath the furrow was not increased in DLB in 2018, rather, the increased RLD in DLB below 60 cm near and away from the furrow suggests that the roots seemed to have grown around the dry soil layer.

### 4.2. Effect of Sub Soiling and Incorporation of Organic Materials on Soil Parameters

Deep soil loosening causes an increase in infiltration capacity of soil [4]. Hartmann et al. [5] summarized that loosened furrows can be preferential pathways for water infiltration, even if changes in porosity characteristics are limited. The increased moisture content in the furrow can reduce penetration resistance, and root growth into the subsoil is facilitated. Besides the effect of deep loosening, the introduction of organic material further changes soil properties. The introduction of compost can increase soil pH levels and soil nitrogen content [30]. Our measurements of soil $N_{min}$ (Figure 4) show that the incorporation of bio compost was a major source of nitrogen for plants. $N_{min}$ of

DLB was about twice as high as C directly after crop emergence (May 2017) and remained higher during the whole experiment. Single deep soil loosening also increased $N_{min}$ in the topsoil compared with C. To what extent the high $N_{min}$ contents in DLB are prone to leaching has to be clarified in future studies to ensure environmental sustainability of the procedure. Also, compost application to the topsoil should be compared with compost incorporation into the subsoil to learn whether improved access to deeper soil layers combined with depositing organic nitrogen sources can secure yields, especially in years with dry spells when topsoils dry out and their nitrogen reserves become unavailable to crops.

Measurements of penetration resistance show that C has a continuous increase in resistance during the whole experimental period (Figure 5). Penetration resistances of DL and DLB demonstrate that the soil was efficiently loosened in up to 60 cm soil depth (DL) and up to 40 cm soil depth (DLB). After the harvest in 2018, penetration resistances were higher than in 2017 in all treatments, probably due to the very dry soil. The penetration resistance of DL was still lower than that of C, while in DLB, below 50 cm soil depth there was no difference from the control. A possible explanation is that the soil was also tendentially drier in DLB below 50 cm soil depth and significantly drier below 60–70 cm soil depth as compared with DL. A reason for these differences may be the high water holding capacity of the compost, which prevented infiltration of water from precipitation to deeper soil layers.

## 5. Conclusions

The present study confirmed that on regularly tilled soils, deep subsoil loosening alone does not necessarily result in higher grain yield, even though the objective of reducing penetration resistance and consequently increasing root growth throughout the soil profile was successfully accomplished. Incorporation of chopped straw, sawdust or green waste compost even resulted in tendentially or significantly lower grain yield as compared with the control. Therefore, these materials do not seem to be suitable for stabilizing the loosened soil structure. In contrast, subsoiling combined with incorporation of compost from biological household wastes increased both root growth and grain yields, probably due to both reduced penetration resistance and higher contents of soil mineral nitrogen. The following years will show how long the effects of reduction in penetration resistance and increased contents of soil mineral nitrogen persist. Furthermore, future studies should quantify N leaching to ensure environmental sustainability of the procedure. The results of the first two years presented here indicate that subsoiling with the introduction of organic material can reduce mechanical impedance and increase soil nitrogen and thereby ensure stable yields during dry periods, which are becoming more frequent under climate change.

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